Impacts on the Grid from Wind Energy Generators at Prospective Sites around the Maltese Islands

by

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ABSTRACT

The threat of global warming, dwindling fossil fuel resources, increasing fuel prices and the liberalisation of the electricity generation has changed the context in which electricity distribution systems are regulated and operated. Malta, as member of the European Union (EU) is obliged by the European Commission (EC) to reach specific energy and environmental targets by 2020. One of the obligations is to have 10% of the energy demand generated from renewable sources by 2020. Malta is promoting renewable energy sources through incentive schemes in order to reach this target while reducing the emissions of green house gases (GHG). The integration of renewable energy resources with the electricity grid is presenting a new challenge to the electricity distribution network operator (DNO). The electricity distribution system is no longer being seen as passive, where power flows from the main generation system to energy consumers, but it is becoming an active one, where consumers are also generating electricity, instigating a bi-directional power flow.

One of the major changes being experienced is the connection of significant levels of embedded generation to the distribution system. Medium to large-scale renewable energy sources (RES) such as solar, wind and wave are being considered for electricity generation in Malta. According to studies carried out, it transpires that wind energy has a good potential in Malta. In fact Mott MacDonald in the document *'Strategy for Renewable Electricity Exploitation in Malta'* has proposed candidate sites in the Maltese islands for the installation of medium to large-scale onshore and offshore wind farms [1]. Wind energy is the most mature in its technology from other RES and is competing well in terms of cost per unit energy with conventional fossil fuel generation sources.

High population density in Malta makes it hard to find sufficient land space to install a large onshore wind farm. Thus, medium-scale onshore wind farms are being considered to be installed in the Maltese islands. One of the main issues when planning an installation of a wind farm is the cost of connection with the grid. In view that the electricity distribution system is based on 11kV circuits, consisting mainly of underground cables and some overhead lines, a connection with the 11kV network will be much cheaper than a connection with the 33kV network. According to the Maltese network code, generating plants up to a maximum rated capacity of 3MVA can be synchronised with the 11kV network [2]. Since wind farm sites are typically located in rural areas, these will be at a long distance from the primary substation, known as Distribution Centre (DC). Consequently, the high impedance between the point of connection and the traditional source will cause the voltage in the circuit to rise, which may exceed statutory limits especially during circumstances of high net power flow into the DC. This is one of the main challenges that network operators are encountering in their attempt to integrate distributed generation with the grid while ensuring a reliable and good quality of supply. This dissertation deals with this challenge, where the impact on the steady-state voltage of the network from wind farms located at identified potential sites is investigated.

Two potential sites for wind farm installation mentioned by Mott MacDonald were investigated in this study. The sites considered in this dissertation are at Kerċem in Gozo and at Wied Rini l/o Baħrija in Malta. Different wind farm sizes connected at different points in the 11kV network were analysed in the worst case operating scenarios through load flow studies carried out by the IPSA+ program. Voltage rise has been identified as a key barrier to the development of medium-sized wind farms when connected with 11kV circuits. Such voltage rise will stress the network components' insulation while having a negative effect on the voltage levels of the low voltage consumers. Mitigation measures which control the voltage rise within permitted limits as established in the network code were established. These will make it possible to integrate larger distributed generators with the grid whilst ensuring a reliable and good quality of supply to consumers.

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I would like to thank my parents, whose absolute support of my education and endeavours has been a constant for as long as I can remember.

Last, but not least, I want to show my great appreciation to my wife Claire, for the great and unlimited support she always give me. She was always patient and understanding throughout this course and gave me a helping hand whenever needed. I cannot find any words to express my gratitude for her support and encouragement, which boosted me to continue with my studies.

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Technical Abbreviations

AEI	Areas of Ecological Importance
APC	Active Power Control
AVC	Automatic Voltage controller
AVHLS	Areas of Very High Landscape Sensitivity
AHLS	Areas of High Landscape Sensitivity
CB	Circuit-Breaker
CCGT	Combined Cycle Gas Turbine
CO_2	Carbon Dioxide
CT	Current-Transformer
DC	Distribution Centre
DFIG	Doubly Fed Induction Generator
DNO	Distribution Network Operator
DSO	Distribution System Operator
E/F	Earth-fault
EIA	Environmental Impact Assessment
EMI	Electromagnetic Interference
FIT	Feed-In-Tariff
FRT	Fault Ride Through
GHG	Greenhouse Gas
GIS	Gas-Insulated Switchgear
HAWT	Horizontal-Axis Wind Turbine
HMI	Human Machine Interface
HV	High Voltage

Hz	Hertz
IDMT	Inverse Definite Minimum Time
IGBT	Insulated-Gate Bipolar Transistor
LVRT	Low Voltage Ride Through
MCCB	Moulded Case Circuit-Breaker
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
NREAP	National Renewable Energy Action Plan
O/C	Over-current
OLTC	On-Load Tap-Changer
ONAN	Oil Natural Air Natural
PCC	Point of Common Coupling
PDS	Project Description Statement
P_{lt}	Long Term Flicker Severity Factor
PMSG	Permanent Magnet Synchronous Generator
P_{st}	Short Term Flicker Severity Factor
PU	Per-Unit
PWM	Pulse Width Modulation
RE	Renewable Energy
RES	Renewable Energy Sources
RMU	Ring-Main Unit
ROCOF	Rate of Change of Frequency
RPM	Revolutions per Minute
S	Slip
SAC	Special areas of Conservation
SCADA	Supervisory Control and Data Acquisition
SF_6	Sulphur Hexafluoride
SPA	Special Protected Areas
TC	Transformer-Centre
THD	Total Harmonic Distortion
TLF	Time-Limit Fuses
TSO	Transmission System Operator
VAWT	Vertical Axis Wind Turbine
VT	Voltage-Transformer

WFCSR	Wind Farm Collector Switch-Room
Z_{sc}	Short-Circuit Impedance

Organisation Abbreviations

EC	European Commission
EMC	Enemalta Corporation
EU	European Union
ISE	Institute of Sustainable Energy
MEPA	Malta Environmental and Planning Authority
MRA	Malta Resources Authority
MRRA	Ministry for Resources and Rural affairs
UNFCCC	United Nations Framework Convention on Climate Change

Dedication

I dedicate this work to my wife

Claire

and my parents

for their continuous support.

Thanks for everything.

CHAPTER 1

INTRODUCTION

1.1 Renewable Energy in Malta

The industrial activity around the globe is causing a significant increase in the GHG emissions. These emissions are causing a global warming and a consequent change in the climate. The Kyoto protocol was adopted in Kyoto, Japan in 1997 and entered into force in 2005 [3]. The Kyoto protocol is an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCCC) where its major feature is the setting of binding targets for 37 industrialized countries and the European community for reducing GHG emissions. One of its several measures is to reduce Carbon Dioxide (CO_2) emissions in the atmosphere when generating electricity by the utilisation of RES instead of fossil fuels.

Directive 2009/28/EC of the European Parliament and of the Council requires that Member States submit the National Renewable Energy Action Plans (NREAP) by June 2010 [4]. The NREAP provides a detailed roadmap of how the member state would reach its legally binding targets by 2020 for its share of renewable energy (RE) of the gross final consumption. This includes sectored targets, technology mix expected to be used, the trajectory to be followed, and measures and reforms that will be undertaken to overcome the barriers in developing RE.

The NREAP for Malta was issued by the Ministry for Resources and Rural affairs (MRRA) in June 2010. Malta has the obligation to reach a 10% target for its share of energy from renewable sources in its final energy consumption by 2020 [5]. This includes energy used for transport, electricity, heating and cooling. The NREAP is based on three main objectives:

- security of supply;
- environmental protection;
- social dimension, affordability and competitiveness.

Mott MacDonald in their report "*Strategy for Renewable Electricity Exploitation in Malta*" stated that although large onshore wind is the most cost-effective technology, there may be concerns about the visual impact and other cumulative effects which may prevent certain wind farms to be built in particular areas in Malta. Offshore wind is the second best technology option in terms of cost. Micro-wind is not considered as feasible due to planning constraints originating from visual impacts on the Maltese townscape. Malta has a good resource for medium and micro-scale wind and massive solar energy potential. Supporting the RE target solely based on more expensive small scale options is very costly for Malta [1].

Gozo is expected to become an Eco-island by 2020. This implies that development in Gozo has to be sustainable to ensure environmental protection while fostering economic development and social progress in the island [6]. The document published by the Ministry for Gozo, "A vision for an Eco-Island", highlights various recommendations received during the public consultation process to promote RE in Gozo. These recommendations include the promotion of micro-wind turbines for small operations and public service buildings; promotion of on-shore wind farms where it is estimated that there is a potential of around 10MW representing about 20% of the total electricity demand in Gozo; promotion of energy from waste; and promotion of solar energy by the installation of photovoltaic panels and solar water heaters on public and private buildings [7].

1.2 Wind Resource Potential in Malta

Wind characteristics depend on the site topography, site elevation above sea level, surface roughness, and site exposure to prevailing winds. Wind measurements at different heights are analysed to determine the wind resource characteristic of a particular site. Wind data in Malta was recorded for three whole years from wind monitoring equipment installed on a 45-metre lattice-type communications mast with effective anemometer heights of 10m and 45m above ground level at Baħrija. Analysis of the mean monthly wind speed over the specified time frame reveals that wind speeds are higher than the average wind speed during the cold season, while during the warm season, wind speeds are lower than the average. The mean monthly wind speeds and the corresponding energy yield for a medium-sized wind turbine at 45m above ground level at Baħrija over a 12 month period are represented in Figure 1.1 [8].

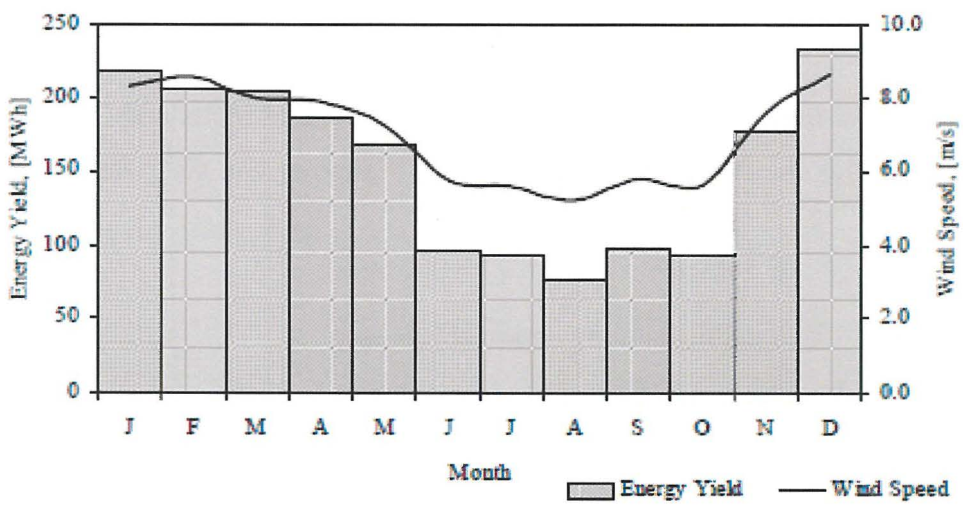


Figure 1.1 – Mean monthly wind speeds and energy yield for a wind turbine at Baħrija [8]

The wind direction frequency distribution for this site confirmed the prevailing north-westerly wind in the Maltese islands. From measured wind speeds at 10m and 45m above ground level, wind speeds at other height levels can be easily extrapolated using the Power Law and a site-specific wind shear exponent of 0.18. Thus mean wind speeds and average power density at different height levels were determined assuming a Rayleigh distribution as shown in Figure 1.2 [8].

Height Above Ground Level [m]	Mean Wind Speed [m/s]	Average Power Density [W/m²]
10	5.0 – 5.5	150 – 200
30	6.5 – 7.0	300 – 350
45	7.0 – 7.5	350 – 400
50	7.0 – 7.5	400 – 450

Figure 1.2 – Mean wind speeds and power densities at different heights at Baħrija [8]

The cumulative land area available for wind turbine technology in the Maltese islands, having an average power density of 300W/m^2 or higher, is 153Km^2. This theoretical land area does not takes into account the technical, social, and environmental constraints. Other research (European Wind Energy Association, EWEA) suggests that only 4% of the theoretical land area would eventually be accessible for wind power generation due to practical constraints. This implies that the cumulative practical land area suitable for wind power generation is approximately 6km^2 [8].

Although potential sites to develop onshore wind farms in Malta and Gozo exist, constraints may hinder such development. Constraints for such development include:

- the lengthy planning approval process;
- public and lobby group acceptability;
- areas of environmental and cultural heritage protection;
- proximity to built up areas including areas of high tourism value;
- construction and maintenance access to the development site;
- effects on the stability of the distribution grid;
- visual impacts;
- landscape impacts;
- light flicker;
- electromagnetic interference (EMI);
- ecological impacts;
- noise and vibration;

- tourism and recreation.

These impacts together with their corresponding mitigation measures will be analysed in detail when undertaking an Environmental Impact Assessment (EIA).

Wind technology has improved considerably over the recent years with turbines now available for sites with a range of wind speeds and the ability to operate in hot and cold climates. The range of turbine sizes is typically between 50m and 120m for turbines up to 3MW nominal capacity. The mature technology of onshore wind made it possible to compete well with fossil fuel generation in many countries [1].

1.3 Prospective Onshore Wind Farm Sites in Malta

Mott MacDonald has identified various large onshore wind farms sites with the assumption that no barriers will hinder the development of such farms. The potential wind farm sites are listed Table 1.1 and illustrated in the Maltese islands map in Figure 1.3. The maximum capacity that can be installed in each site was calculated using 850kW and 2MW wind turbines. The 2MW wind turbines generate more power; however the 850kW wind turbines may be less visually intrusive in the Maltese countryside [1].

Sites	Height above sea level (m)	MW
Gebel Ċiantar, Malta	210 - 250	16
Għemieri, Malta	180 - 210	44
Qasam Ben Borġ, Gozo	150	32
Wardija Ridge, Malta	105 - 140	40
Bajda Ridge, Malta	60 - 75	36
Marfa Ridge, Malta	30 - 120	22
Ta' Ħammud, Malta	30 - 55	24
Ħal Far Airfield (Disused), Malta	45	16
Total Maximum MW		**230**

Table 1.1 – Unconstrained onshore wind farm Sites [1]

According to a report from E.A. Mallia in 2008, two potential sites were identified. One of them is an offshore site at the north shore of Gozo, eastward from Ras il-Qbajjar. The 20m sea depth extends to 1km from shore in certain places. This location has a good wind energy potential as it is exposed to the prevailing wind. The other location is in Baħrija at Wied Rini mast farm. This site is characterised by a number of trellis masts around 50m high set on a 4m by 4m concrete base. These masts were used in the past by the government for telecommunications. Wind speed measurements were already recorded at three different heights above ground, adequate to determine the potential of the wind resource. It does not seem that there will be any apparent bird constraints and the area is located more than 500m away from the periphery of Baħrija and Imtaħleb [9].

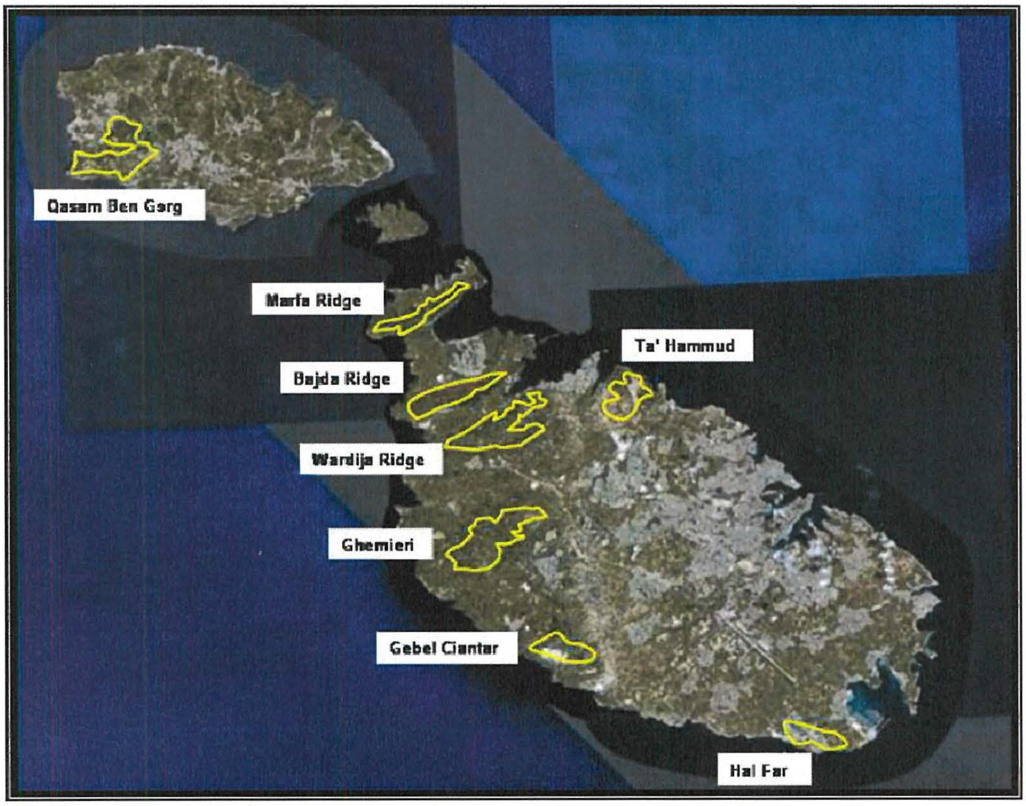


Figure 1.3 - Onshore wind farm sites proposed by Mott MacDonald [10]

In a study carried out by the Institute for Sustainable Energy (ISE) in 2010, two sites in Gozo were identified to be suitable for the installation of onshore wind farms. One of the sites is located on the south western end of the island, roughly west of the villages of Kerċem and Santa Luċija, while the other site is located in the north west of the village of Gharb. Since there is an ISE's wind monitoring station in the former site, this was investigated in more detail [11].

The onshore potential of the wind resource has been assessed by extrapolating measured wind data at Baħrija to form a wind map for the Maltese islands. Identified potential sites shown in Figure 1.4 include Baħrija, Mellieħa Ridge, Marfa Ridge, and an expanse of land running south of Dingli. Sites expected to have a lower potential than those already mentioned are Ħal Far and Delimara [8].

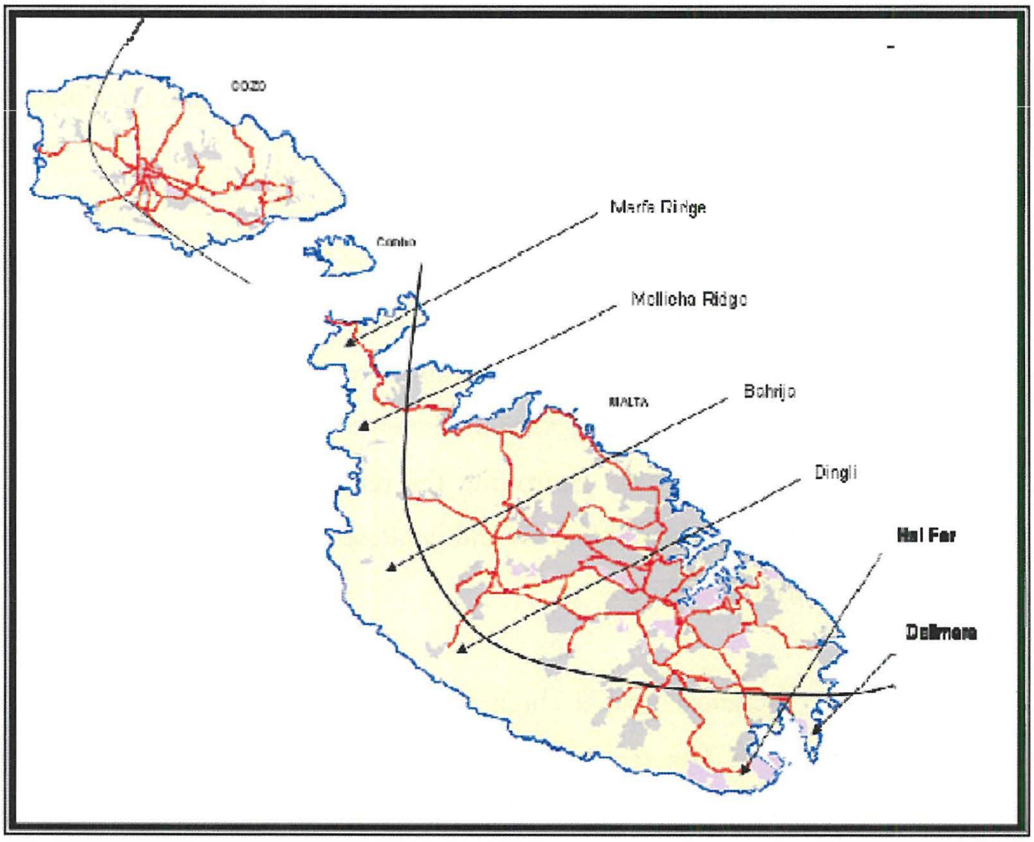


Figure 1.4 – Prospective wind farms sites in the Maltese islands [10]

Two Project Description Statements (PDS) on large scale onshore wind farms have been submitted to MEPA. One of them refers to a 10.2MW wind farm at Wied Rini in the vicinity of Baħrija and Mtaħleb, and the other one refers to a 4.25MW wind farm at Hal Far Industrial Estate. The proposed Wied Rini wind farm consists of twelve wind turbines which will be connected to the national electricity grid by two 11kV cables or one 33kV cable. The Ħal Far wind farm consists of five wind turbines which will be connected with the national electricity grid at the Enemalta DC located within the industrial estate [10] [12].

1.4 Research Approach

The focus of the research in this dissertation is on the integration of wind farms with the 11kV network, in particular, the impacts on the steady state voltage of the electricity distribution network in Malta and Gozo. Medium-sized wind farms consisting of 850kW wind turbines equipped with Doubly-Fed Induction Generators (DFIG) are being considered in this study. Two wind farm sites, one at Kerċem in Gozo, and the other one at Wied Rini l/o Baħrija were considered in this study.

The first step in any research project is to undertake extensive reading about the topic. Chapter 2 is dedicated on the wind turbine technology, including the operation of the generators and their integration with the grid. The impact of voltage rise in the network resulting from the integration of distributed generators and how it can be mitigated by controlling the reactive power is discussed. In Chapter 3 the electricity distribution in the Maltese islands and the respective network code are briefly outlined.

In Chapter 4, the technical details about the wind turbines considered for the analysis are described. The discussion is extended to include the wind farm electrical design including the protection and control systems, and its connection with the grid. The modelling of the wind farm with the 11kV circuit on IPSA+ program is also discussed.

The prospective wind farm site at Gozo as mentioned by Mott MacDonald is discussed in Chapter 5, outlining the constraints and how this is reduced to a small area in Kerċem. The wind farm connection options with the 11kV circuit are discussed. This is followed by a load flow study carried out on IPSA+ for all the wind farm connection options during the worst case scenarios. The results obtained are thoroughly discussed.

Chapter 6 addresses the wind farm site at Wied Rini l/o Baħrija. Site constraints and options for connecting the wind farm with the grid are discussed. Load flow analysis for these connection options during the worst case scenarios are carried out. The results obtained are investigated in detail.

General conclusions, including a synopsis and mitigation measures, are given in Chapter 7 along with suggestions for further work.

CHAPTER 2

WIND TURBINE TECHNOLOGY

2.1 Wind Turbine Architecture

The most common design of wind turbine in today's world is the three-bladed horizontal-axis wind turbine (HAWT), having an upwind rotor and actively yawed to preserve alignment with the wind direction.

The principal subsystems of a typical HAWT are [13]:

- the rotor - consisting of blades and supporting hub;
- drive train - including the rotating parts of the wind turbine (excluding the rotor); consisting of shafts, gearbox, coupling, a mechanical brake, and the generator;
- nacelle and main frame - including wind turbine housing, bedplate, and yaw system;
- tower and foundation;
- machine controls and;
- the electrical system, including cables, switchgear, transformers, and possibly power electronic converters.

The three-bladed HAWT has a separate front bearing, with the low speed shaft connected to a gearbox that provides an output speed suitable for the four-pole generator as shown in Figure 2.1.

Most modern wind turbines operate at variable speed so that the rotor speed is matched with the wind speed to achieve maximum efficiency. Another important advantage of variable speed operation is that noise is reduced. Large wind turbines normally employ active pitch control, where the blade pitch is varied along their axis continuously to control the power output [13].

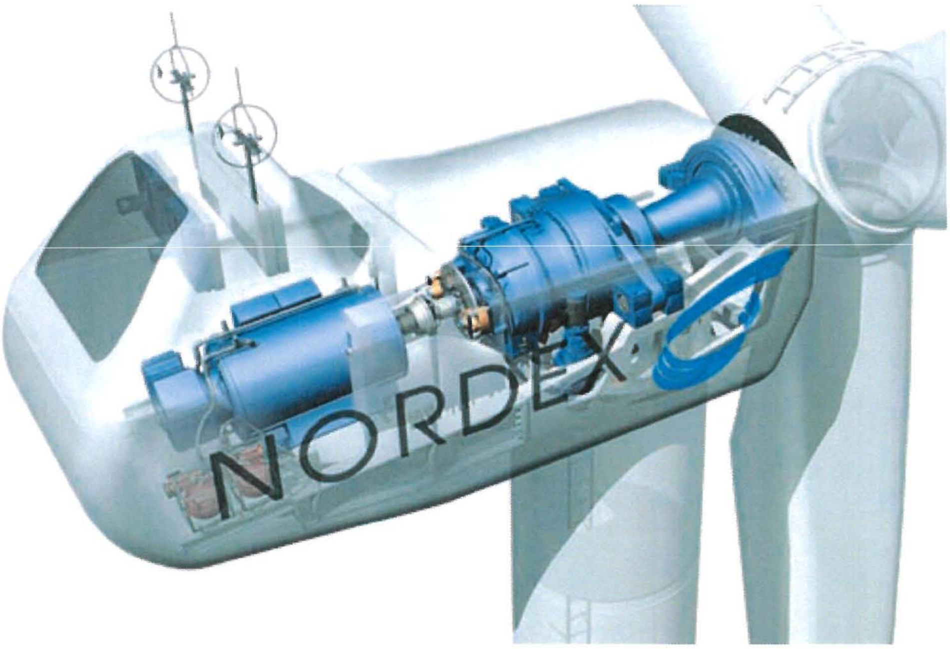


Figure 2.1 - Nacelle layout of a modern wind turbine [13]

The gearbox plays an important role in the wind turbine system as its purpose is to speed up the rate of rotation of the rotor from a low value to a rate suitable for driving the generator. Two types of gearboxes are used in wind turbines; parallel shaft and planetary. Large machines use a planetary gearbox due to its weight and size advantages [13].

A large wind turbine should be suitably supported on a structure that can withstand the continuous loading of the system, taking into consideration the lifetime of the turbine and the worst possible conditions that the system can experience. The most common structures are the tubular steel towers. Concrete towers, concrete bases with steel upper sections, and lattice towers are also used. The stiffness of the tower is a major factor in wind turbine system dynamics because of the possibility of coupled vibrations between the rotor and the tower [13].

2.2 Wind Turbine Theory

The mechanical power output from a wind turbine is given by the following formula:

$$P = \frac{1}{2} C_p \rho A v^3$$

Where, C_p, is the power coefficient;

ρ, is the air density;

A, is the rotor swept area and,

v is the wind speed.

The power coefficient is a fraction of the wind available power that may be converted by the wind turbine into mechanical work. The theoretical maximum of C_p is 59.3%, known as the Betz limit; however in practice values in the range between 25% and 45% are achieved.

The tip-speed ratio, λ, is the ratio of rotor tip speed to wind speed and is calculated by the following formula:

$$\lambda = \frac{\omega R}{v}$$

Where,

ω, is the rotational speed of the rotor;

R, is the radius of the rotor blade and,

v, is the upwind free wind speed in m/s.

The coefficient of performance is not constant but varies with the wind speed, rotational speed of the turbine, and turbine blade parameters such as angle of attack and pitch angle as shown in Figure 2.2.

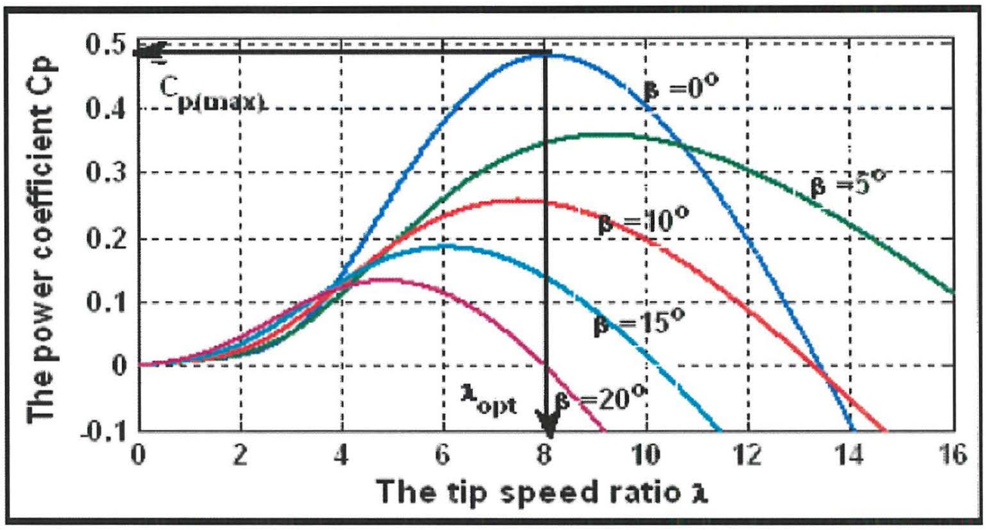


Figure 2.2 - Relationship between power coefficient and tip-speed ratio for different blade pitch angles [14]

One can note from this figure, that for every pitch angle there is a maximum power coefficient at the optimum tip-speed ratio. For a HAWT, the optimum tip-speed ratio varies between 6 and 10. The power coefficient can be improved by modifying the rotor design and by operating at variable speed to maintain a maximum power coefficient over a range of wind speeds. The relationship between the power output and turbine speed for various wind speeds is shown in Figure 2.3.

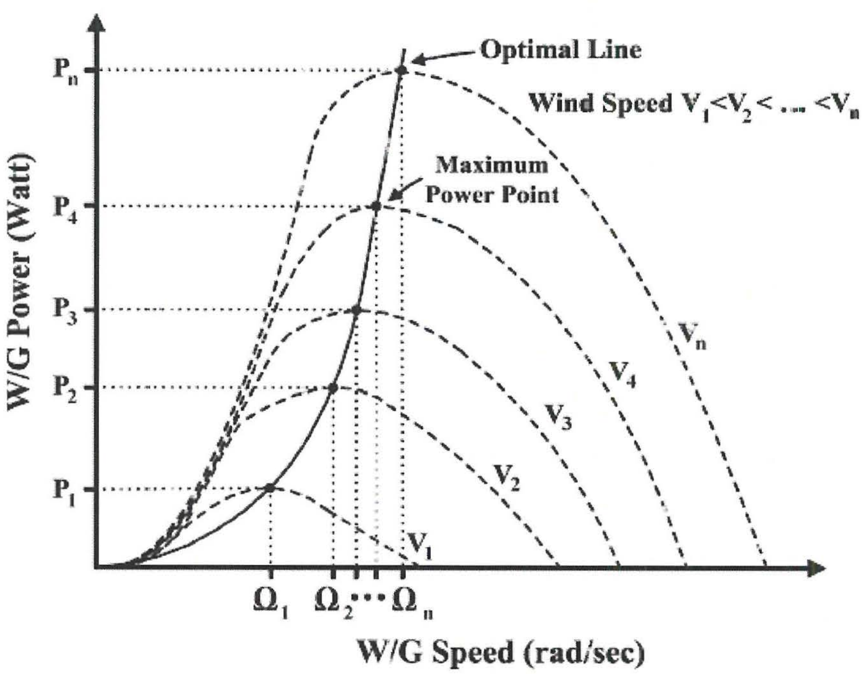


Figure 2.3 - Power - Speed relationship of a wind turbine for various wind speeds [15]

This data is utilised by the maximum power point tracking (MPPT) system where through a closed loop control system the optimal output power is compared to the actual output power and the resulting error is used to control a power interface as illustrated in Figure 2.4. The MPPT system will adjust the actual turbine rotational speed to the optimum value by changing the blade pitch angle. A variable frequency operation with maximum power point tracking achieves between 10% to 15% more output power than a fixed frequency operation. Another advantage of variable speed operation is the reduction of stress on the wind turbine shafts and gears, since the blades absorb the wind torque peaks during the changes of the turbine rotation speed [15].

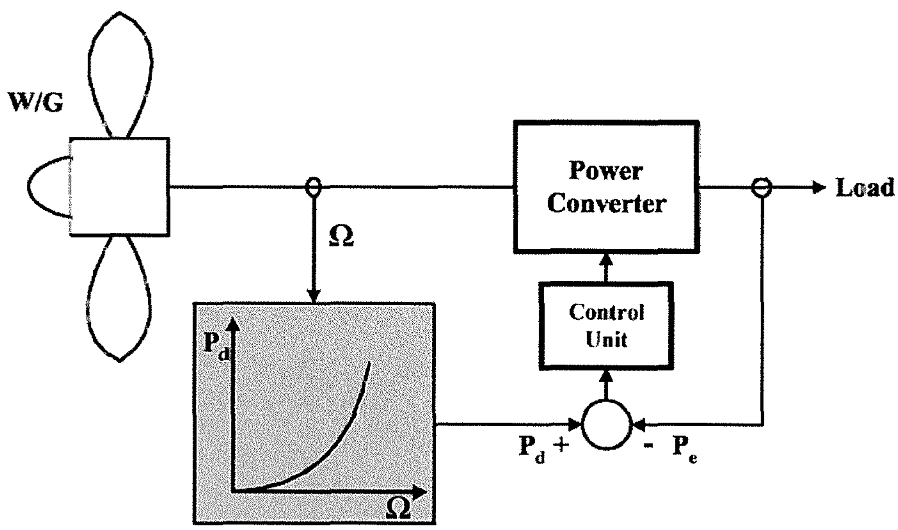


Figure 2.4 - Wind turbine MPPT control system based on rotation speed measurements [15]

Major increases in the output power are achieved by increasing the rotor swept area, or by locating the wind turbines on sites with higher wind speeds. A typical relationship between the wind turbine output power and the wind speed is shown in Figure 2.5. At a very low wind speed, there is insufficient torque exerted by the wind speed on the turbine blades to start rotation. As the wind speed increases, the wind turbine will begin to rotate and generate power. The wind speed at which the wind turbine starts to generate power is called the *cut-in speed* and is typically between 3 and 4m/s. As the wind speed increases from the cut-in speed, the output power from the wind turbine increases accordingly. The power output reaches a limit, typically between 12 and 17m/s, called the *rated power*. The wind speed at which the rated power is reached is called the *rated output wind speed*. The wind turbine power output is kept constant as the wind speed increases beyond the rated output wind speed. As the wind speed reaches the *cut-out speed*, the braking system of the wind turbine will bring it to a standstill in order to avoid the risk of damaging the rotor from the large forces exerted on the wind turbine. The cut-out speed is typically about 25m/s.

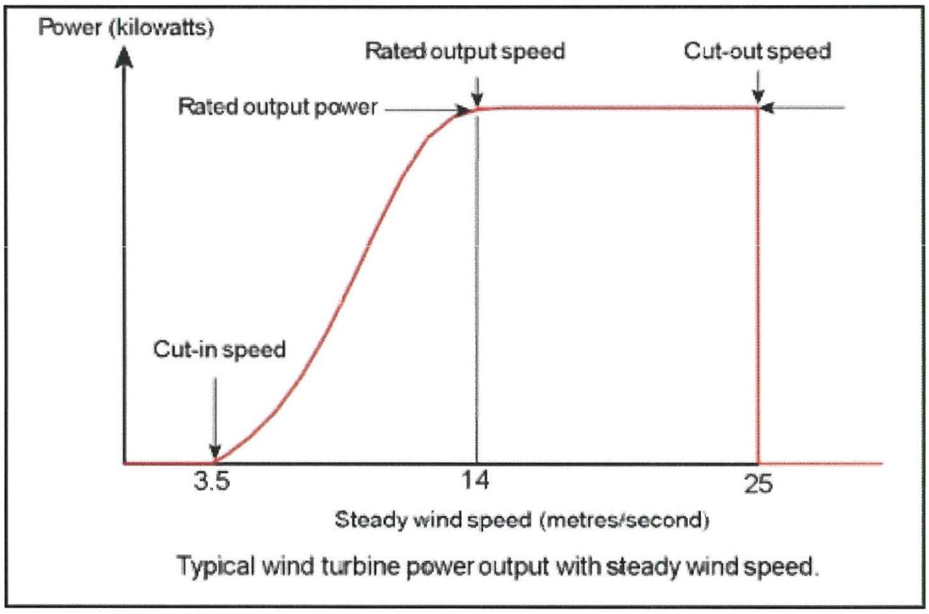


Figure 2.5 - A typical wind turbine output power in relation with wind speed [16]

2.3 Wind Turbine Generator

Generators for large wind turbines can either be asynchronous or synchronous machines. These can be coupled to the grid either directly or through a converter. An electrical machine at no load will rotate at the same speed as the rotating magnetic field, called the synchronous speed. Synchronous speed is given by:

$$n = \frac{60f}{p}$$

where n, is the synchronous speed in rpm;

f, is the frequency of the electrical supply in Hz; and

p, is the number of pole pairs.

2.3.1 Asynchronous Machines

Asynchronous machines, also known as induction machines are the most common type of generator used in wind turbines. Induction machines are popular due to the following characteristics:

- simple and rugged construction;
- may be simply connected and disconnected from the grid;
- relatively inexpensive.

The rotating magnetic field induced in the stator by the phase-displaced currents rotates at exactly synchronous speed corresponding to the electrical network frequency. Since the rotor rotates at a speed slightly different than the synchronous speed, a current is induced in the rotor which in turn induces a magnetic field in the rotor. The interaction of the rotor's induced field and the stator's field causes elevated voltage at the terminals and current to flow from the machine.

An important parameter in characterizing induction machines is the slip, 's'. Slip is the ratio of the difference between synchronous speed, 'n_s', and rotor operating speed, 'n', and synchronous speed:

$$s = \frac{n_s - n}{n_s}$$

When the slip is positive, the machine will operate as a motor while when the slip is negative, the machine will operate as a generator [17]. This is clearly shown in Figure 2.6. From this figure, one can note that the machine starting current is about five times the rated current, while the peak torque is about three times the rated torque.

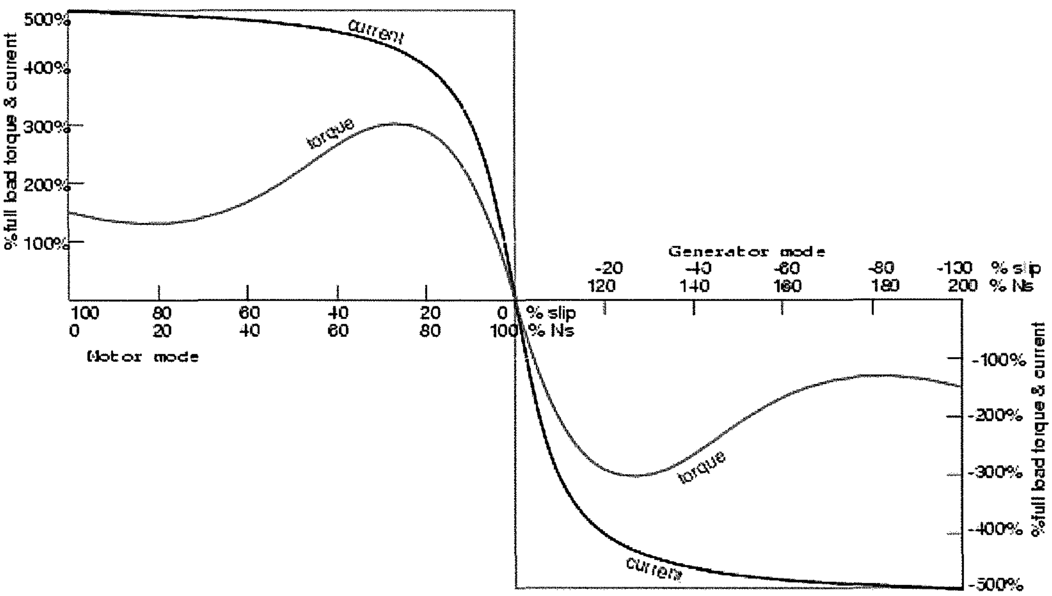


Figure 2.6 - Torque and current relation with slip of an induction machine [18]

The most common type of generator used in large wind turbines is the Doubly Fed Induction Generator (DFIG). The DFIG is an induction generator having a wound rotor connected to the grid through a frequency converter as shown in Figure 2.7. This arrangement allows power to flow into or out of the rotor through the grid. The frequency of the power output from the stator is controlled by both the rotation speed of the rotor and the AC currents fed into the rotor.

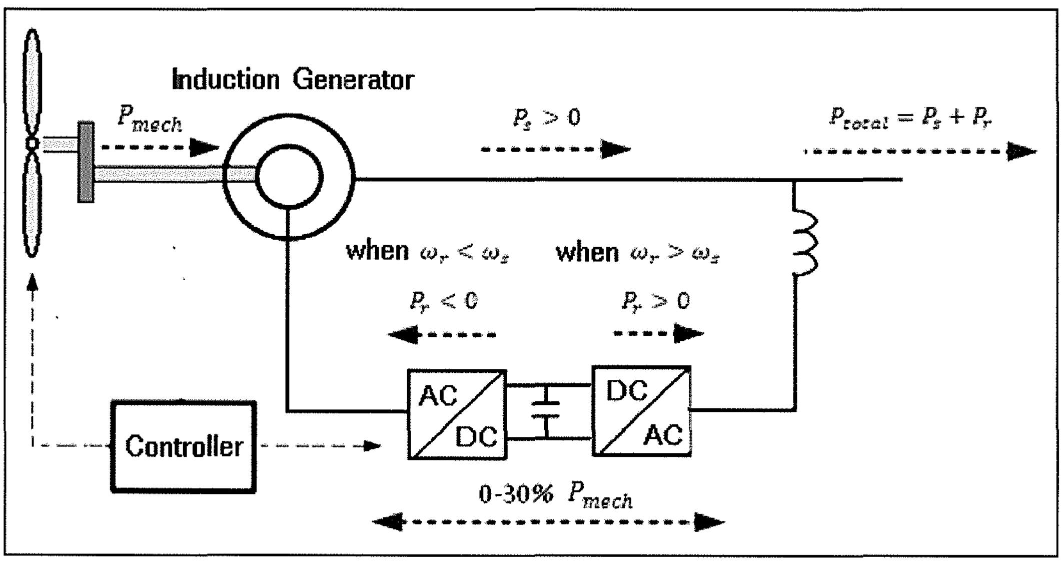


Figure 2.7 - Double Fed Induction Generator (DFIG) for wind turbines [20]

The voltage produced at the stator should also be equal to the network voltage. This is maintained by ensuring a certain magnetic flux at the stator windings. This can be achieved by applying a voltage to the rotor windings that is proportional to the frequency of the voltages applied to the rotor windings, thus ensuring a constant V/f ratio and a constant magnetic flux.

This configuration has the advantage that the power electronics used in the frequency converter need to process about 30% of the rated power. Thus the power electronics used are rated at 30% of the wind turbine rated power. This reduces considerably the cost and the losses of the system [19]. Moreover, the DFIG can control the power factor, and can even supply reactive power to the network if required. This configuration allows a range of operating speeds of the DFIG, from approximately 50% below synchronous speed to 50% above [17].

2.4 Wind Turbine Integration with the Grid

Large-scale integration of wind generation may cause significant impacts on the electricity network operation. Utility grid codes address these impacts and require wind generators to meet certain requirements in order to be connected with the grid. These requirements include the capability of contributing to frequency and voltage control by continuously adjusting the active and reactive power output. Such requirements require the implementation of control schemes by utilising power electronic converters.

Utility grid codes require wind generators to operate similarly to a conventional power plant in order to contribute to a stable grid. Thus, the utility through its grid code impose certain regulations on the wind farm operator. These regulations ensure that the wind farm :

- operates within a specific voltage and frequency range;
- operates within the stipulated control measures for active power, voltage, frequency and reactive power;

- has Low Voltage Ride Through (LVRT) and Fault Ride Through (FRT) properties;
- generates power to the grid of adequate quality without exceeding specified limits of voltage flickering and harmonics; and
- employs adequate protection schemes, properly set in order to discriminate with the grid protection system in case of faults in the wind farm or the grid.

2.4.1 Voltage Variation

A grid can either be weak or strong. Such distinction depends on the short-circuit impedance, Z_{sc}, of the grid. The smaller the Z_{sc}, the smaller is the voltage variation at the Point of Common Coupling (PCC) of the wind generator with the grid. In this case the grid is described as strong. Conversely, if the Z_{sc} is large, the grid is weak. In view that wind farms are normally located in rural areas, a long distance away from load centres, it is common to have a weak grid.

The peak voltage reached along the circuit is at the PCC between the wind farm and the grid. The voltage rise at this point depends on the amount of net real and reactive power flow and on the impedance between the PCC and the source of the circuit. The net power flow in the circuit is the difference between the power generated from the wind farm and the load in the circuit. The voltage at PCC is approximated by the following equation:

$$V_{pcc} \approx V_s + \frac{RP + XQ}{V_{pcc}}$$

where V_{pcc}, is the voltage at the PCC;
V_s, is the voltage at the DC;
R, is the resistance between PCC and the source of the circuit;
X, is the reactance between PCC and the source of the circuit;
P, is the net real power flow between PCC and Distribution Centre; and
Q, is the net reactive power flow between PCC and Distribution Centre.

A representation of the parameters affecting the voltage rise at PCC is shown in Figure 2.8.

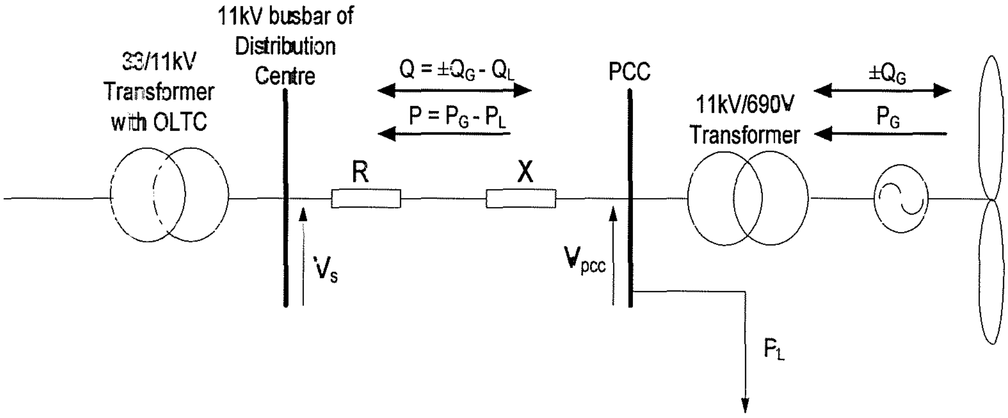


Figure 2.8 – Electrical parameters affecting the voltage rise in the circuit when a wind farm is connected with the grid

The equation shows that the voltage at PCC depends on the voltage of the DC's 11kV busbar voltage added with the voltage drop along the feeder between the PCC and the source of the circuit. Thus the location of the wind farm connection point along the circuit is a crucial factor in determining the voltage rise at the PCC. As wind farms are typically located at a significant distance from load centres, a high impedance value will result between PCC and the source. Thus the wind farm size has to be limited in order to keep the voltage at PCC within the permitted voltage range.

Another factor contributing to the voltage rise is the generated real power and the load on the circuit. The worst case scenario which causes the highest possible voltage rise at the PCC occurs when the wind farm is generating maximum power during minimum load demand in the circuit. This will create the highest net power flow into the DC, which will consequently increase the voltage at PCC. Consequently, the voltage at the 11kV busbar of the DC tend to increase, hence, shifting up the voltage profile of the 11kV circuit. As the voltage at the 11kV busbar exceeds the upper limit allowed by the Automatic Voltage Controller (AVC), the 33kV/11kV transformer performs a tap-change to lower the voltage in the 11kV busbar.

The net reactive power flow between the wind farm and the DC also contributes to the voltage rise effect at the PCC. The DFIG generators of the wind turbines typically control the operating power factor between 0.95 leading and 0.95 lagging. Although reactive power drawn by wind turbine generators acts to limit the voltage rise, the losses in the circuit tend to increase.

2.4.2 Reactive Power Control

Inductive components, such as motors, consume reactive power while capacitive components, such as power cables produce reactive power. Reactive power flow in the network causes voltage drops and power losses. Large reactive currents may cause voltage instability due to considerable voltage drops in the transmission lines. Synchronous generators can produce or consume reactive power by controlling the magnetizing level or the excitation voltage of the generator. A wind turbine equipped with an induction generator without a converter is a consumer of reactive power. In order to minimise power losses and enhance voltage stability, wind turbines are compensated to a level depending on the requirements of the utility. For wind turbines driven by Pulse-Width Modulation (PWM) converters, reactive power can be controlled. Such wind turbines have the possibility to control the voltage at the PCC by controlling the reactive power.

CHAPTER 3

ELECTRICITY DISTRIBUTION SYSTEM IN MALTA

3.1 Electricity Distribution Network

Malta's electricity grid is owned by Enemalta Corporation (EMC). As the grid is isolated and is not connected to any other electricity network, the electricity demand is generated in Malta. At present, EMC operates two Power Stations which supply all the electrical power required by Malta and Gozo. The Power Stations are located at Marsa and Delimara. A new generation plant was recently commissioned at Delimara Power Station producing a total power output into the electricity network of 144MW. These two Power Stations are interconnected together by the existing grid. The generators rely on imported fuels mainly heavy fuel oil and light distillate [21].

Electricity from the two power stations is transmitted and distributed at voltages of 132kV, 33kV or 11kV at a frequency of 50Hz mainly through underground cables and some overhead lines. The distribution network, composed of 132kV and 33kV circuits is shown in Figure 3.1. The majority of the cables are oil impregnated paper insulated cables having copper or aluminium conductors, however XLPE insulated cables were recently installed for the 132kV circuits. DCs strategically located around Malta and Gozo step down the 132kV or 33kV voltage to 11kV voltage level for more localized distribution to areas of demand. A number of 11kV circuits run to different load areas in the system. The general network configuration of 11kV distribution systems is radial, with normally open points between two feeders to allow connection with another feeder in case of a forced outage or maintenance. In turn, the substations step down the 11kV voltage level to 400V. Three-phase voltage at 400V, or 230V single-phase voltage is distributed to general consumers mainly through overhead lines. Gozo is supplied with electricity from Malta through three 33kV submarine cables passing through Comino's 33kV/11kV DC. The electricity network in the Maltese islands consists of nineteen DCs, about 1100 indoor substations and 130 pole-mounted transformers.

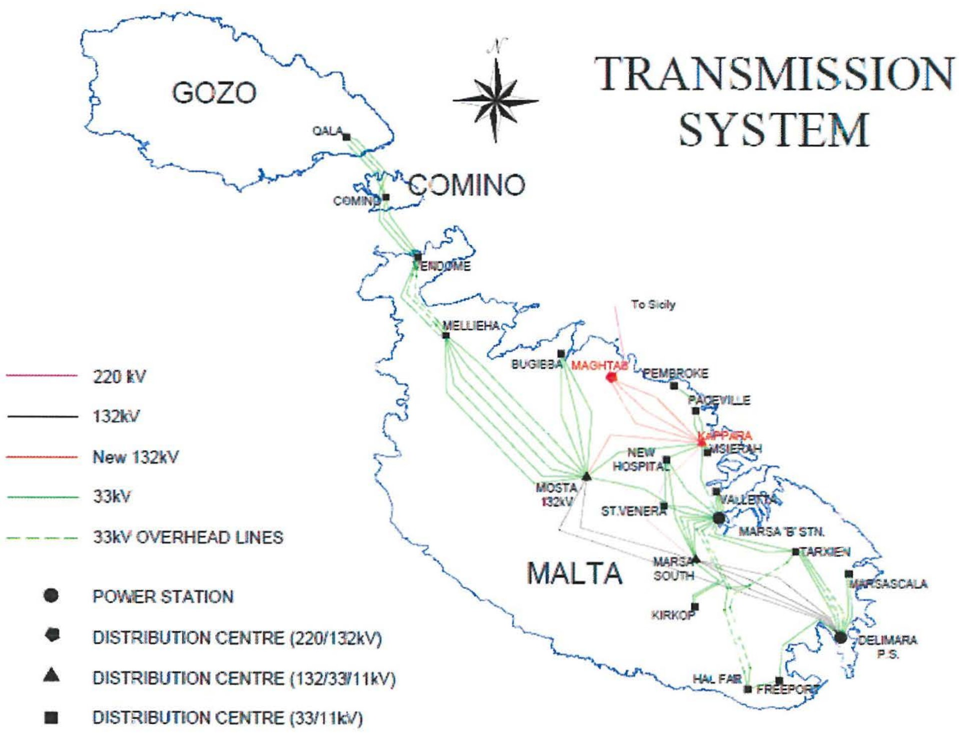


Figure 3.1 – The transmission system of the Maltese Islands [Source: EMC]

All the DCs and the majority of the substations are located indoor. The HV and MV switchgear is mainly Gas-Insulated Switchgear (GIS) type insulated with Sulphur Hexafluoride (SF_6). However oil insulated switchgear also exists in the network. Transformers in the Distribution Centres are oil-filled and equipped with on-load tap-changers (OLTC) which alter the voltage ratio by changing the tap at the primary winding while load current is flowing. The automatic voltage controller (AVC) regulates the secondary voltage of the transformer within a specific bandwidth of a set target voltage. Hence, grid voltage is controlled in response to voltage variations. On the other hand, 11kV/400V transformers in substations are equipped with a fixed tap-changer, which can only be operated manually with the transformer de-energised. HV and MV feeders are mainly protected by line differential relays and protection relays having over-current (O/C) and earth-fault (E/F) functions.

Future plans include the commissioning of a 200MW, 220kV interconnector between Malta and Sicily, commissioning of a 200MW Combined Cycle Gas Turbine (CCGT) followed by the decommissioning of Marsa Power Station. New DCs are being planned in order to enhance the electricity network reliability in areas of increasing load demand [21].

3.2 The Network Code for Malta

EMC is the Distribution System Operator (DSO) in Malta and is responsible for the dispatch of the generation plant and for balancing the distribution system. The network code allows generators to access the network. Generating plants greater or equal to 8MVA are to be synchronised with the 33kV network and are subject to dispatch. Generating plants between 1.6MVA and 8MVA are to be synchronised with the 11kV network and are subject to dispatch if greater than 5MW. Generators with a generating plant smaller or equal to 1.6MVA are to be synchronised at 400V or 11kV and are not subject to dispatch.

The nominal frequency of the distribution system voltage is 50Hz. Under normal operating conditions the mean value measured over 10s shall be within a range of 50Hz ± 1% (49.5 to 50.5Hz) during 99.5% of the year and 50Hz -5/+4% (47.5 to 52Hz) during 100% of the year. The distribution system operates at the nominal voltages as indicated in Table 3.1. The steady-state tolerances of the nominal voltages in the distribution network under normal operating conditions are according to Table 3.2 [2].

In April of 2013, Enemalta Corporation proposed a change in the tolerance of the steady-state voltage of the 11kV voltage level in consultation with the Malta Resourced Authority (MRA). Enemalta Corporation is proposing that the steady-state tolerance of the upper limit is raised from the present +2% to +5%. This will facilitate the integration of generation plants connected within the 11kV network [22].

Low Voltage (LV)	230V - phase to neutral 400V - phase to phase
Medium Voltage (MV)	11,000V (11kV) 33,000V (33kV)
High Voltage (HV)	132,000V (132kV)

Table 3.1 - Nominal voltages of the distribution system in Malta [2]

Nominal Voltage (phase - phase)	Steady-state Tolerance	Impulse Voltage
400V	± 10%	6kV
11kV	−2, -5%	75kV
33kV	+5, -10%	170kV
132kV	± 6%	650kV

Table 3.2 - Operating voltage range of the distribution system in Malta [2]

The network code makes emphasis on the protection requirements of the users. It must be ensured that faults in the user's plant and apparatus do not unreasonably cause disturbance to the distribution system or to other users. On the other hand, faults on the distribution system can cause damages to user's plant and apparatus due to a loss of a phase, over voltage or under voltage. Thus the user shall protect his installation and install protection equipment compatible with protection systems used by EMC in that particular section of the network. Interface circuit breakers in large low voltage (LV) installations and medium voltage (MV) installations have to be fitted with relays acceptable by EMC. These relays shall have three phase O/C and E/F elements and shall have Inverse Definite Minimum Time (IDMT) and definite time characteristics.

The voltage flicker emissions limit at the PCC caused by switching or continuous operation of wind turbine installation is 0.35 for both short and long term flicker severity factors, P_{st} and P_{lt}; consistent with IEC 61000-3-7. The total harmonic voltage distortion limits are given in Table 3.3.

System Voltage	Total Harmonic Voltage Distortion (%)
400V	2.5
11kV	2
33kV	1.5

Table 3.3 - Generator Total Harmonic Voltage Distortion limit [2]

The network code does not permit the generator to remain connected with the distribution system during islanding. Generators rated above 1MW should remain disconnected from the grid until a clearance is obtained from EMC to synchronise with the distribution system in order to ensure system stability and security [2].

CHAPTER 4

WIND FARM DESIGN AND CIRCUIT MODELLING

4.1 Wind Farm Design

4.1.1 Wind Turbine

In the study carried out by Mott MacDonald, 2MW and 850kW wind turbines were considered [1]. Although the 2MW wind turbine generates more power than the 850kW wind turbine, the latter is being considered in this study as it may be less visually intrusive in the countryside. Thus, the Gamesa G58 wind turbine rated at 850kW, shown in Figure 4.1, was chosen for this study.

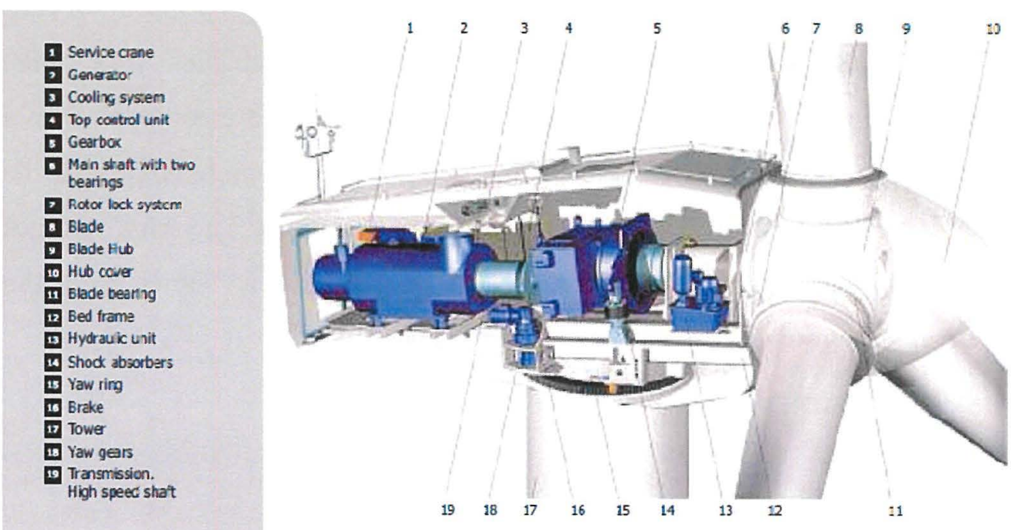
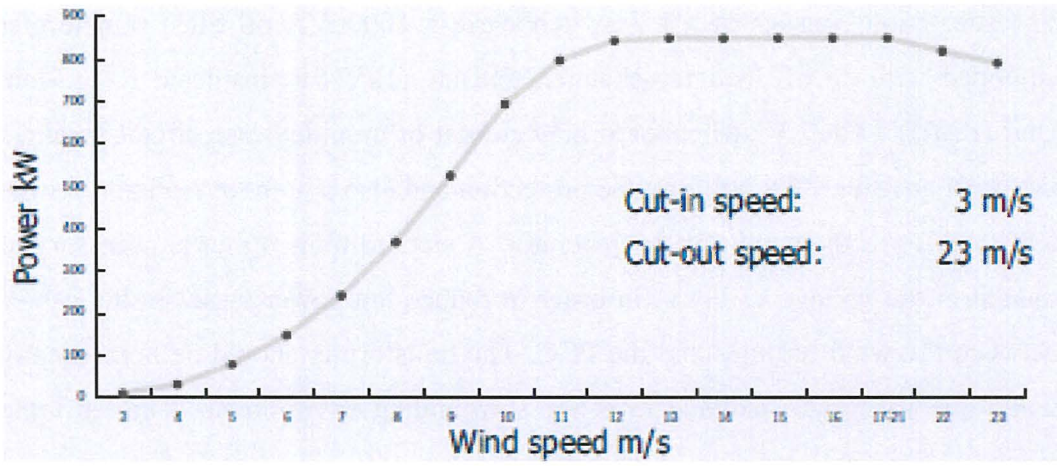


Figure 4.1 – Gamesa G58 Wind Turbine [23]

This wind turbine has a rotor diameter of 58m, rotating clockwise at a variable speed in the range between 15.6 and 30.8 rpm. The wind turbine consists of three blades made from fibreglass pre-impregnated with epoxy resin, mounted on a tubular tower that can have a height between 44m and 71m. The mechanical transmission system is based on a planetary gearbox having a ratio of 1:61.74. In turn, this will drive a four pole, DFIG, rated at 850kW, which will induce a rated voltage of 690V at the stator terminals at a frequency of 50Hz. This variable speed generator operates between 1000rpm and 1950rpm. The generator speed and power is controlled through IGBT converters and PWM electronic control. Thus, it can control the active and reactive power by the injection of rotor currents with variable amplitude, phase and frequency. The power factor can vary in the range between 0.95 leading and 0.95 lagging. The variable speed control system reduces the harmonics and losses, while increasing the efficiency and lifetime of the wind turbine. The Gamesa G58-850kW wind turbine impedance parameters are found in Appendix A.

The wind turbine generators are equipped with a lightning protection system where lightning strikes are conducted from both sides of the blade tip towards the nacelle and tower structure and finally to the earthing system located at the turbine foundations. Thus, the wind turbine blades and electronic components are protected from any risk of damage from lightning. At the cut-out speed, the braking system brings the wind turbine to standstill, in order to protect it from any damages. The braking system is based on aerodynamic braking by means of full-feathering blades and also by a hydraulically-activated mechanical disk brake mounted on the gearbox high speed shaft. The wind turbines are equipped with a SCADA system, where it provides real time operation and remote control of the wind turbines, meteorological masts and electrical substations. The wind turbines have a cut-in speed of 3m/s and a cut-out speed of 23m/s as shown from the power curve in Figure 4.2.



SPEED (m/s)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17-21	22	23
POWER (kW)	9.7	31.2	78.4	148.2	242.7	368.8	525.3	695.0	798.4	844.1	850.0	849.5	849.9	850.0	850.0	819.3	791.1

Figure 4.2 – Gamesa G58-850kW Power Curve [23]

4.1.2 Wind Farm Electrical Design

Each wind turbine in the wind farm is connected to an outdoor prefabricated substation as shown in Figure 4.3. Such substations will step-up the wind turbine generator voltage from 690V to 11kV. Such substations meet the highest safety standards in order to protect both the operator and the general public during an internal electric fault. The kiosk should be well ventilated in order to dissipate the heat generated by the electrical equipment, while ensuring that internal connections are protected from the extreme environmental conditions, such as rainfall, dust and wind. The kiosk should contain an oil containment facility in order to ensure that if an oil leak develops, it would not be of detriment to the environment [24].

Figure 4.3 - Outdoor prefabricated substation [24]

The substation consists of a LV switchboard, a 1000kVA oil-filled transformer equipped with an off-load tap-changer, and an 11kV SF_6 insulated Ring-Main Unit (RMU). The LV switchboard may consist of moulded case circuit-breakers (MCCB) or fuses. This will provide protection and also a point of isolation for the 690V cables of the wind turbine generator. A step-up transformer is necessary to transform the voltage to 11kV, in order to reduce the power losses in the cables between the wind turbines and the PCC. The transformer should be hermetically sealed in order to be isolated from the surrounding environment. This attribute reduces the maintenance requirements due to oil humidification and contamination. The cooling system of the transformer can be of the ONAN (oil-natural, air-natural) type so that electrical energy is not required to drive the oil or air circulation machines. The wind turbine transformer is wound as Delta/Star, with the 690V(Y) neutral point solidly earthed. Thus, the neutral point of the generator is not earthed. A solid earthing system allows a high level of fault current which can be quickly cleared by the protection system, while transient over-voltages are minimised. The RMU provides two connections for neighbouring wind turbines and a tee-off connection for the substation transformer. It also provides protection to the transformer by fuses, normally through Time-Limit Fuses (TLF) connected with current-transformers (CT). In case of a fault, a fuse is blown and the shunt trip-coil is activated, which in turn trips the Circuit-Breaker (CB) feeding the transformer. Each substation is equipped with a Remote Terminal Unit (RTU), responsible for performing the functions attributed to the SCADA system . This system permits the wind farm operator to monitor and control the wind farm remotely. Events, alarms, and energy generation parameters are continuously recorded and shown to the wind farm operator through the Human Machine Interface (HMI).

The wind farm is connected with the wind farm collector switch-room (WFCSR), where the 11kV switchgear to isolate the wind farm from the grid and the metering equipment are located. This is also where the PCC is located since this is the demarcation point between the utility grid and the wind farm. The WFCSR can be connected with the wind farm by one or two feeders. In the case where there is only one feeder, the switch-room will consist of only two or three CB panels, one to connect the wind farm feeder and the others to connect with the utility grid feeders as illustrated in the single-line diagram in Figure 4.4. The switchgear in the WFCSR is equipped with voltage-transformers (VT) and current-transformers (CT) in order to record the import and export energy from the wind farm. The CBs are typically SF_6-insulated, and having a vacuum interrupter sufficiently rated to interrupt the circuit during a fault in the wind farm or the utility network. The CBs are equipped with protection relays, which trip the CB when an abnormal current is detected by the CTs. The protection characteristics are normally coordinated with the utility network protection system in order to ensure that discrimination is in place. This ensures that in cases of faults within the wind farm, the operation of the utility network is not affected.

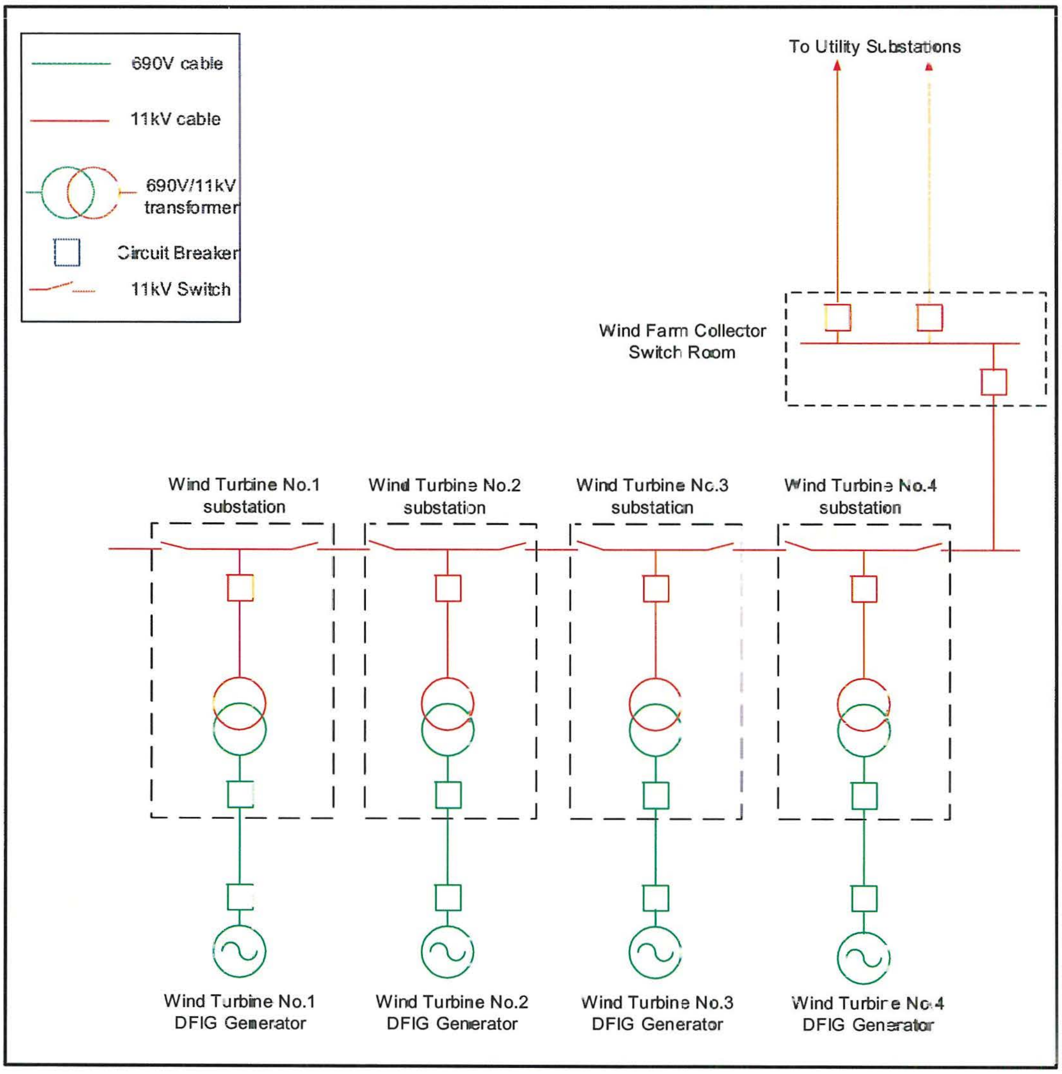


Figure 4.4 –Wind farm connected with the grid via one feeder

In the case of having the wind farm connected to the grid via two feeders, the WFCSR typically consists of four CBs and a Bus-Section CB to serve as a means of isolation in the middle of the busbar. The single line diagram of this arrangement is illustrated in Figure 4.5. This configuration increases the wind farm reliability as it is not necessary to disconnect the wind farm during scheduled maintenance or repairs in the switchgear.

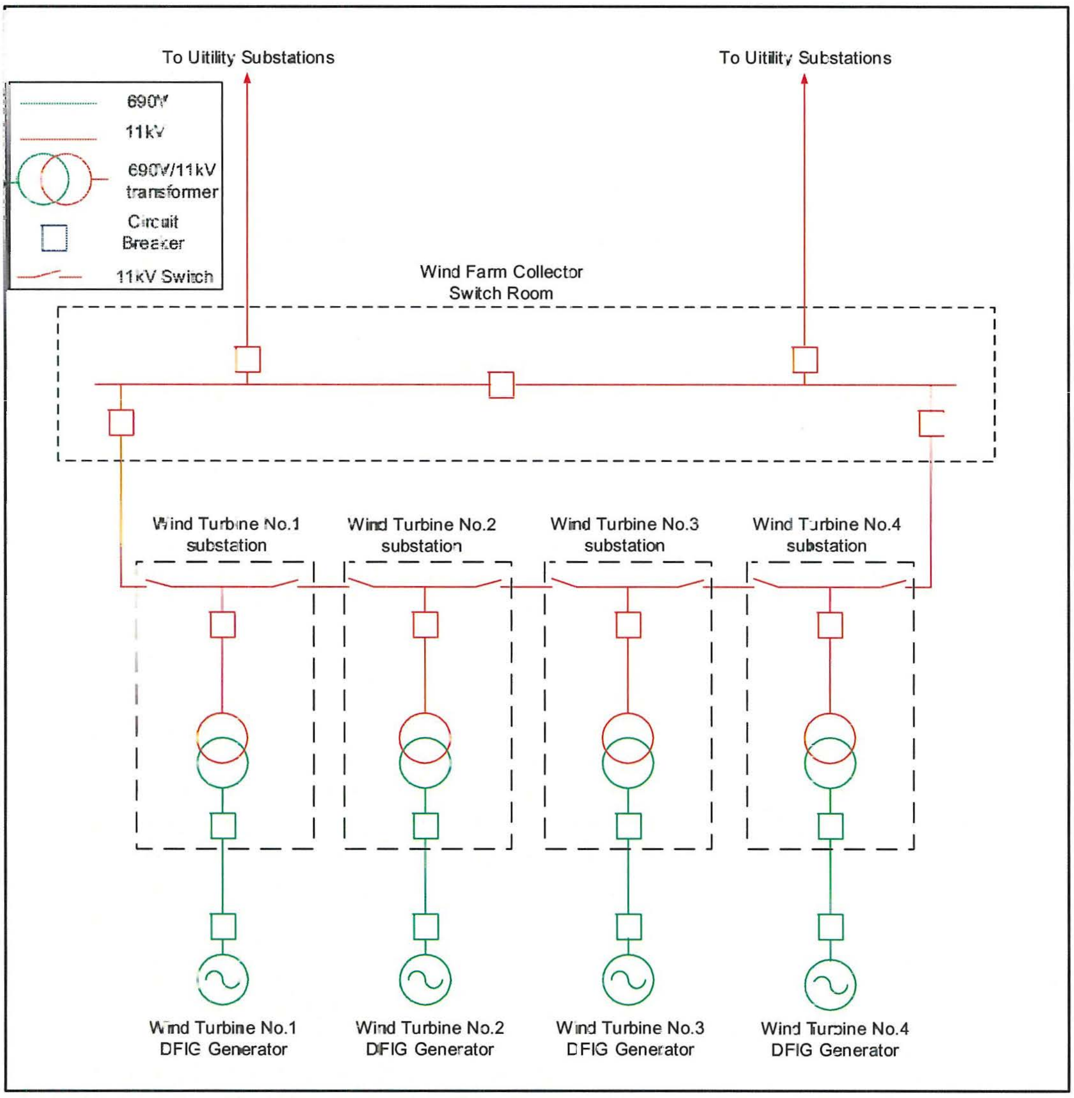


Figure 4.5 - Wind farm connected with the grid via two feeders

The wind turbine transformers' neutral points as well as the metallic enclosures and external conducting parts of all electrical equipment require an adequate connection to the general mass of earth. This is essential in order to:

- establish a low impedance path for earth fault currents and hence, satisfactory operation of the protection system;
- minimise shock hazards to personnel and animals, including control of step and touch potentials;

- ensure satisfactory discharge of lightning currents and control the associated voltages; and
- prevent large potential differences from occurring which are potentially hazardous to both personnel and equipment.
-

Wind turbines are subject to lightning strikes due to their height, thus special earthing requirements are necessary to minimise the risk of faults on the system and danger to personnel. Wind farms are normally located on rocky terrain having a high resistivity, making it more difficult to achieve an adequate earth connection. IEC 61400-24 outlines the lightning protection requirements of wind turbines. The standard emphasises on the requirement of having a continuous metallic ground system connecting all the equipment of the entire wind farm installation. This should include the substations, transformers, wind turbine towers and generators with its associated electronic equipment. This is generally implemented with bare conductors being laid in cable trenches underneath the power collection cables. These conductors provide both bonding of all parts of the wind farm and also serve as a long horizontal electrode to reduce the impedance to ground of the earthing system. At each wind turbine, local earthing is typically provided by placing a ring of bare conductor around the foundation at a depth of about 1m, and by driving vertical rods into the ground. It is also common to bond the steel reinforcing of the wind turbine foundation as well as the tower into this local earthing network [25].

The protection scheme of the wind farm is designed in such a way that if a fault occurs in a particular zone, the protection relays responsible for that zone will trip the CB to isolate the faulty section. Faults are normally caused due to failure of the insulation in the circuits leading to excess currents between phases or between phases and earth. These high currents are only allowed for up to about a second or so in order to limit the hazards. The risks of such fault currents include the risk to life caused by excess voltages as the high currents flow into earth impedance and the risk to the plant itself caused by destructive heating and electro-magnetic effects. Induction machines are not a reliable source of fault current as the machine draws its magnetising current from the network or local capacitors which will not be possible with a voltage collapse during a fault. Thus, the faulty circuit is isolated using fault current from the network and then voltage or frequency sensing relays are used to detect subsequent abnormal conditions. From a protection point of view, the wind farm can be seen as a collection of large electrical machine drives with torque applied to the machine shafts rather than taken to drive mechanical loads. The protection scheme of the wind farm is split into zones as shown in Figure 4.6.

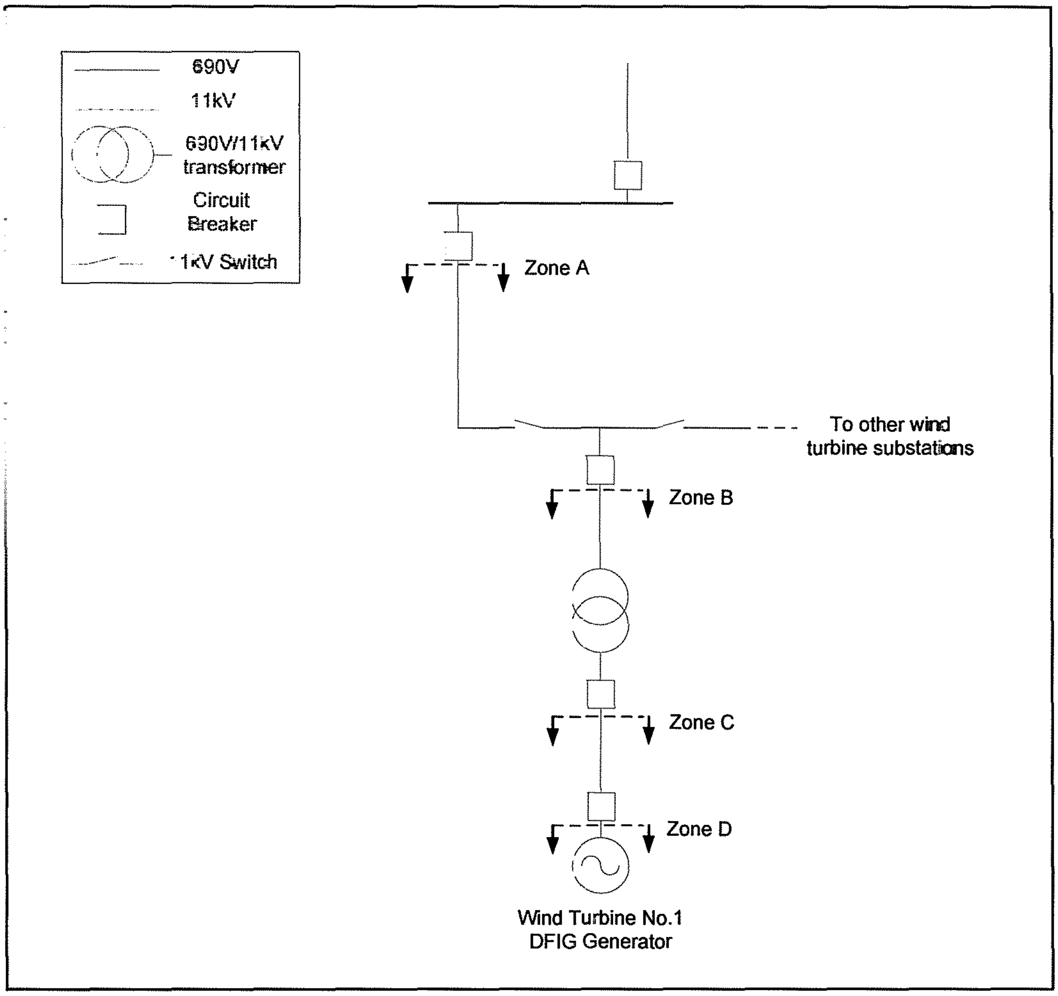


Figure 4.6 – Wind farm protection system zones

At the base of the wind turbine tower, a MCCB protects the pendant cables and the generator. This is shown as zone D. The 690V cables between the tower base cabinet and the wind turbine substation are covered by zone C. These cables are protected through a MCCB in the substation. Zone B consists of the 11kV/690V transformer including the region around its 690V terminals. The tee-off CB in the RMU is responsible for this zone. The 11kV cables between the PCC and the wind turbine substations are protected under zone A. The CBs located in the

WFCSR are responsible for such protection. The CB is equipped with an O/C and E/F relay having IDMT properties. The relationship between the fault current and the time delay to trip the CB is inversely proportional. Thus, the higher the fault current the less is the time required to trip the CB. Line-differential protection relays can also be utilised as the main protection system for this zone. This will improve the protection system as the CBs in the WFCSR will trip instantaneously in case of the fault in this zone, while adequate coordination of the discrimination scheme between CBs in the utility circuit is maintained. The CBs in the WFCSR responsible for the wind farm collector cables are also equipped with island detection protection relays. Such protection relays are based on the Rate of Change of Frequency (ROCOF) or vector-shift techniques. The ROCOF is based on the detection of a change in frequency due to a sudden loss in load, which will change the rotor speed. The relay will trip the CB if the rate of change of frequency with respect to time exceeds a specific set point. The vector-shift relay operates similarly to the ROCOF. When there is a change in frequency, the zero crossing of the generator voltage is moved earlier or later. If this vector shift is larger than a specific set point, the relay will trip the CB.

The wind farm incorporates a SCADA system which allows remote monitoring and control by the wind farm operator. Data from each wind turbine control system is collected at the Remote Terminal Unit (RTU) and transmitted over a fibre-optic cable installed with the 11kV cables to the main workstation [26]. A typical SCADA system configuration is shown in Figure 4.7.

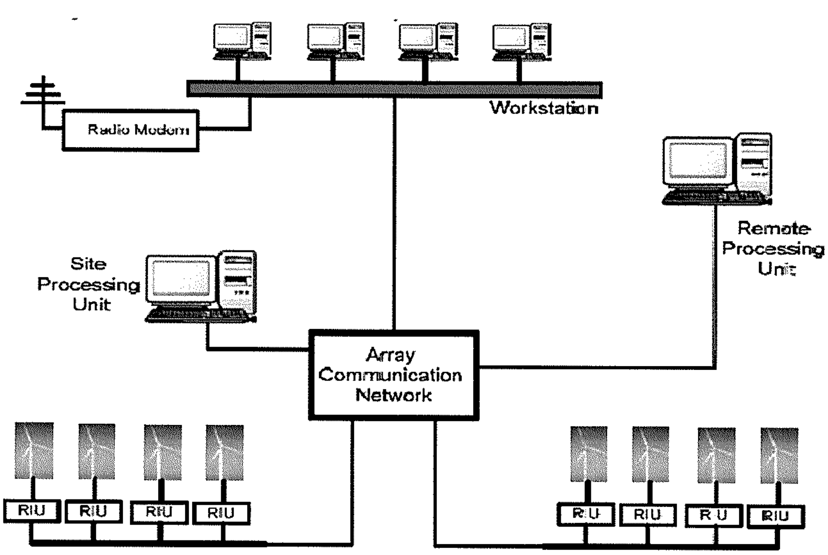


Figure 4.7 - SCADA system of a wind farm [26]

4.2 Circuit Modelling in IPSA+

The main impact on the 11kV network from medium-sized wind farms is the steady-state voltage variations. This is analysed through a load flow study carried out on IPSA+ program. As the wind farms under study are to be connected within the 11kV network, the source of the circuit or Distribution Centre, the 11kV circuit with its substations and the wind farm are modelled in this software. The modelled circuit consists of the following components:

- Grid Infeed;
- 33kV busbar;
- 33kV/11.5kV transformer;
- 11kV busbars;
- 11kV/433V transformers;
- 400V busbars;
- 'Load' connected with each of the 400V busbars;
- Line segments interconnecting the 11kV busbars
- Induction machines operating as generators
- 11kV/690V transformers

The main power generation of the network is modelled through a 'Grid Infeed' component. This is connected with the 33kV busbar of the DC. This 33kV busbar is set as a 'slack bus' so that the real and reactive power varies according to the load demand and losses in the circuit. A transformer is connected between the 33kV and 11kV busbars of the DC. The 33kV/11.5kV transformer is equipped with an OLTC to regulate the 11kV busbar within the bandwidth of a specific target voltage. The AVC is normally set at a target voltage of 11.2kV with a bandwidth of 1.5%. This means that the voltage in the 11kV busbar is allowed to vary between 11.03kV and 11.37kV. If the AVC senses a voltage outside of this range, the OLTC will perform a tap-change after a delay of 120 seconds. Thus, the 11kV busbar of the DC is set as 'Voltage Controlled Bus'. Parameters such as per-unit (PU) impedances, power rating, tap-changer details, and winding configuration are entered in the transformer model.

The distribution substations are represented by an 11kV and 400V busbars and an 11kV/433V transformer connected between these two busbars. The substation transformer is equipped with a fixed tap-changer connected with the primary winding. The secondary voltage is varied by up to ±5% from nominal during off-load in steps of 2.5%. The tap-changer is to be operated at off-load and has five tap positions. The nominal tap is identified as tap '0'. The positive tap positions, '+1' and '+2', increase the voltage on the secondary side while negative tap positions, '-1' and '-2', reduces the voltage on the LV side of the transformer. Parameters of the tap-changer, winding configuration, power rating and PU impedances of the transformer are specified in the substation transformer models. A' load' is connected with the 400V busbars, where real and reactive load demands are specified. The 11kV nodes are interconnected with line segments, where the line's PU impedance and rated capacity is specified for each segment. The circuit details and parameters were provided by EMC.

In view that the wind turbines considered in this study consist of 850kW DFIGs, these are represented through induction machine models. The induction machines PU impedances, mechanical output power, slip, number of poles, power factor, and machine type are specified in the model. Generic control models were used for the wind turbine generators. As the DFIG generates power at 690V, the wind turbine generators are connected with 690V busbars. This voltage is stepped-up to 11kV by 11kV/690V transformers. Transformer parameters are entered in the model.

The model was first tested without wind farm connection, by carrying out a load flow analyses for the utility's 11kV circuit under study. The results obtained were discussed with the utility in order to verify their correctness.

CHAPTER 5

WIND FARM AT KERĊEM, GOZO

5.1 Site Characteristics and Constraints

One of the objectives for Gozo as an eco-island is to have most of its energy generated from environmentally-friendly energy sources. Thus, the government is proposing the development of small onshore wind farm sites with a limited number of wind turbines [6]. The only site in Gozo which is considered by Mott MacDonald to have a good potential is Qasam Ben Borġ, as shown enclosed within the green border line in Figure 5.1. This site is located at the south-west of Gozo at a height of 150m above sea level. The site average wind speed at 50m above ground level is 6.65m/s [1].

The general terrain in Gozo is predominantly agricultural and is steeper than in Malta. According to the landscape assessment study issued by MEPA in 2003, Qasam Ben Borġ extends across Areas of Very High Landscape Sensitivity (AVHLS) and Areas of High Landscape Sensitivity (AHLS). The coastline along the south west of Gozo is dominated by a stretch of spectacular cliffs as shown in Figure 5.2. The Qawra–Dwejra coast is very near to this site. This is characterised by a rocky stretch along the coast dominated by steep cliffs enclosing two main dolines. There is a natural seawater conduit at *'il-Qawra'* which fills the shallowest part of the basin [1].

Figure 5.1 - Qasam Ben Borġ site

Figure 5.2 – Cliffs at the south-west of Gozo [27]

The main attraction at Dwejra bay is the geomorphological structure (*'it-Tieqa'*) which projects from the cliffs known as the Azure Window as shown in Figure 5.3, while a steep sided islet known as *'il-Ġebla tal-Ġeneral'* dominates the mouth of Dwejra bay. The Qawra to Dwejra area including *'il-Ġebla tal-Ġeneral'* is listed as a Natura 2000 site [1].

Figure 5.3 – Azure Window at Dwejra bay [27]

The visual impact of nearby soft stone quarries is quite significant especially when viewed from higher points along this stretch of coast as indicated in Figure 5.4 [27]. *'Wied tal-Kantra'* area at Xlendi is in the vicinity of this site. This is a Natura 2000 site, dominated by a valley which drains into Xlendi bay. Xlendi is the second largest tourism related coastal settlement in Gozo. This area is predominantly agricultural and the steeper side of the valley is characterised by natural rock inclines. The terraced fields overlooking *'Wied tal-Kantra'* area are spectacular when viewed from *'Ta' Sarraflu'* area. The pond at *'Ta' Sarraflu'* area shown in Figure 5.5 is also a protected site. Since it is located on the brow of the ridge, its effect on long distance view is rather limited. The area is also rich in archaeological heritage [27].

Figure 5.4 – Soft-stone quarries at Dwejra [27]

Figure 5.5 – Pond at 'Ta' Sarraflu'

The site is visible from the main town of Rabat and the old fortified citadel, 'Ċitadella'. A VHF Omni-directional Range (VOR) navigation system which is utilised by aircrafts to navigate safely, is one of the major constraints in the site. Apart from the mentioned constraints, there are also problems to access the prospective site. The site is only served by minor rural roads passing through small villages making it impossible for large vehicles transporting the component sections of the wind turbines and associated machinery to get through. Temporary roads would need to be constructed and considering Gozo's very high scenic value and considerable ecological importance, it is most likely that alternative roads would encounter major planning consent issues.

In view of the mentioned environmental and planning barriers, the site marked in Figure 5.1 is considerably reduced as shown enclosed in the green border line in Figure 5.6. A photomontage of a wind farm on this site is shown in Figure 5.7. The site is located high on the cliffs of Gozo's south-western coast in the vicinity of Kerċem, making the site exposed to the prevailing north-westerly winds. The site is at a distance from the coast and residential buildings of Kerċem, Santa Luċija and Xlendi. Thus, the visual impacts, noise effects and shadow flickering on inhabitants living in the surrounding area are minimised. A wind monitoring station managed by the Institute for Sustainable Energy (ISE) was operational in the site some years ago. Thus, wind data for this site is readily available in order to assess its wind energy potential.

Figure 5.6 – Wind farm Site at Kerċem

The dimensions of the wind farm site shown in figure 5.6 are roughly 1km by 1km. This area is sufficient to accommodate a 10MW wind farm. The layout of the wind turbines within the site depends on the wind energy resource characteristics, local topography, and requirements from the planning authorities.

Figure 5.7 - Photomontage of a wind farm at the prospective site at Kerċem [11]

5.2 Wind Farm Connection with the Grid

Electricity is transmitted to Gozo from Malta via three 33kV submarine cables terminated in the 33kV switchgear at Qala DC. This voltage is stepped down to 11kV through two 30MVA transformers. Electricity is distributed throughout the island via a number of 11kV feeders. Distribution substations step down the voltage to 400V three-phase or 230V single-phase supply. The low voltage supply is distributed to residential, domestic and industrial consumers through buried underground cables and areal lines. Another DC is being planned to be commissioned at the centre of the island, in the locality of Xewkija. This proposed DC is expected to improve the reliability of the distribution system in Gozo whilst reducing the power losses and voltage drop along the feeders.

The proposed wind farm at Kerċem is located close to an 11kV overhead line feeding a 250kVA outdoor Transformer-Centre (TC) identified as Kercem VOR Beacon. This overhead line is sourced from Kerċem tat-Taljana substation through a 95mm^2 aluminium cable rated at 3.9MVA. The overhead line is made from bare copper conductors having a cross sectional area of 35mm^2 rated at 4.21MVA. The cheapest connection of the wind farm with the grid is through an overhead line connected with the utility's overhead line at the point where Kerċem VOR Beacon transformer is located as illustrated in Figure 5.8. Since the feeder to Kerċem VOR Beacon TC is radial, the connection lacks adequate reliability. Furthermore, overhead lines in Malta are exposed to the harsh climate especially in coastal areas, making them more susceptible to faults than underground cables. Thus, frequent preventive maintenance of overhead lines is necessary in order to reduce the occurrence of faults. This implies that the wind farm disconnection time is increased when it is connected with an overhead line.

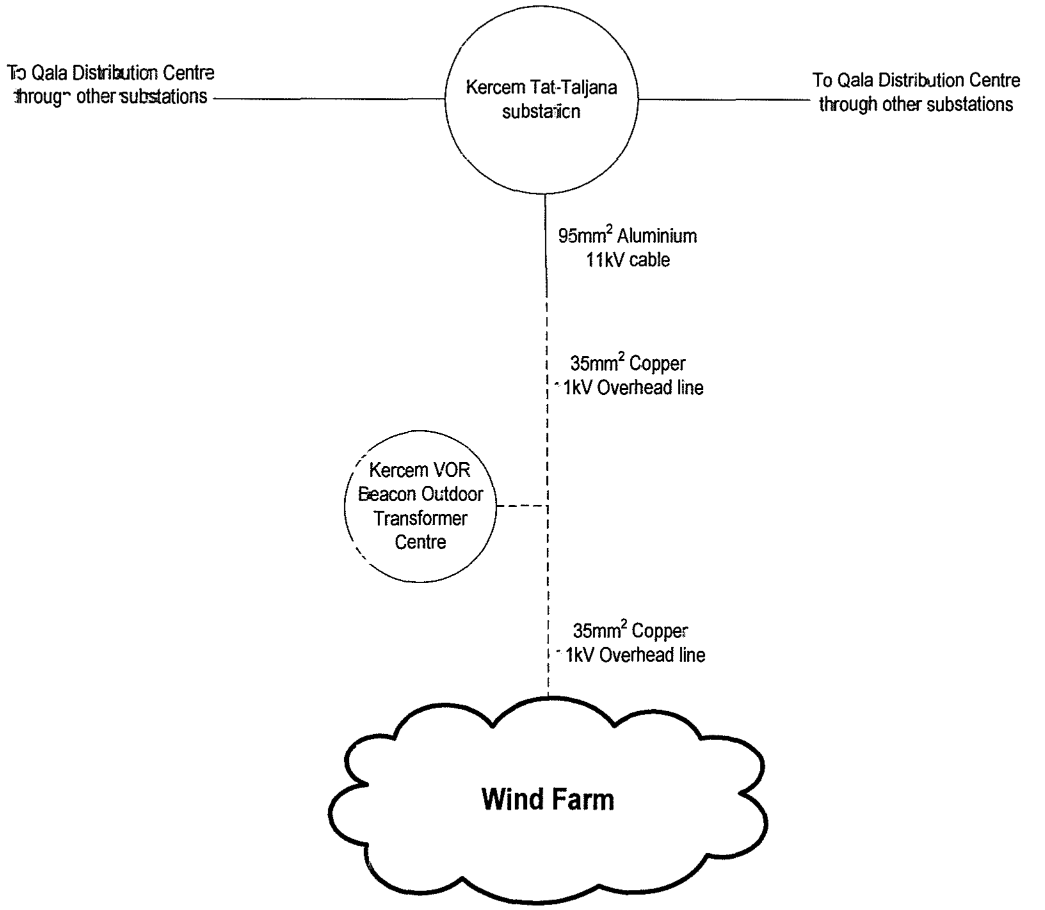


Figure 5.8 – Connection of wind farm with 11kV overhead line between Kerċem tat-Taljana substation and Kerċem VOR Beacon TC

A reliable option could be to connect the wind farm in the ring circuit of the network in the section between Kerċem tat-Taljana and Kerċem substations as illustrated in Figure 5.9. The wind farm can be reliably connected with the utility grid via two underground cables. The cable section between Kerċem tat-Taljana and Kerċem substations is composed of $95mm^2$ and $185mm^2$ aluminium cables, rated at 3.9MVA and 5.72MVA respectively. Furthermore, this connection reduces the impedance between the PCC and the traditional source, hence the voltage rise at the PCC is decreased.

The wind farm size in both scenarios is limited by the 3.9MVA power rating of the 95mm^2 aluminium cables. This means that the largest wind farm that can be connected with the grid will be rated at 3.4MW, consisting of four 850kW wind turbines.

A greater wind farm can be connected between Kerċem tat-Taljana and Kerċem substations without overloading the 11kV circuit, by replacing the 95mm^2 aluminium cables by 185mm^2 aluminium cables. This means that the 95mm^2 aluminium cables in the section between Kerċem tat-Taljana and Victoria Kerċem Rd. substations need to be replaced. This makes it possible to install a wind farm up to a maximum rating of 5.1MW, consisting of six 850kW wind turbines without overloading the circuit. This option is only viable if the steady-state voltage rise in the circuit does not exceed the permitted limits. Furthermore, this depends on the economic feasibility of the project as this involves significant cost to replace such cables.

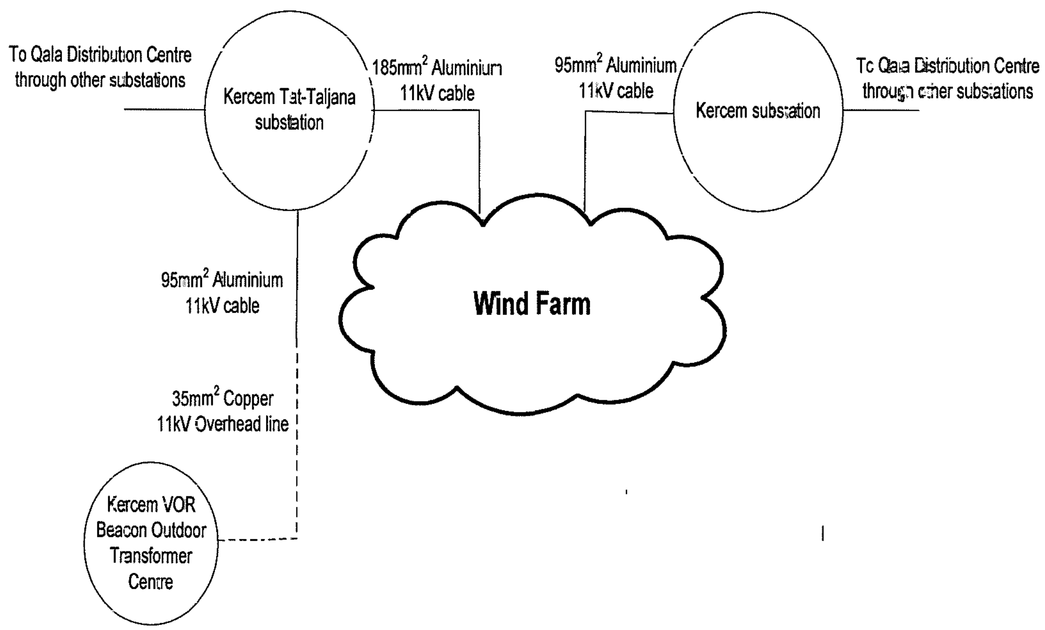


Figure 5.9 - Wind farm connection between Kerċem tat-Taljana and Kerċem substations

5.3 Impacts on the Steady-State Voltage of the Grid

The impacts on the grid from the projected wind farm at Kerċem need to be studied in detail through a load flow analysis. Such analysis determines the power flows through the network and also the voltage levels on the busbars of the substations throughout the entire feeder.

The following four options of wind farm connection with the grid are considered in this analysis:

- **Option 1** - 3.4MW wind farm consisting of four 850kW wind turbines connected through a 35mm^2 copper overhead line with the utility's overhead line feeding Kerċem VOR Beacon TC;
- **Option 2** - 3.4MW wind farm consisting of four 850kW wind turbines connected by two 95mm^2 aluminium cables between Kerċem tat-Taljana and Kerċem substations;
- **Option 3** - 5.1MW wind farm consisting of six 850kW wind turbines connected by two 185mm^2 aluminium cables between Kerċem tat-Taljana and Kerċem substations;
- **Option 4** - 5.1MW wind farm consisting of six 850kW wind turbines connected by two 185mm^2 aluminium cables between Kerċem tat-Taljana and Kerċem substations with the proposed Xewkija DC being the 11kV feeder's main source instead of Qala DC.

5.3.1 Option 1 – 3.4MW Wind Farm Connected with Kerċem VOR Beacon Overhead Line

As already mentioned, the proposed wind farm at Kerċem can be integrated with the utility grid through an overhead line connected with the utility's overhead line feeding Kerċem VOR Beacon TC. As the wind farm consists of four 850kW wind turbines, equivalent to a total of 3.4MW, a 35mm^2 copper overhead line is sufficient to take the full generating capacity of the wind farm. The length of the overhead line from the nearest wind turbine to Kerċem VOR Beacon TC is about

600m. The underground cables looping between every wind turbine substation and the other consist of 95mm^2 aluminium cables having a length of about 200m. The steady-state voltage impact on the circuit is investigated through load flow analysis for the following worst case scenarios:

- **Scenario A** - 3.4MW wind farm generating maximum power at 0.95 leading and lagging power factor during minimum load demand;
- **Scenario B** - 3.4MW wind farm generating 3.15MW at 0.95 leading and lagging power factor during minimum load demand;
- **Scenario C** - 3.4MW wind farm generating maximum power at 0.95 leading and lagging power factor during maximum load demand;
- **Scenario D** - 3.4MW wind farm disconnected during maximum load demand.

A snapshot of the circuit and proposed wind farm modelled in IPSA– software is shown in Figure B.1 of Appendix B.

5.3.1.1 Scenario A - 3.4MW Wind Farm generating maximum power during minimum load demand

The worst case scenario of voltage rise in the network is when the wind farm generates maximum power during minimum load demand. This scenario involves a 3.4MW wind farm operating at 0.95 leading and lagging power factors, with the voltage at the 11kV busbar of Qala DC regulated within the 1.5% bandwidth of 11.2kV. This situation has been analysed through a load flow study in IPSA+ program. The voltage magnitudes resulting in the 11kV and LV busbars are shown in Table B.1.1 of Appendix B. The resulting voltage profiles in the 11kV circuit with respect to its impedance are shown in
Figure 5.10.

Table 5.1 clearly shows that the high reactive power sourced from Qala DC, as the wind farm operates at 0.95 leading power factor, has limited the voltage rise at the

PCC to 5.27% of the nominal voltage. This voltage magnitude just exceeds the 5% voltage rise limit. However, with several substation transformers set at the minimum tap position, the resulting voltage magnitudes in the LV busbars are all within the permitted limits as established in the network code.

3.4MW Wind Farm connected with Kerċem VOR Beacon O/H Line		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	3.4	3.4
Load Demand (MVA)	1.21	1.21
Net Real Power flow into Qala DC (MW)	1.79	1.78
Net Reactive Power flow into Qala DC (MVAr)	-1.48	0.73
Voltage at Source (kV)	11.15	11.26
Voltage at the PCC (kV)	11.58	11.94
Real Power Losses in the Circuit (MW)	0.23	0.18
Reactive Power Losses in the Circuit (MVAr)	0.25	0.21

Table 5.1 - Net Power flow and losses in the 11kV circuit for scenario A in option 1

On the other hand, as the wind farm exports reactive power at a power factor of 0.95, the voltage at the PCC rises to 8.55% of the nominal voltage. Despite setting the substation transformers between Kerċem tat-Taljana substation and the last node of the feeder at the minimum tap position, the resulting voltage magnitudes in the LV busbars still exceed the limits established in the network code. One can note that as the reactive power flow in the circuit is reduced, the losses in the circuit decrease. Thus, it is preferable to operate the wind farm at unity or lagging power factor.

Setting the target voltage of the AVC of the transformer at Qala DC to 11.1kV will not help to reduce the voltage levels in the circuit. The resulting voltage magnitudes at the 11kV busbar for both operating power factor scenarios fall within the 1.5% bandwidth of 11.1kV. Thus, the transformer will not be forced to implement a tap-change to reduce the voltage at the 11kV busbar when it is regulated within the bandwidth of 11.1kV. Another option to regulate the voltage in the circuit within acceptable limits is by limiting the real power generated by the wind farm.

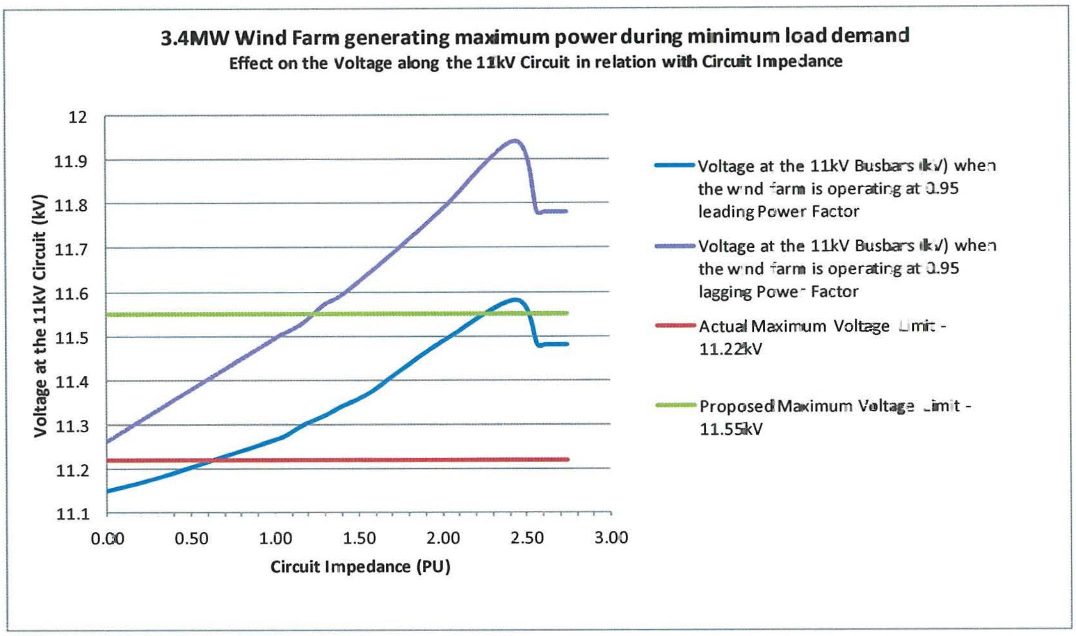


Figure 5.10 - Voltage profile along the 11kV circuit for scenario A in option 1

5.3.1.2 Scenario B - 3.4MW Wind Farm generating 3.15MW during minimum load demand

The voltage at the wind farm's point of connection can be reduced to permitted voltage levels by curtailing the generated real power while the wind-powered generators absorbs maximum reactive power. The maximum power which can be generated without exceeding the 5% voltage rise in the 11kV circuit is 3.15MW. The results obtained in the 11kV and LV busbars as the wind farm operates at 0.95 leading and lagging power factors, with the AVC's target voltage of the transformer at Qala DC set at 11.2kV are shown in Table B.1.2 of Appendix B. The resulting voltage profiles along the 11kV circuit with respect to the circuit impedance are shown in Figure 5.11.

The reduced power generated from the wind farm reduces the net real power flow into Qala DC as indicated in Table 5.2. The curtailed power generation and the reactive power consumption by the wind farm at a power factor of 0.95 has reduced the voltage rise at the PCC to 5% of the nominal voltage. Thus, the maximum voltage in the 11kV circuit does not exceed the proposed upper voltage limit. As several transformers in the circuit are set at their minimum tap position, the resulting voltage magnitudes in the LV busbars are within the permitted limits as established in the network code.

3.4MW Wind Farm connected with Kerċem VOR Beacon O/H Line		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	3.15	3.15
Load Demand (MVA)	1.21	1.21
Net Real Power flow into Qala DC (MW)	1.6	1.58
Net Reactive Power flow into Qala DC (MVAr)	-1.38	0.67
Voltage at Source (kV)	11.15	11.26
Voltage at the PCC (kV)	11.55	11.88
Real Power Losses in the Circuit (MW)	0.2	0.16
Reactive Power Losses in the Circuit (MVAr)	0.22	0.18

Table 5.2 - Net Power flow and losses in the 11kV circuit for scenario B in option 1

Exporting reactive power at a power factor of 0.95 at the reduced real power generation of 3.15MW is not enough to reduce the voltage at PCC to within acceptable limits. In fact the resulting voltage at the PCC exceeds the nominal voltage by 8%. Consequently, the voltage at the LV side of Kerċem VOR Beacon TC exceeds the 10% tolerance from the nominal voltage even though the transformer is set at the minimum tap position. The reduced real power generated, reduces the losses in both power factor extreme scenarios.

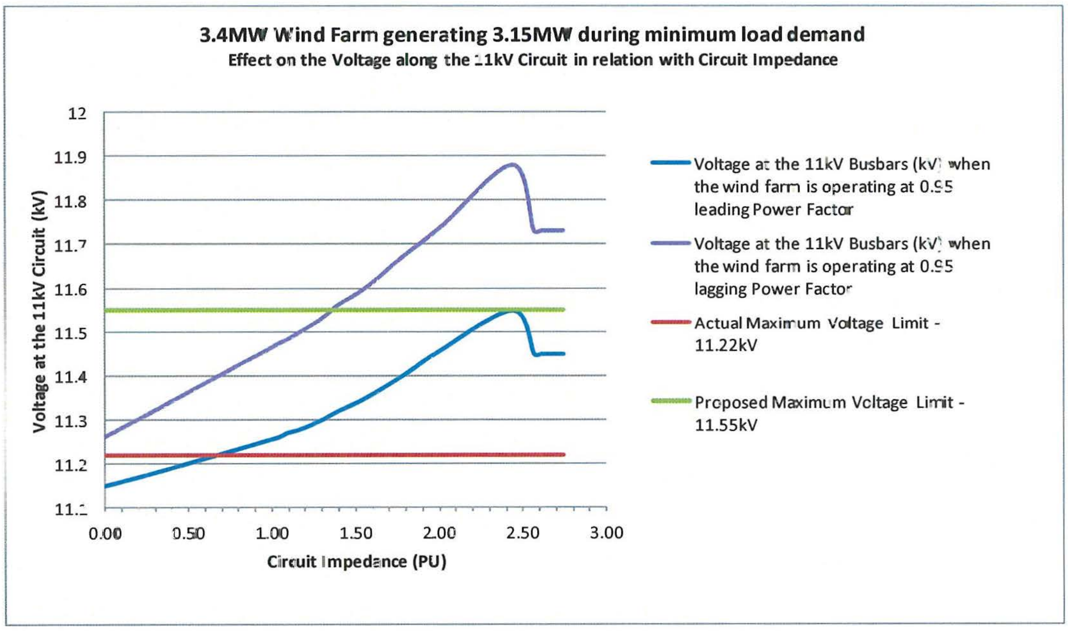


Figure 5.11 - Voltage profile along the 11kV circuit for scenario B in option 1

5.3.1.3 Scenario C - 3.4MW Wind Farm generating maximum power during peak load demand

The scenario of having the 3.4MW wind farm generating maximum power during peak load demand is investigated through a load flow study. The fixed tap-changers of the distribution transformers are kept in the same position as in scenario B. The 11kV busbar at Qala DC is regulated within the 1.5% bandwidth of 11.2kV as in previous scenarios. The steady-state voltage magnitudes resulting at the 11kV and LV busbars while the generators operates at power factors of 0.95 leading and lagging are shown in Table B.1.3 of Appendix B. The resulting voltage profiles along the 11kV circuit with respect to circuit impedance is shown in Figure 5.12.

3.4MW Wind Farm connected with Kerċem VOR Beacon O/H Line		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	3.4	3.4
Load Demand (MVA)	4.49	4.49
Net Real Power flow into Qala DC (MW)	-1.27	-1.19
Net Reactive Power flow into Qala DC (MVAr)	-3.07	-0.83
Voltage at Source (kV)	11.35	11.18
Voltage at the PCC (kV)	11.19	11.29
Real Power Losses in the Circuit (MW)	0.29	0.15
Reactive Power Losses in the Circuit (MVAr)	0.41	0.30

Table 5.3 - Net Power flow and losses in the 11kV circuit for scenario C in option 1

From

Table 5.3, one can note that since the load demand is greater than the generated power from the wind farm, Qala DC is sourcing the net real and reactive power. This has kept the voltage at PCC within acceptable limits for both extreme power factor scenarios. Consequently, the voltage in the LV busbars are within the ±10% tolerance as stipulated in the network code. In such scenario, it is preferable to operate the wind farm at 0.95 lagging power factor so that the losses in the circuit are minimised.

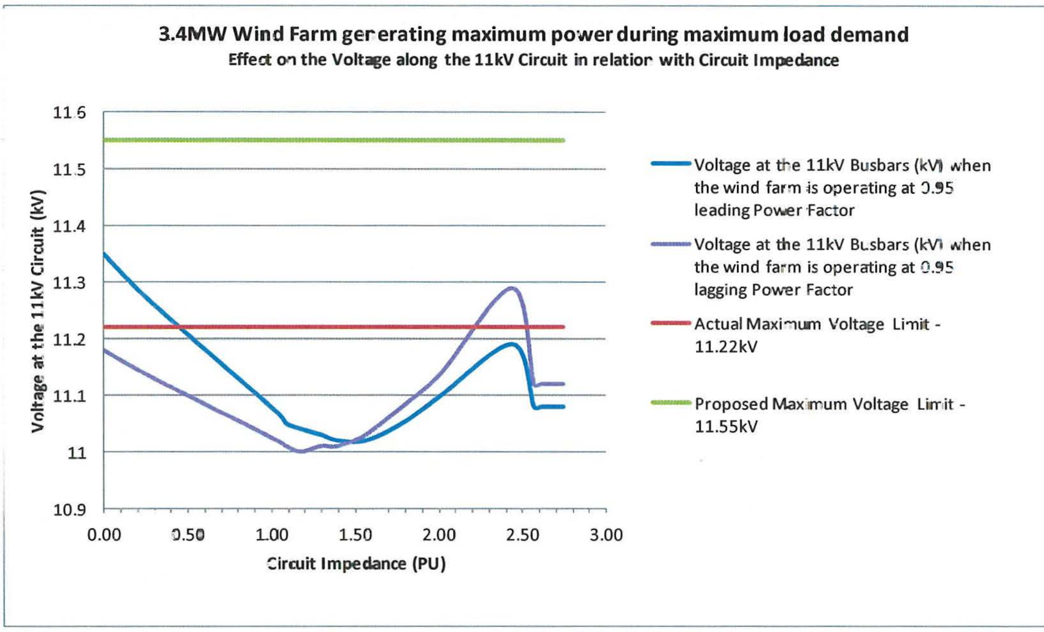


Figure 5.12 - Voltage profile along the 11kV circuit for scenario C in option 1

5.3.1.4 Scenario D - 3.4MW Wind Farm disconnected during peak load demand

As several distribution transformers in the circuit are set at their minimum tap position, this would lead to a considerable voltage drop at the consumer end when the wind farm is disconnected. The scenario of having the entire 3.4MW wind farm disconnected during peak load conditions is analysed. The voltage resulting at the 11kV and 400V busbars are shown in Table B.1.4 of Appendix B. The voltage profile along the 11kV circuit in relation with circuit impedance is shown in Figure 5.13. The tap positions of all the transformers in the distribution substations were kept in the same position as in scenario C.

3.4MW Wind Farm connected with Kerċem VOR Beacon O/H line Switched Off	
Power Generated (MW)	0
Load Demand (MVA)	4.49
Net Real Power flow into Qala DC (MW)	-4.5
Net Reactive Power flow into Qala DC (MVAr)	-1.99
Voltage at Source (kV)	11.12
Minimum Voltage in the Circuit (kV)	10.25
Real Power Losses in the Circuit (MW)	0.32
Reactive Power Losses in the Circuit (MVAr)	0.37

Table 5.4 - Net Power flow and losses in the 11kV circuit for scenario D in option 1

It is evident from

Table 5.4 that the minimum voltage in the 11kV circuit is well below the limit of 10.45kV. From the voltage profile in Figure 5.13, one can note that a considerable number of nodes in the circuit exceeds the 5% voltage drop limit. In fact the lower voltage limit in the 11kV circuit was exceeded in the section between Victoria substation and the last node in the circuit. Such significant voltage drop in the circuit is mainly due to the I^2R losses caused by high load and significant circuit impedance. Such voltage drop in the 11kV circuit added with the effect of having several transformers set at the minimum tap position, has caused a minimum voltage in the LV side of 376V. If a maximum voltage drop of 6% across the LV lines is assumed, the lowest voltage at the consumer end is around 353V. This implies that the resulting voltage magnitudes at the consumer terminals violates the permitted limits as established in the network code. The situation can be improved by reducing the load and impedance of the LV circuits. such that the voltage drop in the LV feeders does not exceed 4.2%.

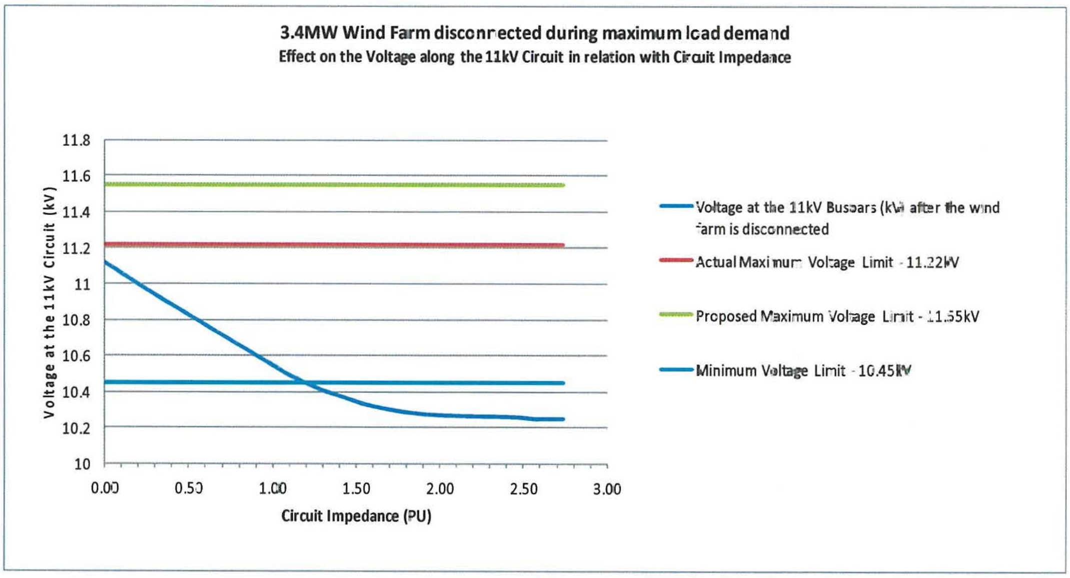


Figure 5.13 - Voltage profile along the 11kV circuit for scenario D in option 1

5.3.2 Option 2 - 3.4MW Wind Farm Connected between Kerċem tat-Taljana and Kerċem Substations

Another option for connecting the wind farm with the grid is for it to be electrically inserted between Kerċem tat-Taljana and Kerċem substations. The WFCSR is typically placed close to the point of connection. The two 95mm^2 aluminium cables between the WFCSR and the wind turbines substations are typically laid through the public roads. The approximate length of each cable is about 1850m. Figure 4.5 illustrates the single line diagram for such arrangement. The bus-section CB in the WFCSR is switched on, while one of the ring-switches of the RMU in the section between wind turbine substation 2 and 3 is switched off. From a power flow perspective, the 3.4MW wind farm is seen as split in two 1.7MW generation units. The power from each of these two generation units is fed into their respective cables towards the busbar of the WFCSR. From this common busbar, the generated power is distributed according to the load demand towards both sides of the feeder. A snapshot from IPSA+ software of the modelled wind farm connected with grid is shown in Figure B.2 of Appendix B. The impact of the 3.4MW wind farm on the network is analysed for the following scenarios:

- **Scenario A** - 3.4MW wind farm generating maximum power at 0.95 leading and lagging power factor during minimum load demand;
- **Scenario B** - 3.4MW wind farm generating maximum power at 0.95 leading and lagging power factor during maximum load demand;
- **Scenario C** - 3.4MW wind farm disconnected during maximum load demand.

5.3.2.1 Scenario A - 3.4MW Wind Farm generating maximum power during minimum load demand

The worst case scenario for steady state voltage rise on the circuit is experienced when the 3.4MW wind farm generates maximum power during minimum load demand. The voltage magnitudes resulting at the 11kV and LV busbars in the circuit from the impact of the wind farm operating at 0.95 leading and lagging power factors with the 11kV busbar at Qala DC regulated within the 1.5% bandwidth of 11.2kV are shown in Table B.2.1 in Appendix B. The resulting voltage profiles in relation with circuit impedance are shown in Figure 5.14.

3.4MW Wind Farm connected between Kerċem tat-Taljana and Kerċem Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	3.4	3.4
Load Demand (MVA)	1.21	1.21
Net Real Power flow into Qala DC (MW)	1.83	1.81
Net Reactive Power flow into Qala DC (MVAr)	-1.45	0.76
Voltage at Source (kV)	11.15	11.26
Voltage at the PCC (kV)	11.52	11.82
Real Power Losses in the Circuit (MW)	0.19	0.15
Reactive Power Losses in the Circuit (MVAr)	0.22	0.18

Table 5.5 - Net Power flow and losses in the 11kV circuit for scenario A in option 2

Operation of the wind farm at 0.95 leading power factor does not cause the voltage at the PCC to exceed the 5% voltage rise of the nominal voltage. From Table 5.5, it is clear that this is due to the significant import of reactive power from Qala DC as compared with the wind farm operation at 0.95 lagging power factor. Another reason, is that the impedance between PCC and Qala DC is reduced to 2.01pu from the impedance of 2.44pu in option 1. Since several transformers are set at their minimum tap position, the resulting voltage levels in the LV busbars of all the substations in the circuit are within the ±10% limit.

As the wind farm generates reactive power at a power factor of 0.95, the losses along the feeder decrease. However the voltage in the 11kV circuit rises up to 7.45% of the nominal voltage. Consequently, the voltage at several LV busbars exceeds the upper limit of 440V despite setting the transformers at their minimum tap position.

In view that the resulting voltage magnitudes in the 11kV busbar of Qala DC for the leading and lagging power factors, that is, 11.15kV and 11.26kV respectively, are within the 1.5% bandwidth of 11.1kV, setting the AVC target voltage to 11.1kV will not help reduce the voltage rise in the circuit.

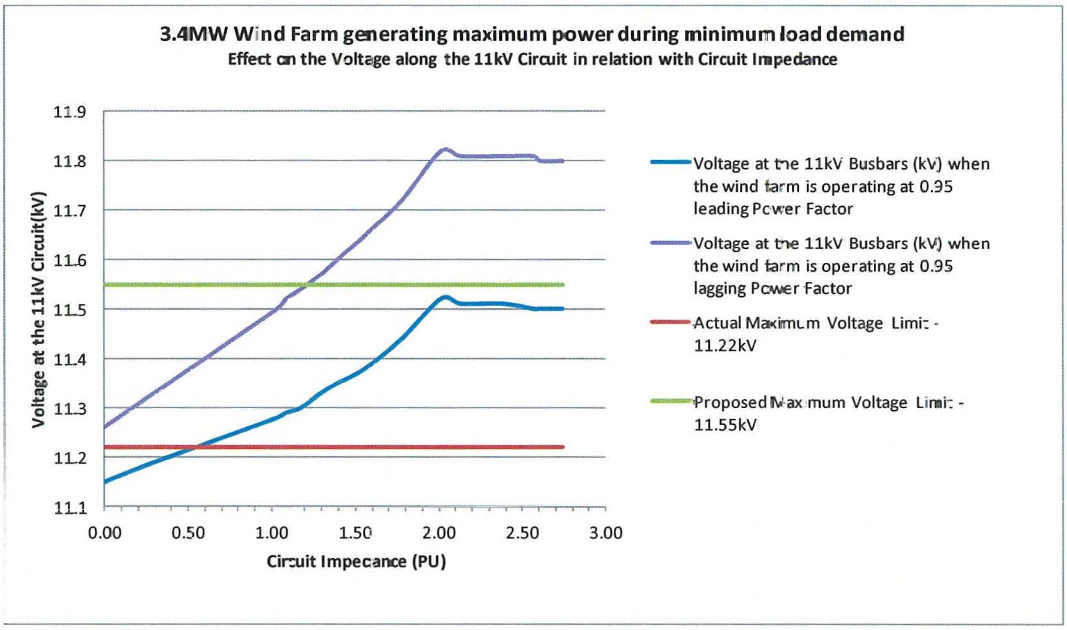


Figure 5.14 - Voltage profile along the 11kV circuit for scenario A in option 2

5.3.2.2 Scenario B - 3.4MW Wind Farm generating maximum power during maximum load demand

The voltage magnitudes at the 11kV and LV busbars resulting from the impact of the 3.4MW wind farm while generating maximum power at 0.95 leading and lagging power factors during maximum load demand are shown in Table B.2.2 in Appendix B. The 11kV busbar of Qala DC is regulated within the 1.5% bandwidth of 11.2kV. The transformers' tap positions are kept as in scenario A. The resulting voltage profiles of the 11kV circuit in relation with circuit impedance are shown in Figure 5.15.

From Table 5.6, one can note that the load demand is greater than the power generated by the wind farm. Thus Qala DC has to source real and reactive power for both power factors scenarios. This has kept the voltage at the 11kV and LV circuits within the limits established in the network code. In such scenario, it is preferable to operate the wind farm in lagging power factor mode, as the losses in the circuit are minimised.

3.4MW Wind Farm connected between Kerċem tat-Taljana and Kerċem Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	3.4	3.4
Load Demand (MVA)	4.49	4.49
Net Real Power flow into Qala DC (MW)	-1.23	-1.16
Net Reactive Power flow into Qala DC (MVAr)	-3.03	-0.8
Voltage at Source (kV)	11.35	11.18
Voltage at the PCC (kV)	11.12	11.16
Real Power Losses in the Circuit (MW)	0.25	0.12
Reactive Power Losses in the Circuit (MVAr)	0.37	0.27

Table 5.6 - Net Power flow and losses in the 11kV circuit for scenario B in option 2

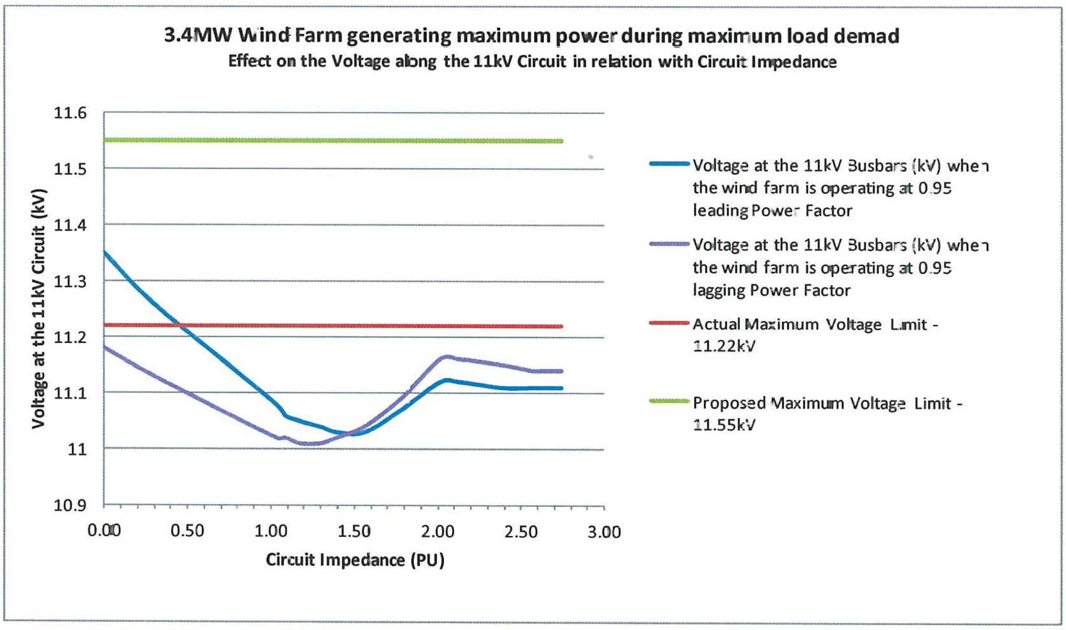


Figure 5.15 - Voltage profile along the 11kV circuit for scenario B in option 2

5.3.2.3 Scenario C - Wind Farm disconnected during peak load demand

The voltage magnitudes resulting at the 11kV and LV busbars in the circuit after the wind farm is disconnected are shown in Table B.2.3 in Appendix B. The voltage profile along the 11kV circuit with respect to circuit impedance is shown in Figure 5.16. The substation transformers are kept in the same tap positions as in the previous scenarios.

3.4MW Wind Farm connected between Kerċem tat-Taljana and Kerċem Substations Switched Off	
Power Generated (MW)	0
Load Demand (MVA)	4.49
Net Real Power flow into Qala DC (MW)	-4.5
Net Reactive Power flow into Qala DC (MVAr)	-1.88
Voltage at Source (kV)	11.12
Minimum Voltage in the Circuit (kV)	10.24
Real Power Losses in the Circuit (MW)	0.32
Reactive Power Losses in the Circuit (MVAr)	0.37

Table 5.7 - Net Power flow and losses in the 11kV circuit for scenario C in option 2

Table 5.7 clearly shows that the resulting voltage drop in the 11kV circuit as the wind farm is disconnected is quite significant. In fact, the voltage drop at the last node of the radial circuit is 6.9% of the nominal voltage which exceeds the permitted 5% limit. Such significant voltage drop causes the voltage in the 11kV busbars of several substations in the 11kV circuit to be lower than the 10.45kV limit. Consequently, the LV busbars experience a considerable decrease in voltage especially in those substations where the transformers are set at the minimum tap position. The minimum voltage appearing at the LV busbars of the circuit is 376V. A voltage drop of 6% along the LV lines results in a voltage of 353V at the consumer terminals, which violates the limits established in the network code. This situation can be improved by reducing the voltage drop in the LV circuits to less than 4.2%, by reducing the load and impedance in the LV lines.

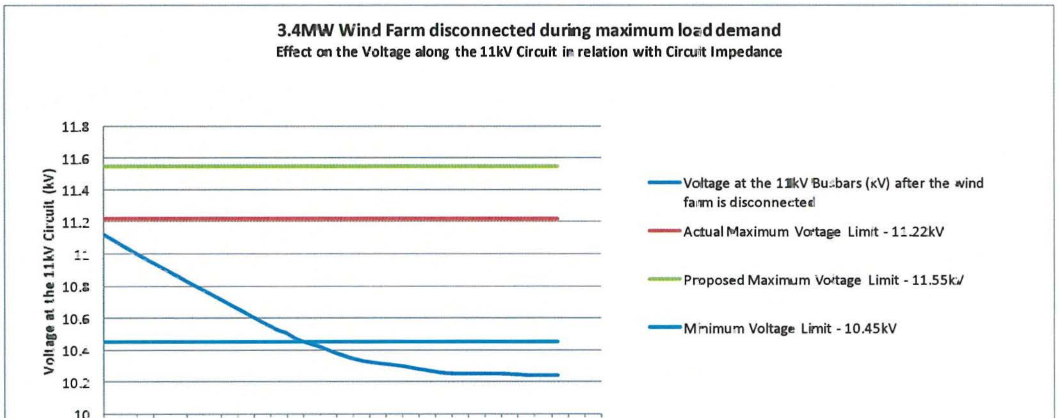


Figure 5.16 - Voltage profile along the 11kV circuit for scenario C in option 2

5.3.3 Option 3 - 5.1MW Wind Farm Connected between Kerċem tat-Taljana and Kerċem Substations

The wind farm size is limited by the existing 95mm^2 aluminium cables, rated at 3.9MVA, in the section between the FCC and Victoria Kerċem Rd substation. In order to accommodate a larger wind farm, the cables in this section need to be replaced by 185mm^2 aluminium cables, rated at 5.7MVA. The total length of cable that needs to be replaced is about 1800 metres. This will make it possible to install up to six 850kW wind turbines without overloading the 11kV circuit. However the viability of such option depends on the steady-state voltage rise in the circuit which will be determined by a load flow analysis.

The modelled wind farm is connected with the grid by two 185mm^2 aluminium cables. The cables looping between the wind turbines also consists of 185mm^2 aluminium conductor cables. The wind farm and the 11kV circuit are modelled in the IPSA+ program as shown in the snapshot in Figure B.3 in Appendix B. The impact of the wind farm on the grid is analysed for the following scenarios:

- **Scenario A** - 5.1MW Wind Farm generating maximum power at 0.95 leading and lagging power factor during minimum load demand;
- **Scenario B** - 5.1MW Wind Farm generating 4.25MW at 0.95 leading and lagging power factor during minimum load demand;
- **Scenario C** - 5.1MW Wind Farm generating maximum power at 0.95 leading and lagging power factor during maximum load demand;
- **Scenario D** - 5.1MW Wind Farm disconnected during maximum load demand.

5.3.3.1 Scenario A - 5.1MW Wind Farm generating maximum power during minimum load demand

The 5.1MW wind farm, consisting of six 850kW wind turbines, is analysed in the worst case scenario to verify whether the steady-state voltage of the 11kV circuit exceeds the permitted limits. The wind farm is analysed at its two extreme operating modes, that are, at 0.95 leading and lagging power factors. The voltage resulting at the 11kV and LV busbars of all the nodes in the circuit for both operating power factors are shown in Table B.3.1 in Appendix B. The resulting voltage profiles of the 11kV circuit with respect to circuit impedance are shown in Figure 5.17.

5.1MW Wind Farm connected between Kerċem tat-Taljana and Kerċem Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	5.1	5.1
Load Demand (MVA)	1.21	1.21
Net Real Power flow into Qala DC (MW)	3.25	3.24
Net Reactive Power flow into Qala DC (MVAr)	-2.15	1.17
Voltage at Source (kV)	11.12	11.28
Voltage at the PCC (kV)	11.65	12.1
Real Power Losses in the Circuit (MW)	0.38	0.31
Reactive Power Losses in the Circuit (MVAr)	0.42	0.35

Table 5.8 - Net Power flow and losses in the 11kV circuit for scenario A in option 3

Table 5.8 clearly shows that the significant flow of net power into Qala DC has caused a considerable voltage rise at the PCC exceeding the 5% of the nominal voltage in both operating power factor scenarios. When the wind farm operates at a leading power factor of 0.95, the voltage rise at the PCC is 5.9% of the nominal voltage. Such voltage rise in the 11kV circuit does not cause the voltage at the LV busbars to exceed the 10% voltage rise limit with the transformers being set at the minimum tap position.

However, as the wind farm exports reactive power at a power factor of 0.95, the voltage rise at the PCC reaches 10% of the nominal voltage. The high increase in the voltage magnitudes of several nodes in the 11kV circuit has caused the voltage at the LV busbars to exceed the upper limit of 440V despite having the transformers set at their minimum tap position.

Since both operating power factor modes causes the voltage in the 11kV circuit to exceed the proposed 5% voltage rise limit, the wind farm cannot be operated in such scenario. Setting the voltage set-point of the AVC at Qala DC to 11.1kV will not cause the transformer to perform a tap-change to reduce the voltage. Thus, a solution would be to limit the real power generation of the wind farm.

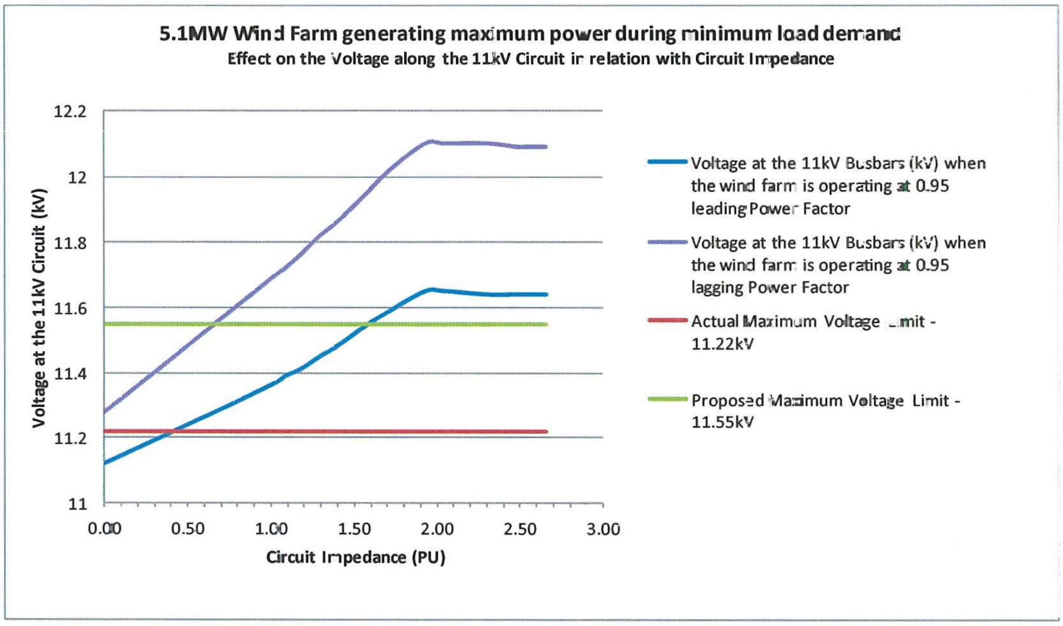


Figure 5.17 - Voltage profile along the 11kV circuit for scenario A in option 3

5.3.3.2 Scenario B - 5.1MW Wind Farm generating 4.25MW during minimum load demand

The impact on the steady-state voltage of the circuit from various curtailed real power generation values are analysed through a load flow study. The resulting maximum real power generation at the maximum possible reactive power absorption that produces acceptable voltage results in the 11kV circuit is 4.25MW. This implies that one of the six wind turbines has to be switched off during minimum load demand. The voltage magnitudes at the 11kV and LV busbars resulting from the impact of the wind farm while generating 4.25MW at 0.95 leading and lagging power factors are shown in Table B.3.2 in Appendix B.

The resulting voltage profiles of the 11kV circuit in relation with circuit impedance are shown in Figure 5.18.

5.1MW Wind Farm connected between Kerċem tat-Taljana and Kerċem Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	4.25	4.25
Load Demand (MVA)	1.21	1.21
Net Real Power flow into Qala DC (MW)	2.56	2.53
Net Reactive Power flow into Qala DC (MVAr)	-1.8	0.93
Voltage at Source (kV)	11.13	11.27
Voltage at the PCC (kV)	11.55	11.93
Real Power Losses in the Circuit (MW)	0.26	0.21
Reactive Power Losses in the Circuit (MVAr)	0.31	0.26

Table 5.9 - Net Power flow and losses in the 11kV circuit for scenario B in option 3

As indicated in Table 5.9, the reduced net real power flowing towards the primary substation causes the voltage at the PCC to decrease in both operating power factor scenarios. However, the wind farm has to consume reactive power at a power factor of 0.95 in order to reduce the voltage at the PCC to 11.55kV. Consequently, the voltage at the LV busbars does not exceed the 10% voltage rise limit with the transformers being set at the minimum tap position.

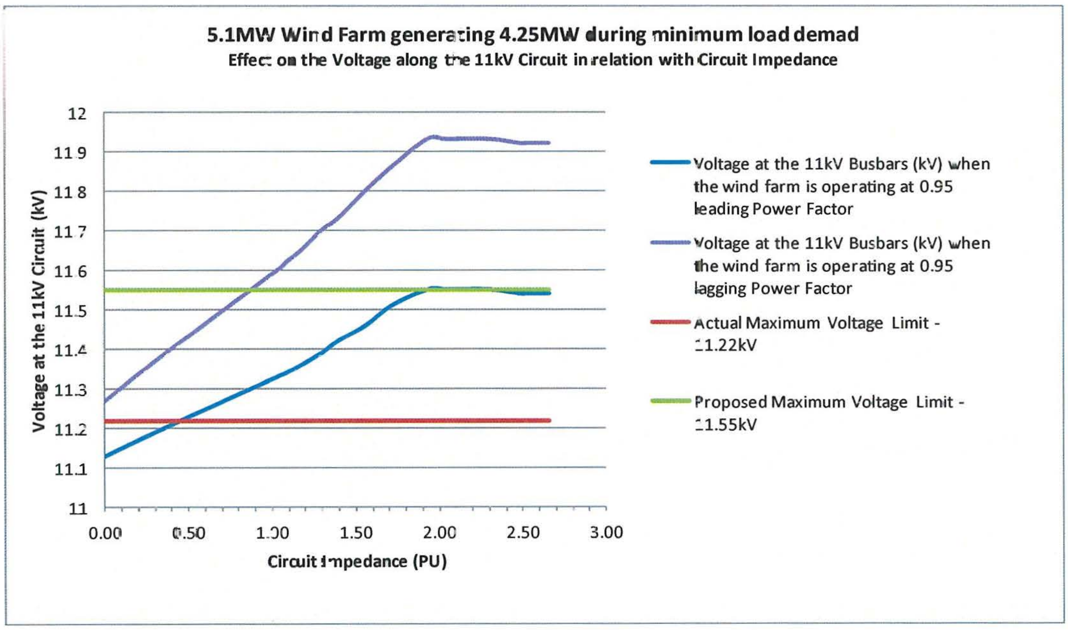


Figure 5.18 - Voltage profile along the 11kV circuit for scenario B in option 3

As the wind farm exports reactive power at a power factor of 0.95, the voltage rise resulting at the PCC is 8.45%. Such excessive voltage rise causes the voltage at the LV busbars to exceed the limits established in the network code despite having the transformers set at the minimum tap position.

5.3.3.3 Scenario C - 5.1MW Wind Farm generating maximum power during maximum load demand

The impact from the 5.1MW wind farm, while generating maximum power during maximum load demand on the steady-state voltage of the circuit, is analysed. This will verify whether such size of wind farm is technically possible to be installed without violating the voltage limits established in the network code. The substations transformers were kept in the same tap positions as in the previous scenarios. The voltage magnitudes resulting at the 11kV and LV busbars of the nodes in the circuit are shown in Table B.3.3 in Appendix B. The resulting voltage profiles of the 11kV circuit with respect to circuit impedance are shown in Figure 5.19.

5.1MW Wind Farm connected between Kerċem tat-Taljana and Kerċem Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	5.1	5.1
Load Demand (MVA)	4.49	4.49
Net Real Power flow into Qala DC (MW)	0.28	0.39
Net Reactive Power flow into Qala DC (MVAr)	-3.69	-0.32
Voltage at Source (kV)	11.32	11.2
Voltage at the PCC (kV)	11.29	11.5
Real Power Losses in the Circuit (MW)	0.35	0.15
Reactive Power Losses in the Circuit (MVAr)	0.50	0.33

Table 5.10 - Net Power flow and losses in the 11kV circuit for scenario C in option 3

As indicated in Table 5.10, the small amount of net real power exported into Qala DC, and reactive power imported from the same DC, kept the voltage at the PCC within acceptable limits for both extreme operating power factors scenarios. Thus, the resulting voltage at the LV busbars of the substations does not exceed the upper limit of 440V. It is preferable that during high load demands, the wind farm exports reactive power as the losses in the circuit are minimised.

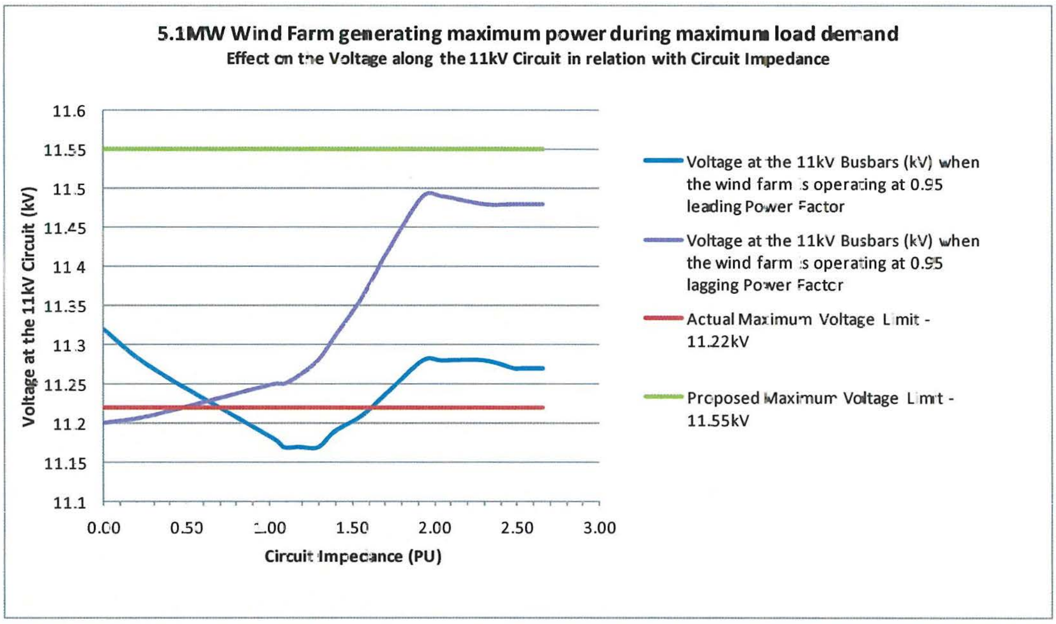


Figure 5.19 - Voltage profile along the 11kV circuit for scenario C in option 3

5.3.3.4 Scenario D - 5.1MW Wind Farm disconnected during maximum load demand

In view that several fixed tap-changers of the substation transformers are set at their minimum tap position, the voltage drop especially at the general consumer end can be of great concern, during wind farm disconnection. Thus in this scenario, the impact on the steady-state voltage from the disconnection of the 5.1MW wind farm during peak load demand is analysed. The voltage magnitudes resulting at the 11kV and LV busbars after wind farm disconnection are shown in Table B.3.4 in Appendix B. The voltage profile of the 11kV circuit in relation with circuit impedance is shown in Figure 5.20.

From Table 5.11, it can be noted that the voltage drop in the 11kV circuit reaches 6.7%, thus violating the limits established in the network code. The lowest voltage resulting in the LV busbars is 377V, with the transformer in the substation set at the minimum tap position. If a 6% voltage drop along the LV lines is assumed, a voltage of 354V results at the consumer terminals, hence violating the limits established in the network code. This problem can be mitigated by better load sharing between the LV circuits such that the voltage drop along the LV lines is reduced to below 4.5%.

5.1MW Wind Farm connected between Kerċem tat-Taljana and Kerċem Substations Switched Off	
Power Generated (MW)	0
Load Demand (MVA)	4.49
Net Real Power flow into Qala DC (MW)	-4.5
Net Reactive Power flow into Qala DC (MVAr)	-1.89
Voltage at Source (kV)	11.12
Minimum Voltage in the Circuit (kV)	10.26
Real Power Losses in the Circuit (MW)	0.32
Reactive Power Losses in the Circuit (MVAr)	0.38

Table 5.11 - Net Power flow and losses in the 11kV circuit for scenario D in option 3

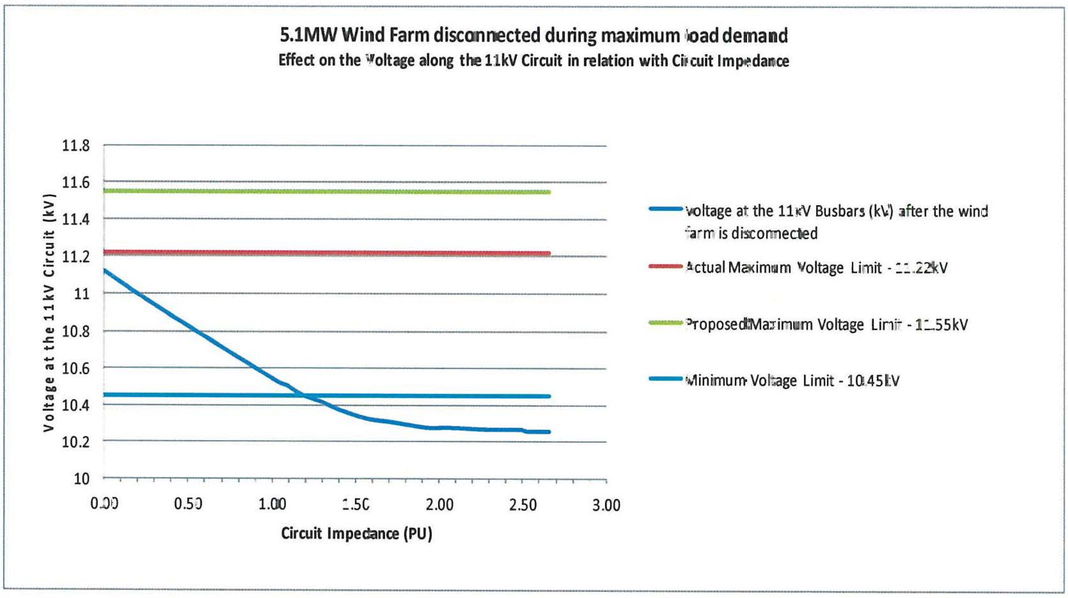


Figure 5.20 - Voltage profile along the 11kV circuit for scenario D in option 3

5.3.4 Option 4 - 5.1MW Wind Farm Connected between Kerċem tat-Taljana and Kerċem Substations with the Planned Xewkija DC as the Main Source

The planned Xewkija DC is to be located at the central region of the island. Thus the DC will be much closer to the wind farm under consideration. Consequently, the number of substations in the circuits are reduced, thus reducing the total circuit impedance due to a shorter cable route length. This will decrease the voltage drop in the circuit between the wind farm and the DC, hence reducing the voltage rise at the PCC. The set up and connection of the 5.1MW wind farm between Kerċem tat-Taljana and Kerċem substations is the same as in option 3. The 95mm^2 aluminium cable segments between the WFCSR and Kerċem Rd substation still need to be replaced by 185mm^2 aluminium cables in order to be sufficiently rated without being overloaded from the wind farm generation power. The 33/11kV transformer at Xewkija DC is planned to be similar to the one at Qala DC, having a power rating of 30MVA. Thus, the 11kV busbar voltage is assumed to be regulated within the 1.5% bandwidth of 11.2kV.

The modified 11kV circuit and wind farm are modelled in IPSA+ as shown in the snapshot in Figure B.4 in Appendix B. The impact on the network from the 5.1MW wind farm is analysed for the following scenarios:

- **Scenario A** - 5.1MW wind farm generating maximum power at 0.95 leading and lagging power factors during minimum load demand;
- **Scenario B** - 5.1MW wind farm generating maximum power at 0.95 leading and lagging power factors during maximum load demand;
- **Scenario C** - 5.1MW wind farm disconnected during maximum load demand.

5.3.4.1 Scenario A - 5.1MW Wind Farm generating maximum power during minimum load conditions

The impact on the steady-state voltage of the circuit from the 5.1MW wind farm in the worst case scenario is analysed through a load flow study. This analysis will verify whether such size of a wind farm can be technically operated in this scenario without exceeding the steady-state voltage limits of the network. The resulting voltage magnitudes at the 11kV and LV busbars in the circuit are shown in Table B.4.1 in Appendix B. The voltage profiles resulting in the 11kV circuit with respect to circuit impedance are shown in Figure 5.21. From this figure, it can be noted that the circuit impedance between the PCC and the DC is reduced from 1.93pu to 0.96pu.

5.1MW Wind Farm connected between Kerċem tat-Taljana and Kerċem Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	5.1	5.1
Load Demand (MVA)	0.61	0.61
Net Real Power flow into Xewkija DC (MW)	3.97	3.92
Net Reactive Power flow into Xewkija DC (MVAr)	-2	1.3
Voltage at Source (kV)	11.12	11.29
Voltage at the PCC (kV)	11.42	11.71
Real Power Losses in the Circuit (MW)	0.24	0.21
Reactive Power Losses in the Circuit (MVAr)	0.38	0.33

Table 5.12 - Net Power flow and losses in the 11kV circuit for scenario A in option 4

From Table 5.12, it is evident that the reduced minimum load demand has increased the net power flow into Xewkija DC. However, the reduced impedance between PCC and the DC, and the reactive power consumption by the wind farm at a power factor of 0.95, limits the voltage rise in the circuit within acceptable limits. In fact, the voltage rise at the PCC is 3.8%, which is less than the proposed 5% voltage rise limit. Hence, the voltage at the LV busbars is within the permitted limits.

Conversely, as the wind farm exports reactive power at a power factor of 0.95, the voltage at the PCC well exceeds the proposed 5% voltage rise limit. However, by setting the substation transformers in the circuit at the minimum tap positions, the voltage in the LV busbars are maintained below the upper limit of 440V.

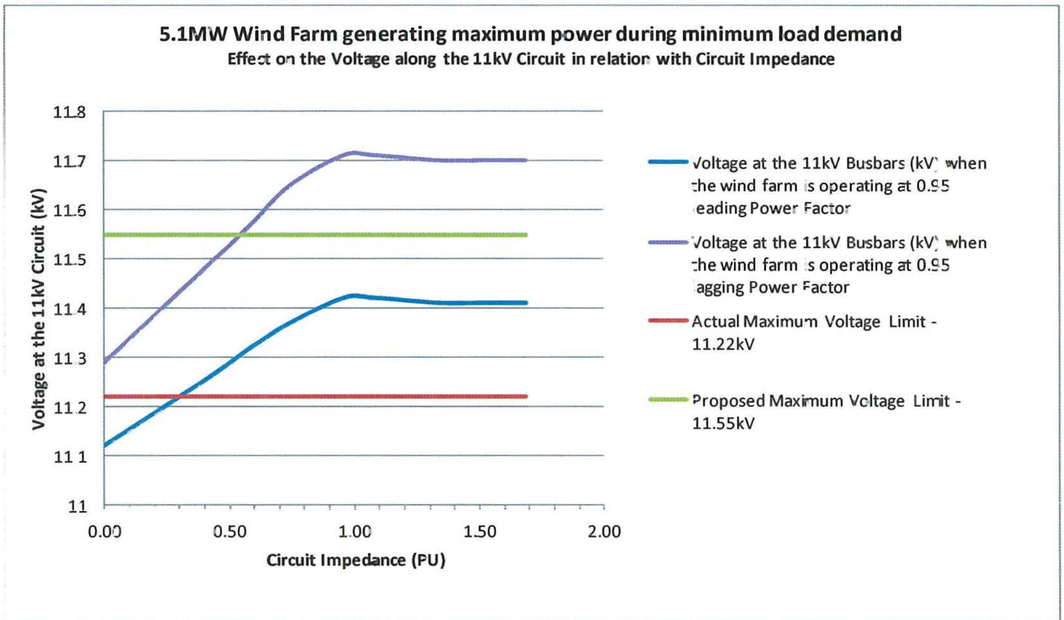


Figure 5.21 - Voltage profile along the 11kV circuit for scenario A in option 4

5.3.4.2 Scenario B - 5.1MW Wind Farm generating maximum power during maximum load conditions

The impacts on the steady-state voltage of the circuit from the 5.1MW wind farm while generating maximum power at 0.95 leading and lagging power factor during maximum load demand are analysed through a load flow study. The voltage magnitudes resulting at the 11kV and LV busbars of the nodes in the circuit, are shown in Table B.4.2 in Appendix B. The voltage profiles resulting in the 11kV circuit in relation with circuit impedance are shown in Figure 5.22.

As illustrated in Table 5.13, the maximum load demand is significantly reduced. Thus, the net power flowing into Xewkija DC increases when compared with the existent circuit configuration. However, the reduced circuit impedance between PCC and the DC has kept the resulting voltage magnitudes at the PCC for both extreme operating power factor scenarios within acceptable limits. Consequently, the resulting voltage at the LV busbars is within the permitted limits as stipulated in the network code.

5.1MW Wind Farm connected between Kerċem tat-Taljana and Kerċem Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	5.1	5.1
Load Demand (MVA)	2.52	2.52
Net Real Power flow into Xewkija DC (MW)	2.26	2.2
Net Reactive Power flow into Xewkija DC (MVAr)	-2.85	0.45
Voltage at Source (kV)	11.36	11.25
Voltage at the PCC (kV)	11.5	11.52
Real Power Losses in the Circuit (MW)	0.2	0.14
Reactive Power Losses in the Circuit (MVAr)	0.38	0.30

Table 5.13 - Net Power flow and losses in the 11kV circuit for scenario B in option 4

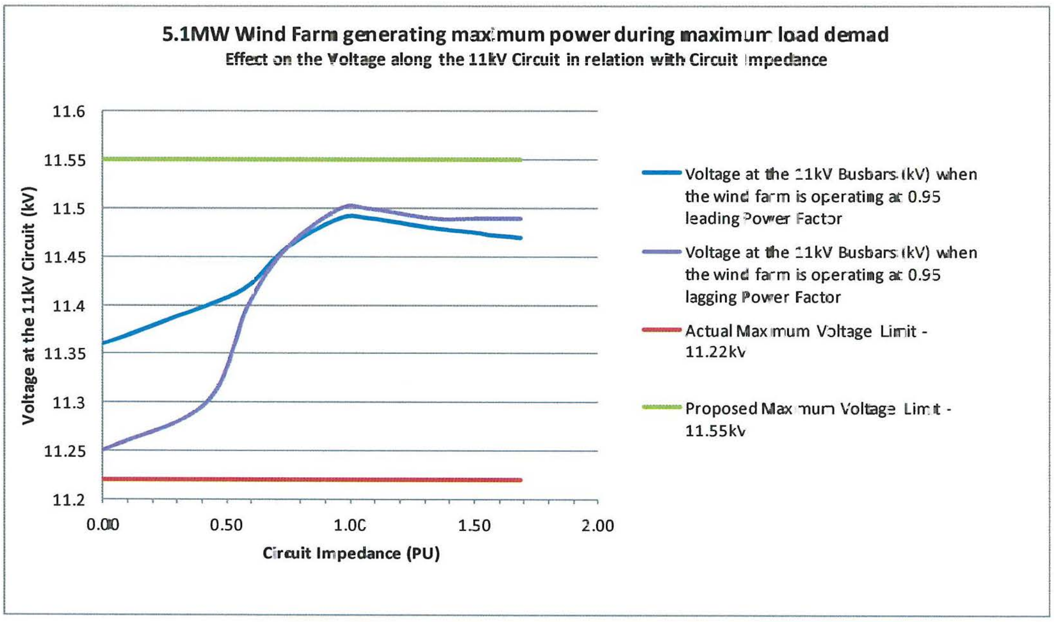


Figure 5.22 - Voltage profile along the 11kV circuit for scenario B in option 4

5.3.4.3 Scenario C - 5.1MW Wind Farm disconnected during peak load demand

The fixed tap-changers of all the substation transformers in the circuit are kept in the same tap position as in the previous scenario, that is, at the tap position of '-1'. The voltage magnitudes at the 11kV and LV busbars resulting from the disconnection of the wind farm during maximum load demand are shown in Table B.4.3 in Appendix B. The resulting voltage profile along the 11kV circuit in relation with circuit impedance is shown in

Figure 5.23.

5.1MW Wind Farm connected between Kerċem tat-Taljana and Kerċem Substations Switched Off	
Power Generated (MW)	0
Load Demand (MVA)	2.52
Net Real Power flow into Xewkija DC (MW)	-2.41
Net Reactive Power flow into Xewkija DC (MVAr)	-0.99
Voltage at Source (kV)	11.17
Minimum Voltage in the Circuit (kV)	10.92
Real Power Losses in the Circuit (MW)	0.06
Reactive Power Losses in the Circuit (MVAr)	0.12

Table 5.14 - Net Power flow and losses in the 11kV circuit for scenario C in option 4

As indicated in Table 5.14, the voltage drop resulting throughout the 11kV circuit is of 0.73% of the nominal voltage. The minimum voltage resulting in the LV busbars is 412V. If a 6% voltage drop along the LV line is assumed, the minimum voltage resulting at the consumer end will be 387V, which is within the permitted limits as specified in the network code.

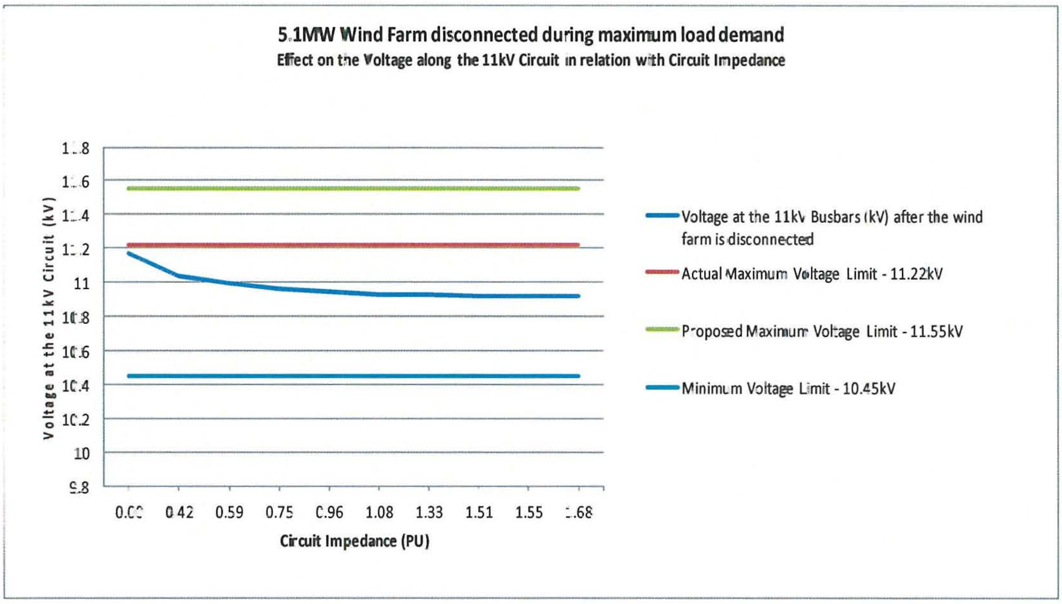


Figure 5.23 - Voltage profile along the 11kV circuit for scenario C in option 4

5.4 Conclusions

The cheapest connection of the prospective wind farm in Kerċem is through an overhead line connected with the existing overhead line feeding Kerċem VOR Beacon DC. The capacity of the existing 11kV cables installed in the feeder limits the wind farm's rated power to 3.4MW. The wind farm connection with the grid will require the installation of an about 600m length of 35mm^2 copper line. The impedance of the circuit between the PCC and Qala DC is 2.44pu. This impedance causes the voltage at PCC to exceed the 5% of the nominal voltage, when the wind farm generates maximum power at 0.95 leading power factor during minimum load demand. In order to reduce the voltage at PCC to 11.55kV, the generated power has to be reduced to 3.15MW during periods of minimum load demand. However, one must determine the probability of such occurrence and the resulting energy being lost due to such power curtailment. The disadvantage of having an overhead line connection is that it is more prone to faults especially during extreme weather conditions. Moreover, overhead lines require frequent maintenance as they are exposed to the harsh climate conditions.

The impedance between PCC and Qala DC can be reduced to 2.01pu by connecting the 3.4MW wind farm between Kerċem tat-Taljana and Kerċem substations. However, the connection is more costly to implement as it involves the installation of 1850m length of 95mm^2 aluminium cables, together with the associated communication and earthing cables, buried in the ground. Such connection is more reliable than an overhead line connection due to lower failure rate. However, since buried cables are less accessible, it is more expensive and time consuming to repair. The wind farm can be connected with the 11kV circuit via two cables to increase the wind farm reliability. Such connection will ensure a higher energy yield than an overhead line connection. The reduced impedance keeps the voltage rise at the PCC below 5% of the nominal voltage as the wind farm generates maximum power at 0.95 leading power factor during minimum load demand. The impacts on the steady-state voltage from the two connection options of the 3.4MW wind farm generating maximum power at 0.95 leading power factor during minimum load demand are compared by a graphical representation as shown in

Figure 5.24.

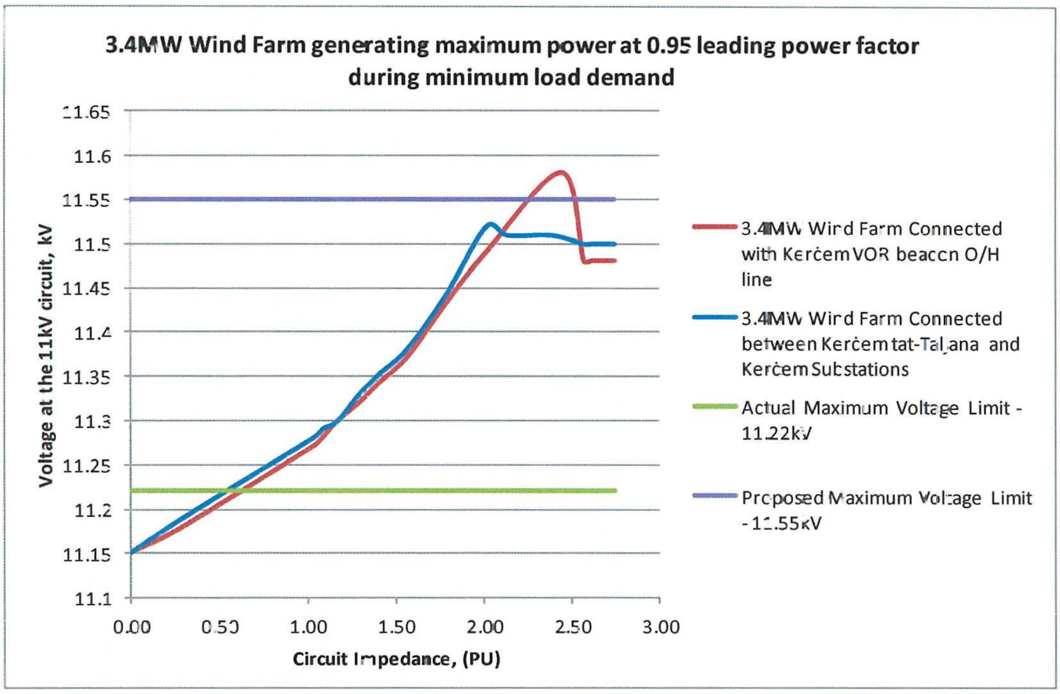


Figure 5.24 - Impact on the steady state voltage from the two connection options of the 3.4MW wind farm

As the net power flow towards the primary substation reduces, the voltage rise along the circuit is reduced. In fact, it is clearly shown that as the load reaches its peak during maximum power generation from the wind farm, the voltage magnitudes in the nodes along the circuit reduces considerably. In view that the maximum load demand is higher than the maximum power generation from the wind farm, it is possible to export reactive power from the wind farm at a power factor of 0.95 without exceeding the 5% voltage rise at the PCC. As the wind farm exports reactive power, the power losses in the circuit are reduced. The power factor of the wind farm should ideally be controlled according to the voltage at the PCC. Preferably, the wind turbines should export maximum reactive power to reduce the losses in the network while generating more revenue, however as the net power flow towards the primary substation rises, the lagging power factor of the generated power may be shifted to leading mode in order to keep the voltage in the circuit within permitted limits.

Several substation transformers, especially those located in the vicinity of the wind farm up to the end of the circuit needs to be set at the minimum tap position in order to keep the voltage in the LV side within the permitted limits during worst case operating scenarios. This poses a problem when the wind farm is disconnected during maximum load demand. The voltage drop along the 11kV circuit can result in a voltage magnitude as low as 10.24kV at the end of the circuit, which falls below the permitted lower limit of 10.45kV. Considering a 6% voltage drop along the LV lines, the resulting voltage at the consumer terminals will fall below the 360V limit. The voltage drop along the LV lines should be less than 4.2% in order to retain the voltage within permitted limits. This LV drop issue can be improved by the following measures:

- better load balancing between the LV feeders and their phases;
- reinforcing the LV circuits through the installation of new feeders so as to reduce the circuit impedance and load;
- commissioning of new substations to relieve the load in the circuits while reducing the circuit impedance; and
- replacing transformers with those equipped with OLTC for better voltage regulation on the LV side.

Replacing the cable segments between the wind farm's PCC and Victoria Kerċem Rd substation by 185mm^2 aluminium cable increases the rated cable capacity to 5.7MVA. This involves the replacement of about 1800m length of cable. This will make it possible to install an additional two 850kW wind turbines, thus having a wind farm rated at 5.1MW. Moreover, the replaced cable slightly reduces the overall impedance between PCC and Qala DC to 1.93pu. Nevertheless, the significant rise in net power flow towards the primary substation during maximum generation at 0.95 leading power factor and minimum load demand still causes the voltage in several nodes in the 11kV circuit to exceed the 5% of the nominal voltage. Thus, one of the wind turbines needs to be switched off during such scenario in order to lower the voltage at the PCC to below 11.55kV. As the net power flow into Qala DC reduces during peak load demand, it enables the wind farm to operate at maximum real and reactive power generation without causing the voltage at the PCC to exceed 5% of the nominal voltage.

The planned Xewkija DC will reduce the load in the distribution circuits in Gozo, which are currently being sourced from Qala DC. Better load sharing between the two DCs and hence reduced circuit impedances, will definitely allow an increased penetration of distributed generation in the island. In fact, from the analysis carried out on the circuit with the 5.1MW wind farm generating maximum power at 0.95 leading power factor during minimum load demand, it resulted that the voltage rise at PCC is just 3.8% of the nominal voltage. The reduced impedance between the PCC and the DC to 0.96pu was more than enough to compensate for the significant increase in the net power flow towards Xewkija DC. Figure 5.25 clearly shows the comparison between the resulting voltage profiles of the 11kV circuits with their main source being Qala DC and Xewkija DC, from the impact of a 5.1 MW wind farm generating maximum power at 0.95 leading power factor during minimum load demand.

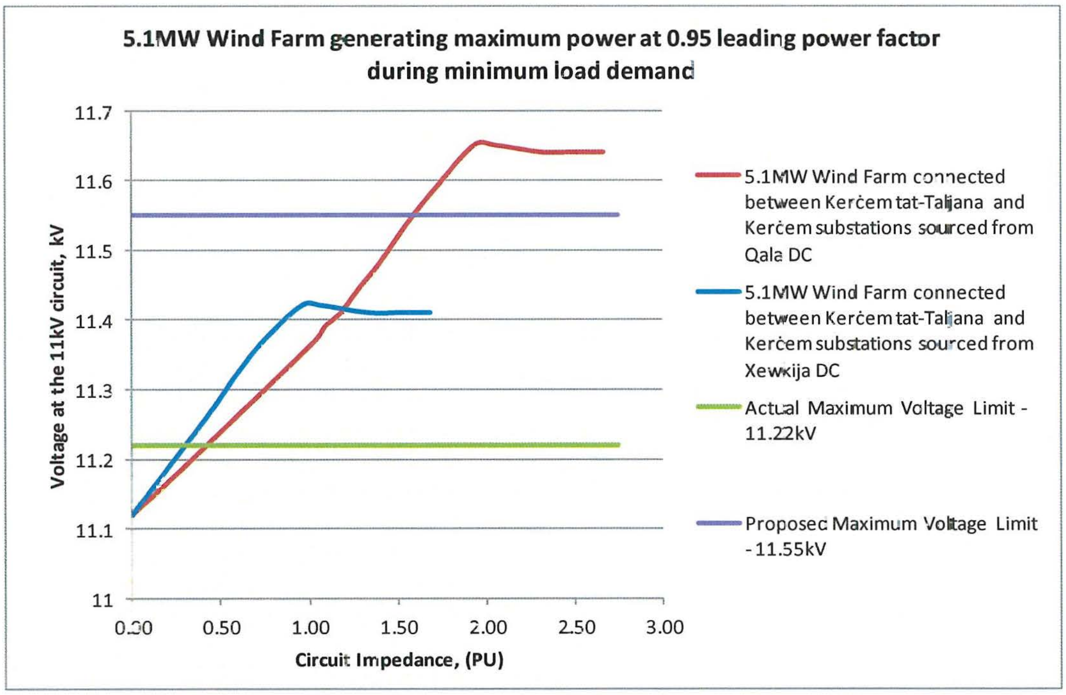


Figure 5.25 - Voltage profiles resulting in the 11kV circuit sourced from Qala DC and Xewkija DC from the impact of a 5.1MW wind farm

The reduction in the peak load demand from 4.88MVA to 2.6MVA, combined with the reduced circuit impedance, causes a significant reduction in the voltage drop in the circuit as the wind farm is disconnected. In fact the minimum voltage resulting in the 11kV, and LV lines assuming a 6% voltage drop, are 10.92kV and 387V respectively, which are within the limits established in the network code.

CHAPTER 6

WIND FARM AT WIED RINI, MALTA

6.1 Site Characteristics and Constraints

One of the prospective sites identified by Mott MacDonald for the development of large-scale onshore wind farm is Għemieri as indicated in Figure 1.3. The site is located to the north and north-west of Rabat and its height above sea level is between 180m and 210m. The maximum available wind potential on unconstrained availability of the resource, and without considering any technical, environmental, planning and legislative barriers, is 44MW [1]. Farrugia et al. and E.A. Mallia have identified Baħrija which forms part of Għemieri area, as one of the candidate sites for wind farm development [8] [9]. On-site wind measurements taken at Baħrija resulted in an annual mean wind speed between 7 and 7.5m/s at 45m height above ground level. Such wind speeds make the site ideal for wind farm development [8].

The proposed wind farm to be considered in this study is located at Wied Rini as indicated in Figure 6.1. Wied Rini is located far-off from residential settlements. Thus, possible impacts that might have on such settlements, mainly visual, noise and shadow-flicker, are mitigated.

Figure 6.1 – Wind Farm site at Wied Rini l/o Baħrija [28]

The site is easily accessible from existing roads as indicated in Figure 6.2, which can be upgraded without the need to construct new ones. Roads should preferable be wide with limited curvature and slope in order to make it possible to transport the massive wind turbine components.

Figure 6.2 - Access roads towards the proposed wind farm site at Wied Rini

A wind monitoring station already exists on site. The wind monitoring equipment such as anemometers, wind vanes and data logger are installed on one of the existing telecommunication lattice tower as shown in Figure 6.3. Wind measurement data collected by this station can be utilised to predict the energy yield from the proposed wind farm during its lifetime. This contributes in determining the feasibility of such a project.

Figure 6.3 - Wind monitoring station at the proposed wind farm site at Wied Rini

On the other hand, there are certain environmental and planning constraints which may limit the size of the wind farm. Certain locations of the proposed site are designated as Protected Areas including Special Areas of Conservation (SAC) under the Natura 2000, Special Protected Areas (SPA), and Areas of Ecological Importance (AEI). The site extends across AVHLS and AHLS. The east of the site is about 2km from Mdina and in direct view of its fortifications. In view that

Mdina is a protected historic city, the landscape around it is also protected as this sets the context of the city. The site is characterised with disused telecommunication lattice towers as shown in Figure 6.4. These may need to be removed for safety reasons as their structural condition is critical.

Figure 6.4 - Disused telecommunication lattice towers at Wied Rini

On site, there is also a telecommunication station consisting of a lattice transmitting tower, owned by one of the main telecommunications companies in Malta as shown in Figure 6.5. The wind turbines may cause interference in the electromagnetic radiation transmitted from this station. Such effects on the communications systems should be studied in detail to determine their extent and the mitigation measures required to reduce such impact.

The impact on the utility grid from the wind farm is another major constraint which may limit the wind farm size. The wind farm causes the voltage on the network to rise especially in nodes along the circuit in the vicinity of the PCC. Such voltage rise may exceed the limits established in the network code. Another constraint which limits the size of a wind farm is the capacity of the cables installed in the utility's network. These impacts are going to be analysed through load flow analysis using the IPSA+ software.

Figure 6.5 - Telecommunication station at Wied Rini

6.2 Wind Farm Connection with the Grid

The 11kV distribution circuit at Mtaħleb is sourced from Mellieħa DC. This DC is supplied by 33kV circuits from Mosta DC, where two 10MVA transformers step-down the voltage to 11kV level. These transformers provide supply to several 11kV distribution feeders which provide electricity supply to areas at the North of Malta, such as, Mellieħa, Mġarr, Għajn Tuffieħa, Wardija, Rabat, and Baħrija. These transformers regulate the steady-state voltage of the 11kV busbars by means of an OLTC which ensures that the voltage is maintained within the bandwidth of a pre-determined voltage set-point. The AVC target voltage is normally set at 11.2kV with a bandwidth of ±1.5%.

The prospective wind farm under study is assumed to consist of 850kW Gamesa G58 wind turbines. These turbines have a hub height ranging between 49m and 74m, and have a rotor diameter of 58m. The proposed wind farm site is very close to Mtaħleb Wied Rini Relay Stn substation. This substation is located on one of the 11kV circuits supplied from Mellieħa DC. The 11kV feeder supplying this area from Mellieħa DC is identified as St.Paul's Bay l-Imbordin feeder and, consists of a mixture of underground cables and overhead lines. The maximum and minimum loads experienced by this circuit in 2012 are 3.15MVA and 0.93MVA respectively. These extreme loads are being considered for the analysis of the impacts from the wind farm on the network. In this study, two options are being considered for the connection of a wind farm with the grid.

The cheapest connection option is to connect the wind farm in the circuit section between Mtaħleb Wied Rini Relay Stn. and Rabat l-Andrijiet substations. This section consists of a 95mm^2 aluminium cable located in the road adjacent to the proposed wind farm site. As this cable is rated at 3.9MVA, the wind farm cannot consist of more than four 850kW wind turbines, thus limiting the maximum wind farm size to 3.4MW. The circuit length from Mellieħa DC up to the proposed PCC of the wind farm under study is about 15km.

The other option, which makes it possible to accommodate a larger wind farm in this site, is to connect the wind farm between Fiddien Booster and Rabat tas-Salib substations. The circuit between Fiddien Booster substation and Mellieħa DC consists of 185mm^2 aluminium cables, rated at 5.72MVA. This makes it possible to install a wind farm consisting of six 850kW wind turbines, rated at 5.1MW. However, this will require the installation of about 2.6km length of 11kV cables together with the associated fibre optic and earthing cables between the wind farm and the PCC. This will considerably increase the cost of the project. Besides of having the possibility of installing a larger wind farm with this option, the distance between Mellieħa DC and the PCC is reduced by about 2.6km, thus reducing the voltage drop between these two nodes.

The feasibility of these options depends on an in-depth analysis of the impacts that such wind farms can have on the network. The main issue is the considerable cable impedance between the primary substation and the PCC, which may cause a significant voltage rise along various nodes in the circuit.

6.3 Impact on the Steady-State Voltage of the Grid

The impact on the steady-state voltage of the network is analysed through a load flow study using the IPSA+ software. Such analysis will determine the voltage variations at the 11kV and LV nodes in St.Paul's Bay l-Imbordin circuit. Furthermore, the analysis presents the power flows and the resulting power losses in the circuit.

The following two wind farm connection options are considered for the analysis of the impact on the grid from the wind farm:

> **Option 1** - 3.4MW wind farm connected between Mtaħleb Wied Rini Relay Stn. and Rabat l-Andrijiet substations;
> **Option 2** - 5.1MW wind farm connected between Fiddien Booster and Rabat tas-Salib substations.

6.3.1 Option 1 – 3.4MW Wind Farm connected between Mtaħleb Wied Rini Relay Stn and Rabat l-Andrijiet Substations

The wind farm will be connected to the PCC between Mtaħleb Wied Rini Relay Stn and Rabat L-Andrijiet substations through two 95mm^2 aluminium cables. The WFCSR will consist of an 11kV switchboard, and the necessary metering arrangements. The 11kV switchboard consists of four CBs and a bus-section CB as indicated in

Figure 6.6. The wind turbine substations are looped from one to another through 95mm^2 aluminium cables having a length of about 200m. The 11kV circuit consisting of Mellieħa DC, 11kV distribution substations and the wind farm are

entered in IPSA+ program as shown in the snapshot from the program in Figure C.1 in Appendix C.

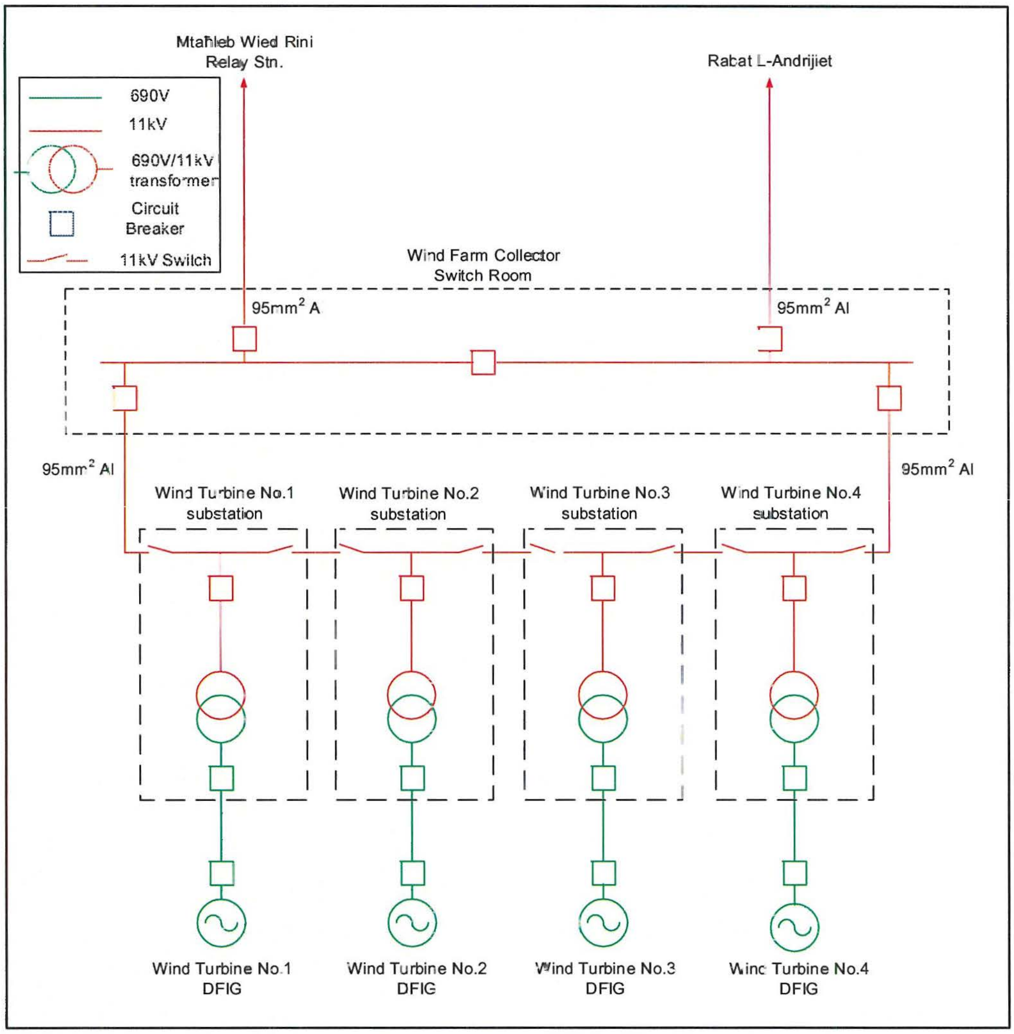


Figure 6.6 - Wind farm connection between Mtaħleb Wied Rini Relay Stn and Rabat l-Andrijiet Substations

The impacts of the wind farm integration with the grid are investigated through a load flow analysis for the following worst case scenarios:

- **Scenario A** - 3.4MW wind farm generating maximum power at 0.95 leading and lagging power factors during minimum load demand with the 11kV busbar of Mellieħa DC regulated at 11.2kV;
- **Scenario B** - 3.4MW wind farm generating maximum power at 0.95 leading and lagging power factors during minimum load demand with the 11kV busbar of Mellieħa DC regulated at 11.1kV;

- **Scenario C** - 3.4MW wind farm generating 2.55MW at 0.95 leading and lagging power factors during minimum load demand with the 11kV busbar voltage at Mellieħa DC regulated at 11.1kV;
- **Scenario D** - 3.4MW wind farm generating maximum power at 0.95 leading and lagging power factors during maximum load demand with 11kV busbar voltage at Mellieħa DC regulated at 11.2kV;
- **Scenario E** - 3.4MW wind farm generating maximum power at 0.95 leading and lagging power factors during maximum load demand with the 11kV busbar voltage at Mellieħa DC regulated at 11.1kV; and
- **Scenario F** - 3.4MW wind farm disconnected during maximum load demand with the 11kV busbar voltage at Mellieħa DC regulated at 11.1kV.

6.3.1.1 Scenario A - 3.4MW Wind Farm generating maximum power during minimum load demand with the 11kV busbar voltage at Mellieħa DC regulated at 11.2kV

This scenario involves a 3.4MW wind farm generating maximum power at 0.95 leading and lagging power factor during minimum load demand in the circuit. The voltage magnitudes, resulting at the 11kV and LV busbars of the circuit, are shown in Figure C.1.1 in Appendix C. The resulting voltage profiles of the 11kV circuit against the circuit impedance are shown in Figure 6.7.

Table 6.1 clearly shows that the high net power flow into Mellieħa D.C and the high impedance between the PCC and the primary substation causes a sharp voltage rise along the 11kV circuit. When the wind farm consumes reactive power at a power factor of 0.95, the voltage at the PCC rises to 6.2% of the nominal voltage. Consequently, the distribution transformers in the vicinity of the wind farm are set at the minimum tap position in order to keep the voltage at the LV busbars below the voltage rise limit.

3.4MW Wind Farm connected between Imtaħleb Wied Rini Relay Stn and Rabat l-Andrijiet Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	3.4	3.4
Load Demand (MVA)	0.93	0.93
Net Real Power flow into Mellieħa DC (MW)	2.04	2.02
Net Reactive Power flow into Mellieħa DC (MVAr)	-1.4	0.82
Voltage at Source (kV)	11.09	11.31
Voltage at the PCC (kV)	11.68	12.18
Real Power Losses in the Circuit (MW)	0.25	0.21
Reactive Power Losses in the Circuit (MVAr)	0.28	0.23

Table 6.1 - Net Power flow and losses in the 11kV circuit for scenario A in option 1

Conversely, as the wind farm exports reactive power at a power factor of 0.95, the voltage in the 11kV circuit increases further. In fact the voltage at the PCC increases by 10.7% of the nominal voltage. Such voltage rise in the 11kV circuit causes the voltage in the LV busbars to rise significantly. Setting the fixed tap-changers of most of the distribution transformers at their minimum tap position is not sufficient to keep the voltage in the LV busbars of the substations within the permitted limits.

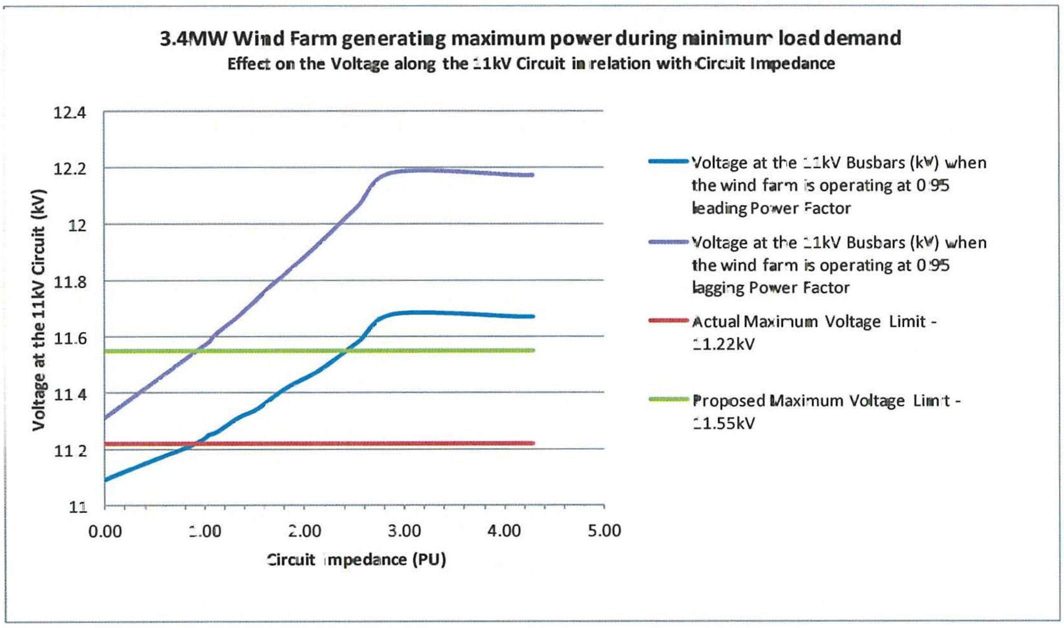


Figure 6.7 - Voltage profile along the 11kV circuit for scenario A in option 1

6.3.1.2 Scenario B - 3.4MW Wind Farm generating maximum power during minimum load demand with the 11kV busbar voltage at Mellieħa DC regulated at 11.1kV

As the voltage set-point of the AVC of the transformer at Mellieħa DC is lowered to 11.1kV with a bandwidth of 1.5%, the allowed voltage variation in the 11kV busbar is in the region between 10.93kV and 11.27kV. This will permit the voltage at the 11kV circuit to exceed the 11kV busbar voltage of Mellieħa DC by a voltage in the range between 283V and 616V. Hence, a higher net power is allowed to flow into the primary substation without exceeding the upper voltage limit of 11.55kV. The impact from the 3.4MW wind farm on the grid during maximum generation and minimum load demand, with the 11kV busbar of Mellieħa DC regulated within the bandwidth of 11.1kV is analysed. The voltage magnitudes resulting at the 11kV and LV busbars of the substations in the circuit are shown in Table C.1.2 in Appendix C. The resulting voltage profiles with respect to circuit impedance along the 11kV circuit are shown in Figure 6.8.

From
Table 6.2 and Figure 6.8, one can note that the results for the 0.95 leading power factor operating scenario are the same as those obtained in scenario A. A voltage magnitude of 11.09kV in the 11kV busbar of Mellieħa DC regulated within the target voltage of 11.2kV falls within the 1.5% bandwidth of the 11.1kV set-point. Thus, the same tap position in the transformer at Mellieħa DC is maintained.

3.4MW Wind Farm connected between Imtaħleb Wied Rini Relay Stn and Rabat l-Andrijiet Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	3.4	3.4
Load Demand (MVA)	0.93	0.93
Net Real Power flow into Mellieħa DC (MW)	2.04	2.01
Net Reactive Power flow into Mellieħa DC (MVAr)	-1.4	0.81
Voltage at Source (kV)	11.09	11.05
Voltage at the PCC (kV)	11.68	11.93
Real Power Losses in the Circuit (MW)	0.25	0.22
Reactive Power Losses in the Circuit (MVAr)	0.28	0.24

Table 6.2 - Net Power flow and losses in the 11kV circuit for scenario B in option 1

When the wind farm exports reactive power at a power factor of 0.95, the transformer at Mellieħa DC performs a tap-change to reduce the voltage in the 11kV busbar, thus shifting down the voltage at the PCC. However, the voltage rise at the PCC is 8.5% of the nominal voltage which is still far away from the permitted limits. Consequently, the voltage magnitudes at the LV busbars exceed the upper voltage limit even though the transformers are set at the minimum tap position. The voltage at the 11kV busbars can be reduced to permitted levels by limiting the power generated from the wind farm.

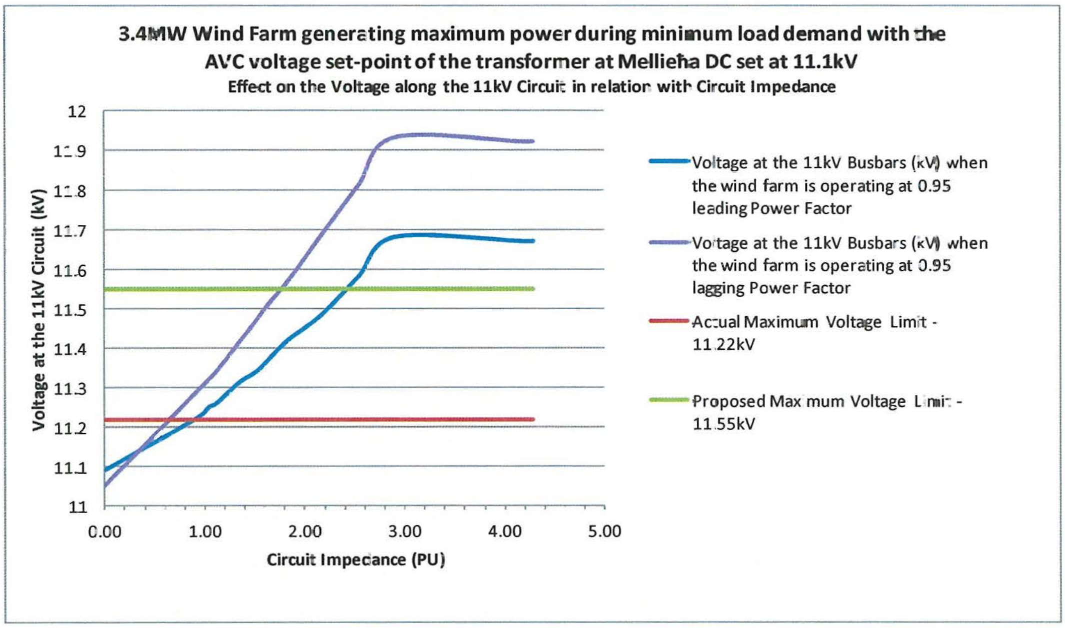


Figure 6.8 - Voltage profile along the 11kV circuit for scenario B in option 1

6.3.1.3 Scenario C - 3.4MW Wind Farm generating 2.55MW during minimum load demand with the 11kV busbar voltage at Mellieħa DC regulated at 11.1kV

As the wind farm generating power is curtailed, the net power flow towards the primary substation is reduced, thus lowering the voltage at the PCC. After experimenting with various real power generation values with the 11kV busbar at Mellieħa DC being regulated within the 1.5% bandwidth of 11.1kV, the maximum real power that produces acceptable voltage results is 2.55MW. This means that one of the four wind turbines needs to be disconnected in such scenario. The voltage magnitudes resulting at the 11kV and LV busbars from the generation of

2.55MW at both extreme operating power factors are found in Table C.1.3 in Appendix C. The voltage profiles in relation with the 11kV circuit impedance are shown in Figure 6.9.

3.4MW Wind Farm connected between Imtaħleb Wied Rini Relay Stn and Rabat l-Andrijiet Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	2.55	2.55
Load Demand (MVA)	0.93	0.93
Net Real Power flow into Mellieħa DC (MW)	1.3	1.31
Net Reactive Power flow into Mellieħa DC (MVAr)	-1.05	0.6
Voltage at Source (kV)	11.12	11.02
Voltage at the PCC (kV)	11.53	11.66
Real Power Losses in the Circuit (MW)	0.14	0.12
Reactive Power Losses in the Circuit (MVAr)	0.18	0.15

Table 6.3 - Net Power flow and losses in the 11kV circuit for scenario C in option 1

From Table 6.3, one can note that when the wind farm consumes reactive power at a power factor of 0.95, the voltage rise in the 11kV circuit is less than 5% of the nominal voltage. The substation transformers located in the vicinity of the wind farm are set at the minimum position in order to maintain the voltage levels in the LV busbars within the permitted limits.

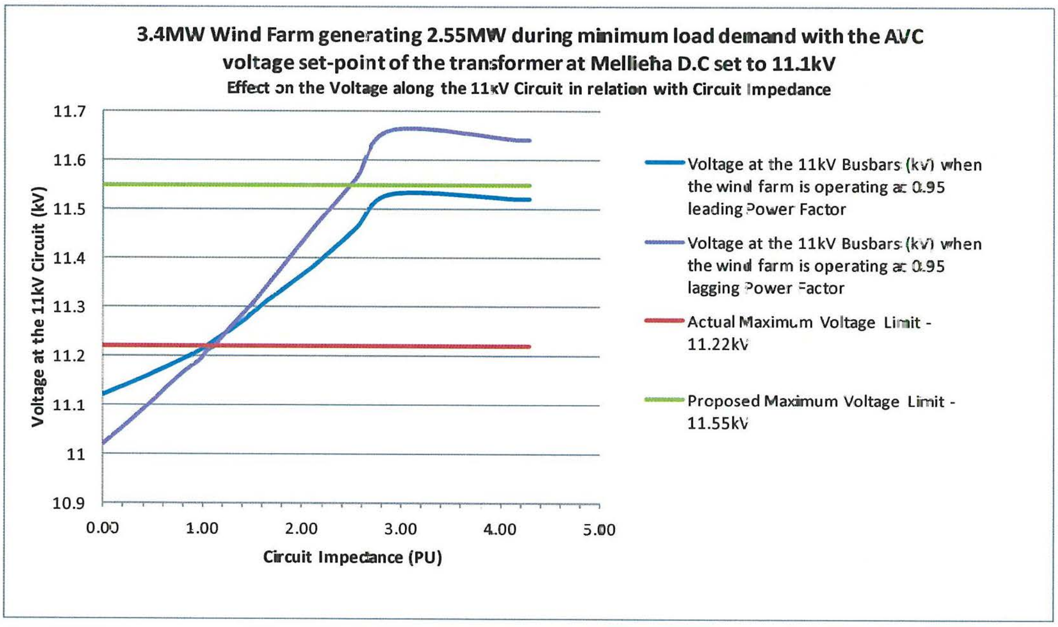


Figure 6.9 - Voltage profile along the 11kV circuit for scenario C in option 1

Conversely, as the wind farm exports reactive power at a power factor of 0.95, the voltage rise at the PCC is 6% of the nominal voltage. Due to this increase in voltage along the 11kV circuit, more distribution transformers are set at their minimum tap position in order to keep the voltage in the LV busbars within the permitted limits.

6.3.1.4 Scenario D - 3.4MW Wind Farm generating maximum power during maximum load demand in the circuit with the 11kV busbar voltage at Mellieħa DC regulated at 11.2kV

The voltage magnitudes at the 11kV and LV busbars, resulting from the impact of a 3.4MW wind farm generating maximum power at 0.95 leading and lagging power factors during maximum load demand, with the AVC's set-point at Mellieħa DC set at 11.2kV, are shown in Table C.1.4 in Appendix C. The resulting voltage profiles of the 11kV circuit with respect to circuit impedance are shown in Figure 6.10.

3.4MW Wind Farm connected between Imtaħleb Wied Rini Relay Stn and Rabat l-Andrijiet Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	3.4	3.4
Load Demand (MVA)	3.15	3.15
Net Real Power flow into Mellieħa DC (MW)	-0.1	-0.12
Net Reactive Power flow into Mellieħa DC (MVAr)	-1.56	0.65
Voltage at Source (kV)	11.34	11.28
Voltage at the PCC (kV)	11.56	11.79
Real Power Losses in the Circuit (MW)	0.18	0.13
Reactive Power Losses in the Circuit (MVAr)	0.24	0.18

Table 6.4 - Net Power flow and losses in the 11kV circuit for scenario D in option 1

Table 6.4 indicates that the maximum load demand added with the losses in the circuit has caused a small amount of real power to be sourced from Mellieħa DC into the 11kV circuit. However, the high circuit impedance between the PCC and the primary substation still causes the voltage rise at the PCC to slightly exceed the 5% of the nominal voltage, when the wind farm is consuming reactive power at a power factor of 0.95. The tap positions of the distribution transformers are kept the same as in scenario C. The voltage resulting at the LV busbars of the substations are within the permitted limits as specified in the network code.

Operating the wind farm at 0.95 lagging power factor further increases the steady-state voltage along the feeder as shown in Figure 6.10. The voltage rise at the PCC is of 7.18%. However, this rise in voltage did not cause the voltage in the LV busbars to exceed the 10% voltage rise limit.

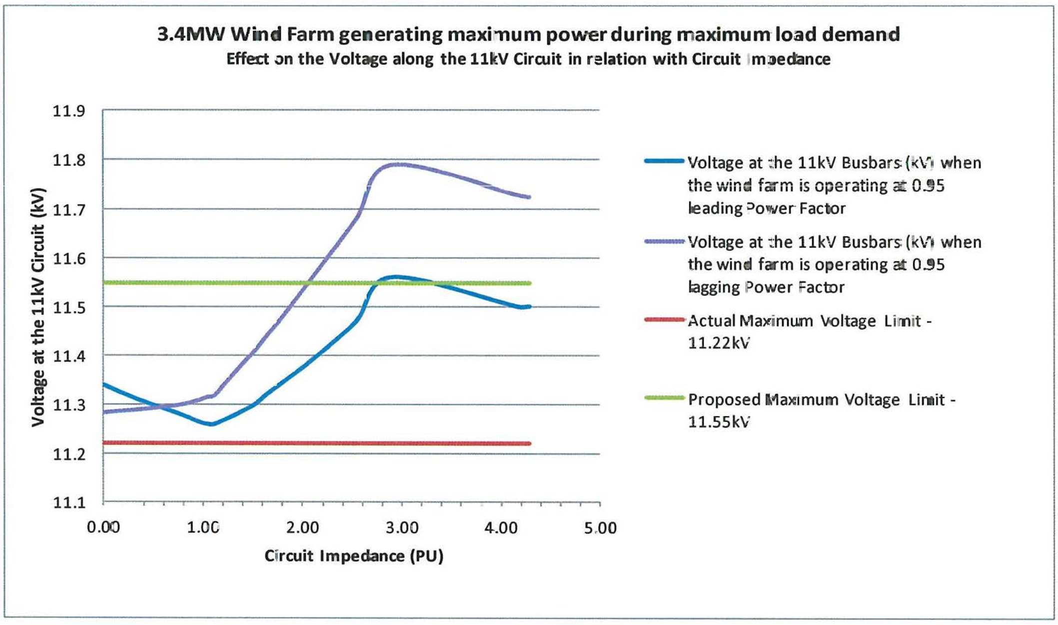


Figure 6.10 - Voltage profile along the 11kV circuit for scenario D in option 1

6.3.1.5 Scenario E - 3.4MW Wind Farm generating maximum power during maximum load demand in the circuit with 11kV busbar voltage at Mellieħa DC regulated at 11.1kV

The voltage magnitudes resulting at the 11kV and LV busbars of the substations in the circuit, when the wind farm generates maximum power during maximum load demand, with the 11kV busbar voltage at Mellieħa DC regulated within the bandwidth of 11.1kV are shown in Table C.1.5 in Appendix C. The voltage profiles resulting at the 11kV circuit with respect to circuit impedance are shown in figure 6.11. The tap positions of the 11kV/433V distribution transformers are kept the same as in scenario C.

3.4MW Wind Farm connected between Imtaħleb Wied Rini Relay Stn and Rabat l-Andrijiet Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	3.4	3.4
Load Demand (MVA)	3.15	3.15
Net Real Power flow into Mellieħa DC (MW)	-0.12	-0.13
Net Reactive Power flow into Mellieħa DC (MVAr)	-1.57	0.64
Voltage at Source (kV)	11.06	11.02
Voltage at the PCC (kV)	11.27	11.53
Real Power Losses in the Circuit (MW)	0.19	0.13
Reactive Power Losses in the Circuit (MVAr)	0.26	0.19

Table 6.5 - Net Power flow and losses in the 11kV circuit for scenario E in option 1

One can note from Table 6.5, that the operation of the wind farm at maximum power generation at 0.95 leading power factor increases the voltage at the PCC by 2.45% of the nominal voltage, which is well below the proposed upper voltage limit. Hence, the resulting voltage magnitudes in the LV busbars are within the permitted limits as stipulated in the network code.

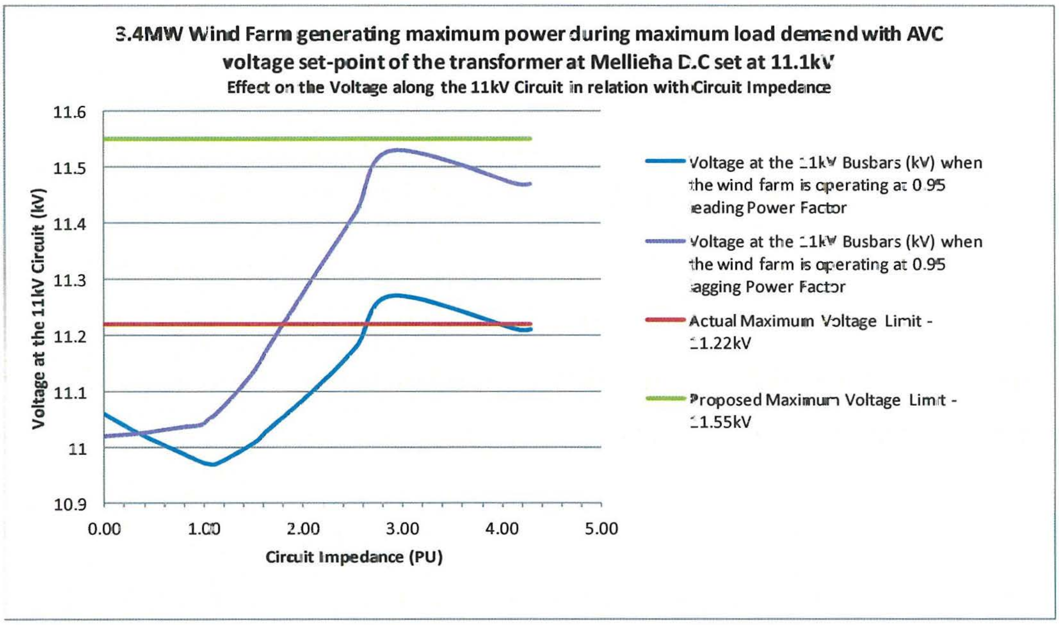


Figure 6.11 - Voltage profile along the 11kV circuit for scenario E in option 1

Conversely, as the wind farm generates maximum power at 0.95 lagging power factor, the voltage at the PCC rises by 4.8% of the nominal voltage. The resulting voltage magnitudes in the LV busbars of the substations are within the ±10% tolerance of the nominal voltage. In such scenario, the wind farm should preferably export reactive power so that the losses in the circuit are minimised.

6.3.1.6 Scenario F - 3.4MW wind farm disconnected during maximum load demand with the 11kV busbar voltage of Mellieħa DC regulated at 11.1kV

The impact of the disconnection of a 3.4MW wind farm during maximum load demand with the 11kV busbar at Mellieħa DC regulated within the bandwidth of 11.1kV is investigated through a load flow analysis. This is the worst case of voltage drop in the 11kV and LV nodes. The I^2R losses in the circuit during maximum load cause a considerable voltage drop in the 11kV circuit especially near the end of the feeder where the wind farm is located. Since several transformers in the vicinity of the wind farm are set at their minimum tap position, the voltage magnitudes in the LV busbars decrease substantially. The resulting voltage magnitudes in the 11kV and LV busbars are illustrated in Table C.1.6 in Appendix C. The voltage profile along the 11kV circuit with respect to circuit impedance is shown in Figure 6.12.

3.4MW Wind Farm connected between Imtaħleb Wied Rini Relay Stn and Rabat l-Andrijiet Substations Switched Off	
Power Generated (MW)	0
Load Demand (MVA)	3.15
Net Real Power flow into Mellieħa DC (MW)	-3.29
Net Reactive Power flow into Mellieħa DC (MVAr)	-0.36
Voltage at Source (kV)	11.16
Minimum Voltage in the Circuit (kV)	10.49
Real Power Losses in the Circuit (MW)	0.15
Reactive Power Losses in the Circuit (MVAr)	0.20

Table 6.6 - Net Power flow and losses in the 11kV circuit for scenario F in option 1

One can note from Table 6.6, that the voltage drop at the remote end of the circuit is 4.6% of the nominal voltage. Consequently, the resulting voltage in the LV busbar of the substation at the end of the radial circuit is 391V. If a 6% voltage drop along the LV lines is assumed, the resulting voltage experienced by the consumers at the last part of the LV circuit is approximately 367V, implying an 8.1% voltage drop from the nominal voltage. Thus, the resulting voltage drops at the 11kV and LV circuits are within the permitted limits as established in the network code.

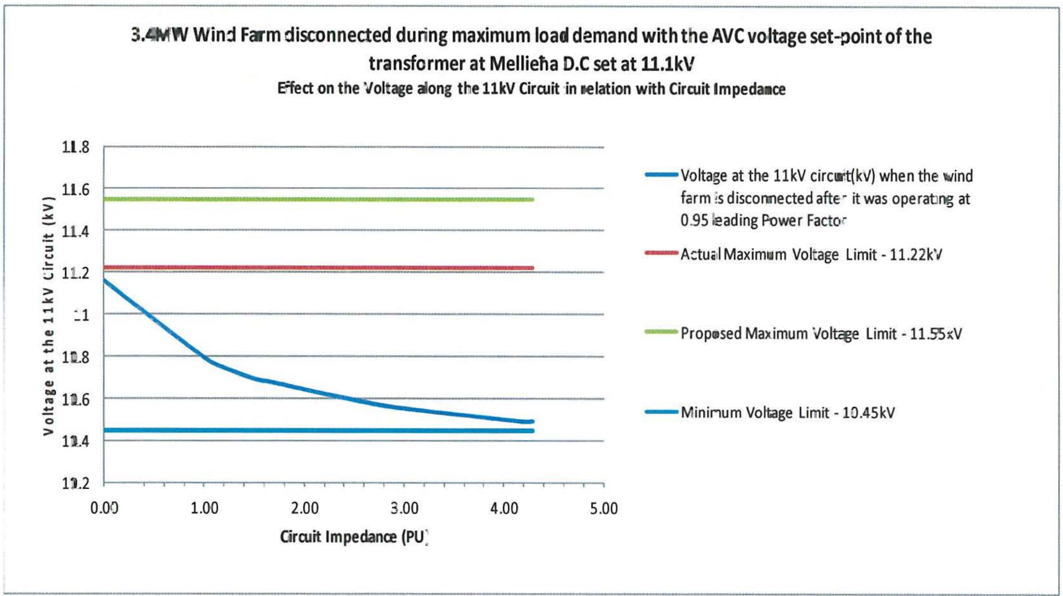


Figure 6.12 - Voltage profile along the 11kV circuit for scenario F in option 1

6.3.2 Option 2 – 5.1MW Wind Farm Connected between Fiddien Booster and Rabat tas-Salib Substations

The option of connecting a wind farm in the section of the 11kV circuit between Fiddien Booster and Rabat tas-Salib substations provides more benefits. As already mentioned, a larger wind farm can be accommodated as the 11kV cables between this section and Mellieħa DC have a higher rated power capacity, while the voltage drop between the PCC and the DC is decreased. However, the maximum rated power of the wind farm, which can be technically installed without adversely affecting the steady-state voltage of the distribution circuit, needs to be determined through load flow analysis in the worst case scenarios.

The wind farm is connected to the WFCSR through two 185mm^2 aluminium cables, rated at 5.72MVA, thus making it possible to install up to a maximum of six 850kW wind turbines, equivalent to a 5.1MW wind farm. These cables are terminated in 11kV CB panels in the WFCSR as shown in Figure 6.13. The 11kV switchboard consists of two CBs on each side separated by a Bus-Section CB. The Bus-Section CB is normally in the ON position; however this can be switched off to segregate the busbars for maintenance purposes without affecting wind farm operation. The wind turbine substations are looped through 185mm^2 aluminium cables. This wind farm configuration and its connection with the 11kV circuit is modelled in the IPSA+ program as shown in the snapshot at Figure C.2 in Appendix C.

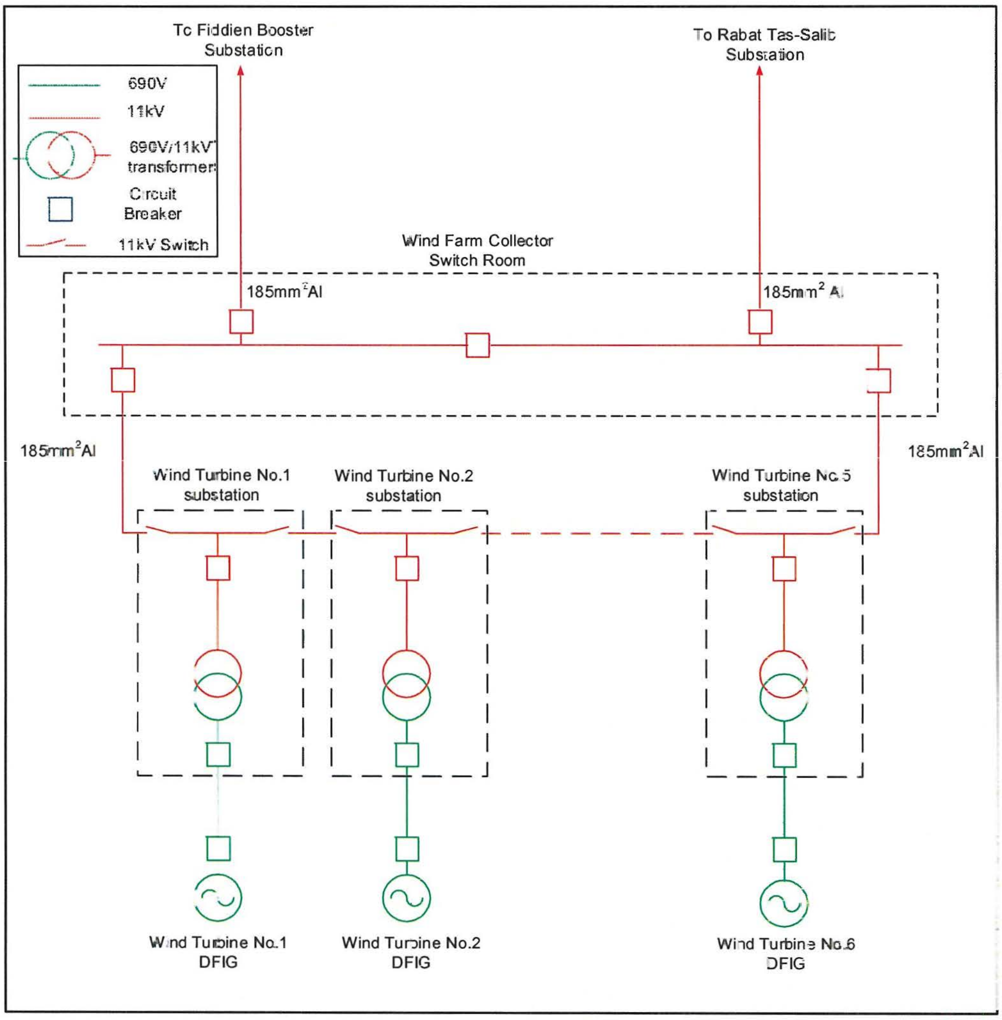


Figure 6.13 - Wind farm connection between Fiddien Booster and Rabat tas-Salib Substations

The impacts on the steady-state voltage of the circuit are analysed through a load flow study for the following scenarios:

- **Scenario A** - 5.1MW wind farm generating maximum power at 0.95 leading power factor during minimum load demand with the 11kV busbar voltage at Mellieħa DC regulated within the bandwidth of 11.2kV and 11.1kV;
- **Scenario B** - 5.1MW wind farm generating 4.75MW at 0.95 leading and lagging power factor during minimum load demand

with the 11kV busbar voltage at Mellieħa DC regulated within the bandwidth of 11.1kV;

- **Scenario C** - 5.1MW wind farm generating maximum power at 0.95 leading and lagging power factor during maximum load demand with the 11kV busbar voltage at Mellieħa DC regulated within the bandwidth of 11.2kV;
- **Scenario D** - 5.1MW wind farm generating maximum power at 0.95 leading and lagging power factor during maximum load demand with the 11kV busbar voltage at Mellieħa DC regulated within the bandwidth of 11.1kV; and
- **Scenario E** - 5.1MW wind farm disconnected during maximum load demand with the 11kV busbar voltage at Mellieħa DC regulated within the bandwidth of 11.1kV.

6.3.2.1 Scenario A - 5.1MW wind farm generating maximum power at 0.95 leading power factor during minimum load demand with the 11kV busbar voltage at Mellieħa DC regulated within the bandwidth of 11.2kV and 11.1kV

The impact of a 5.1MW wind farm on the steady-state voltage of the circuit under the worst case scenario, that is, maximum power generation during minimum load demand is analysed through a load flow study. The wind farm in this scenario generates maximum power at a leading power factor of 0.95, whilst the 11kV busbar of Mellieħa DC is regulated within the bandwidth of 11.2kV and 11.1kV. The results obtained confirm whether power curtailment is required in such scenario. The voltage magnitudes resulting at the 11kV and LV busbars of the substations along the circuit are shown in Table C.2.1 of Appendix C. The voltage profiles of the 11kV circuit in relation with circuit impedance are shown in Figure 6.14.

From Table 6.7 one can note that the significant flow of net power into the primary substation causes a considerable voltage difference between the PCC and the 11kV busbar of Mellieħa D.C. In fact, as the 11kV busbar voltage of Mellieħa DC is regulated within the bandwidth of 11.2kV, the voltage rise at PCC is of

7.7%. Consequently, the voltage at the LV busbars of several substations exceeds the 10% voltage rise limit, even with the transformers set at the minimum tap position.

5.1MW Wind Farm connected between Fiddien Booster and Rabat Tas-Salib Substations operating at 0.95 leading power factor		
	11kV busbar of Mellieħa DC regulated within the bandwidth of 11.2kV	11kV busbar of Mellieħa DC regulated within the bandwidth of 11.1kV
Power Generated (MW)	5.1	5.1
Load Demand (MVA)	0.93	0.93
Net Real Power flow into Mellieħa DC (MW)	3.52	3.5
Net Reactive Power flow into Mellieħa DC (MVAr)	-2.06	-2.08
Voltage at Source (kV)	11.31	11.02
Voltage at the PCC (kV)	11.85	11.58
Real Power Losses in the Circuit (MW)	0.39	0.41
Reactive Power Losses in the Circuit (MVAr)	0.49	0.52

Table 6.7 - Net Power flow and losses in the 11kV circuit for scenario A in option 2

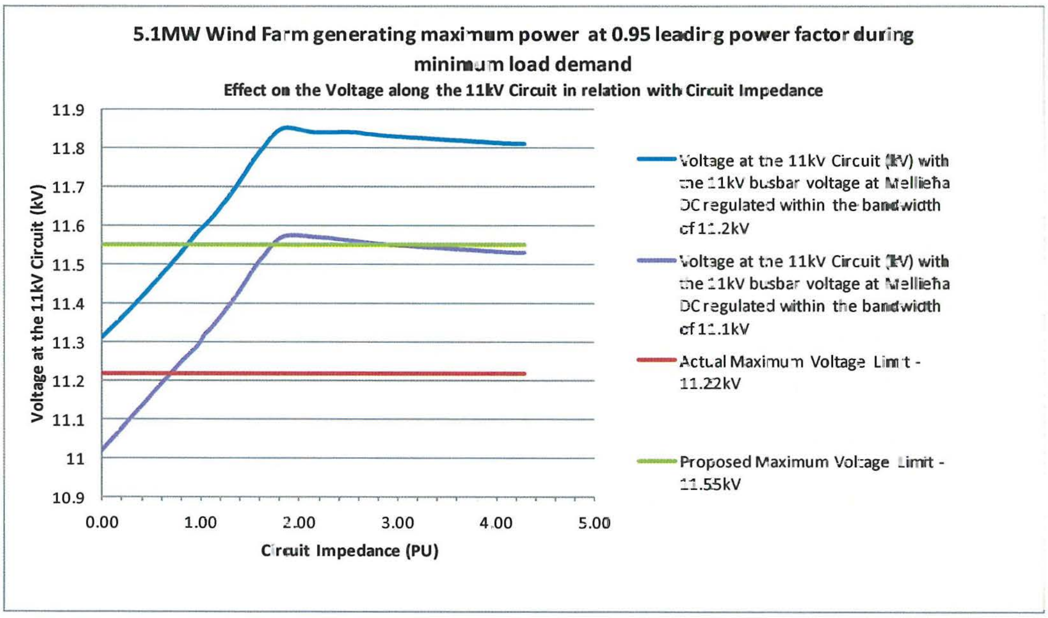


Figure 6.14 - Voltage profile along the 11kV circuit for scenario A in option 2

As the AVC's set-point of the 11kV busbar at Mellieħa DC is reduced to 11.1kV, the voltage rise at the PCC reduces to 5.27%, which slightly exceeds the proposed upper limit. The resulting voltage magnitudes at the LV busbars are within the permitted limits. Thus, the real power generated from the wind farm has to be curtailed in order to decrease the voltage at the PCC to acceptable levels. One can also observe from Table 6.7, that the losses increase as the voltage levels in the 11kV circuit are reduced.

6.3.2.2 Scenario B - 5.1MW wind farm generating 4.75MW at 0.95 leading and lagging power factor during minimum load demand with the 11kV busbar voltage at Mellieħa DC regulated within the bandwidth of 11.1kV

The maximum power that can be generated at 0.95 leading power factor from the wind farm during minimum load demand without exceeding the 5% voltage rise in the 11kV circuit is 4.75MW. This means that the real power output of the wind farm is reduced by 0.35MW. The voltage magnitudes at the 11kV and LV busbars resulting from the generation of 4.75MW at 0.95 leading and lagging power factor, with Mellieħa DC's 11kV busbar voltage regulated within the bandwidth of 11.1kV, are shown in Table C.2.2 of Appendix C. The voltage profiles resulting in the 11kV circuit with respect to circuit impedance are shown in Figure 6.15.

5.1MW Wind Farm connected between Fiddien Booster and Rabat Tas-Salib Substations		
	0.95 leading power factor	0.95 lagging power factor
Power Generated (MW)	4.75	4.75
Load Demand (MVA)	0.93	0.93
Net Real Power flow into Mellieħa DC (MW)	3.22	3.19
Net Reactive Power flow into Mellieħa DC (MVAr)	-1.92	2.06
Voltage at Source (kV)	11.04	11.09
Voltage at the PCC (kV)	11.55	11.86
Real Power Losses in the Circuit (MW)	0.35	0.3
Reactive Power Losses in the Circuit (MVAr)	0.45	0.38

Table 6.8 - Net Power flow and losses in the 11kV circuit for scenario B in option 2

From Table 6.8, one can observe that as the real power generated from the wind farm is curtailed to 4.75MW, whilst consuming reactive power at a power factor of 0.95, the voltage at the PCC is reduced to permitted levels. Consequently, by having the substation transformers in the vicinity of the wind farm set at the minimum tap position, the resulting voltage levels in the LV busbars of the substations are within the permitted limits. Thus, the decreased impedance in the circuit between the PCC and Mellieħa DC permits a higher power generation in the 11kV circuit than the other connection option.

Conversely, as the wind farm exports reactive power at a power factor of 0.95, the voltage rise at the PCC reaches 7.8% of the nominal voltage. This rise in the steady-state voltage of the 11kV circuit causes the voltage at some of the LV busbars to exceed the upper limit even though the transformers are set at the minimum tap position.

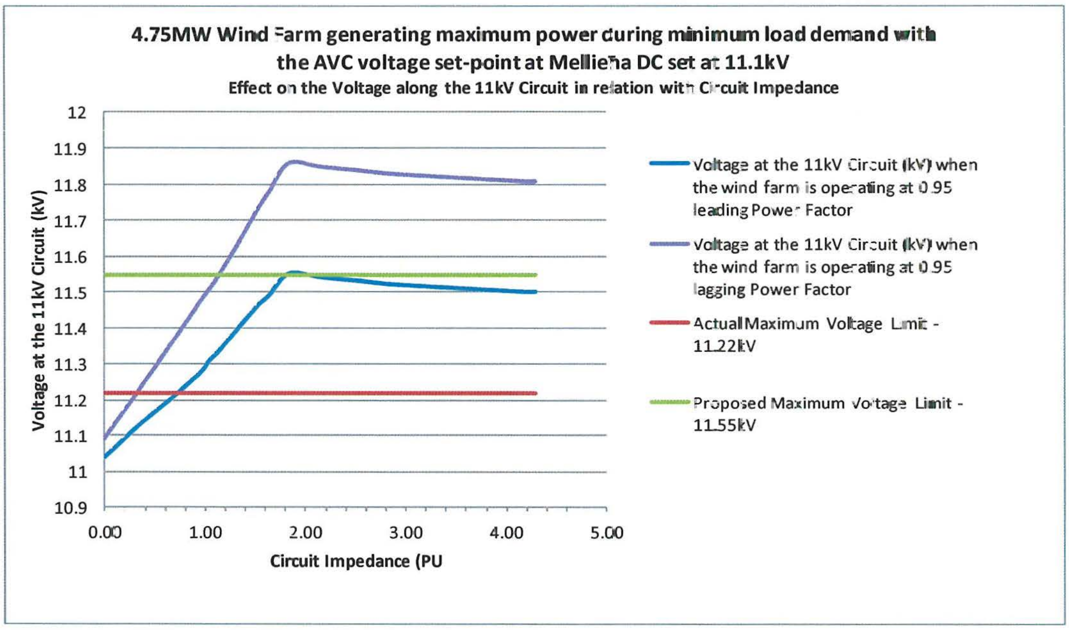


Figure 6.15 - Voltage profile along the 11kV circuit for scenario B in option 2

6.3.2.3 Scenario C - 5.1MW wind farm generating maximum power at 0.95 leading and lagging power factor during maximum load demand with the 11kV busbar voltage at Mellieħa DC regulated within the bandwidth of 11.2kV

The voltage magnitudes resulting at the 11kV and LV busbars of the substations in the circuit are shown in Table C.2.3 of Appendix C. The voltage profiles in relation with the circuit impedance along the 11kV circuit are shown in Figure 6.16. The substation transformers in the circuit are set at the same tap positions of the previous scenario.

5.1MW Wind Farm connected between Fiddien Booster and Rabat tas-Salib Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	5.1	5.1
Load Demand (MVA)	3.15	3.15
Net Real Power flow into Mellieħa DC (MW)	1.41	1.39
Net Reactive Power flow into Mellieħa DC (MVAr)	-2.21	1.11
Voltage at Source (kV)	11.29	11.34
Voltage at the PCC (kV)	11.52	11.86
Real Power Losses in the Circuit (MW)	0.28	0.21
Reactive Power Losses in the Circuit (MVAr)	0.39	0.30

Table 6.9 - Net Power flow and losses in the 11kV circuit for scenario C in option 2

Table 6.9 vividly shows that the reduced net power flow into the primary substation decreases the voltage difference between the PCC and the 11kV busbar of Mellieħa DC. In fact as the wind farm generates maximum power at 0.95 leading power factor, the voltage in the 11kV circuit is maintained within the permitted limits. Consequently, the resulting voltage magnitudes at the LV busbars are within the permitted limits.

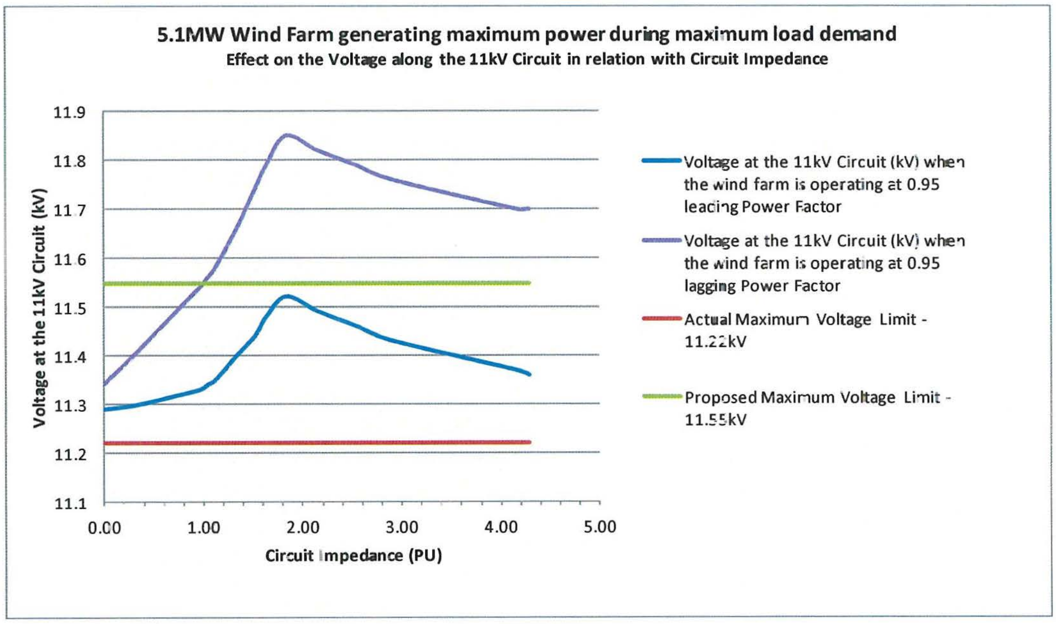


Figure 6.16 - Voltage profile along the 11kV circuit for scenario C in option 2

Conversely, as the wind farm generates maximum power at 0.95 lagging power factor, the resulting voltage rise in the 11kV circuit is well above the 5% of the nominal voltage. This causes the voltage in the LV busbars to exceed the upper voltage limit, even though the transformers are set at the minimum tap position.

6.3.2.4 Scenario D - 5.1MW wind farm generating maximum power at 0.95 leading and lagging power factor during maximum load demand with the 11kV busbar voltage at Mellieħa DC regulated within the bandwidth of 11.1kV

The voltage magnitudes resulting at the 11kV and LV busbars from the impact of the wind farm as it generates maximum power during maximum load demand, with the 11kV busbar voltage of Mellieħa DC regulated within the bandwidth of 11.1kV, are shown in Table C.2.4 of Appendix C. The voltage profiles of the 11kV circuit in relation with circuit impedance are shown in Figure 6.17.

5.1MW Wind Farm connected between Fiddien Booster and Rabat tas-Salib Substations		
	0.95 leading Power Factor	0.95 lagging Power Factor
Power Generated (MW)	5.1	5.1
Load Demand (MVA)	3.15	3.15
Net Real Power flow into Mellieħa DC (MW)	1.38	1.38
Net Reactive Power flow into Mellieħa DC (MVAr)	-2.2	1.1
Voltage at Source (kV)	11	11.07
Voltage at the PCC (kV)	11.24	11.6
Real Power losses in the Circuit (MW)	0.29	0.22
Reactive Power Losses in the Circuit (MVAr)	0.41	0.30

Table 6.10 - Net Power flow and losses in the 11kV circuit for scenario D in option 2

As the AVC's voltage set-point of Mellieħa DC is lowered to 11.1kV with a bandwidth of 1.5%, the transformer performs a tap-change in order to reduce the voltage in the 11kV busbar, since the voltage exceeds 11.26kV as indicated in the previous scenario. As indicated in Table 6.10, the voltage rise at the PCC is equivalent to 2.18% of the nominal voltage. This implies that the wind farm can operate at a power factor closer to unity in order to reduce the losses in the 11kV circuit. The resulting voltage magnitudes at the LV busbars of the substations in the circuit are within the permitted limits.

The increase in net power flow towards Mellieħa DC as the wind farm exports reactive power at a power factor of 0.95, causes the voltage at the PCC to slightly exceed the 5% voltage rise limit. However, since several transformers are set at the minimum tap position, the resulting voltage magnitudes at the LV busbars are within the permitted limits.

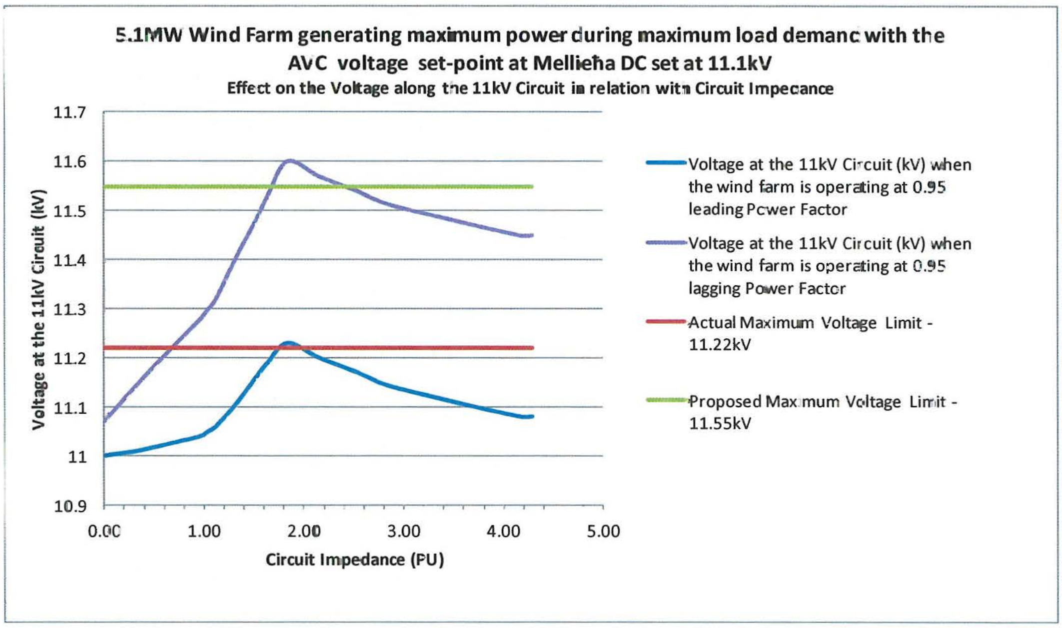


Figure 6.17 - Voltage profile along the 11kV circuit for scenario D in option 2

6.3.2.5 Scenario E - 5.1MW wind farm disconnected during maximum load demand with the 11kV busbar voltage at Mellieħa DC regulated within the bandwidth of 11.1kV

The voltage magnitudes resulting at the 11kV and LV busbars of the substations in the circuit, after the 5.1MW wind farm is disconnected during maximum load demand, are shown in Table C.2.5 of Appendix C. The resulting voltage profile against the circuit impedance along the 11kV circuit is shown in Figure 6.18.

From Table 6.11, one can deduce that the voltage drop in the 11kV circuit during maximum load demand is 4.64%, which is within the permitted limits. The lowest voltage magnitude resulting at the LV busbars of the circuit is 392V, with the transformer in this substation set at the minimum tap position. If a 6% voltage drop along the LV lines is assumed, this results in a voltage of 368V at the consumer terminals. This is equivalent to a voltage drop of 8% which is within the limits established in the network code.

3.4MW Wind Farm connected between Fiddien Booster and Rabat tas-Salib Substations Switched Off	
Power Generated (MW)	0
Load Demand (MVA)	3.15
Net Real Power flow into Mellieħa DC (MW)	-3.28
Net Reactive Power flow into Mellieħa DC (MVAr)	-0.36
Voltage at Source (kV)	11.16
Minimum Voltage in the Circuit (kV)	10.49
Real Power Losses in the Circuit (MW)	0.15
Reactive Power Losses in the Circuit (MVAr)	0.20

Table 6.11 - Net Power flow and losses in the 11kV circuit for scenario E in option 2

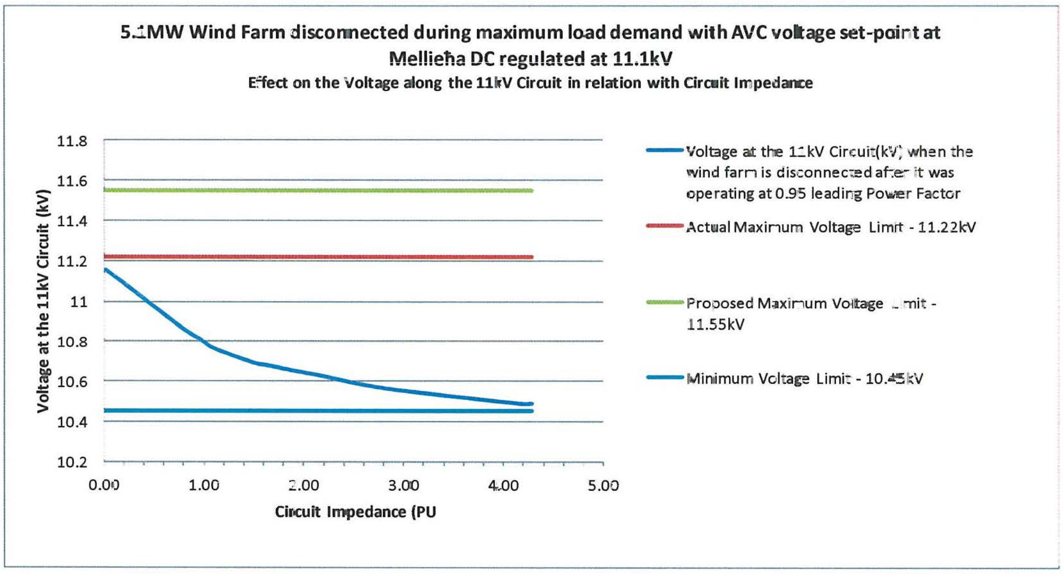


Figure 6.18 - Voltage profile along the 11kV circuit for scenario E in option 2

6.4 Conclusions

The wind farm at Wied Rini l/o Baħrija poses several challenges to the network operator. The considerable cable route length between the wind farm and the DC, resulting in a high circuit impedance, can cause significant voltage rise at certain nodes in the circuit.

The cheapest connection point for the wind farm is with the cable segment between Mtaħleb Wied Rini Relay Stn and Rabat l-Andrijiet substations, as the 95mm^2 aluminium cable between these two substations is passing through the site. This part of the circuit limits the maximum power rating of the wind farm to 3.4MW, consisting of four 850kW wind turbines. The wind farm may be connected with the 11kV circuit by one, or two cables for increased reliability. In the analysis carried out, the wind farm is considered to be connected by two 95mm^2 aluminium cables. The impedance between the PCC and Mellieħa DC is 2.9pu. When the 3.4MW wind farm generates maximum power at 0.95 leading power factor during minimum load demand, the resulting voltage at certain nodes in the circuit exceeds the 5% voltage rise of the nominal voltage, with the voltage magnitude at the 11kV busbar of Mellieħa DC being 11.09kV. Thus, the power of the wind farm has to be reduced to 2.55MW by switching off one of the wind turbines in order to decrease the voltage in the 11kV circuit to below 11.55kV. As the 3.4MW wind farm generates maximum power at 0.95 leading power factor during maximum load demand, the voltage at the PCC slightly exceeds 5% of the nominal voltage. As the resulting voltage at the 11kV busbar of Mellieħa DC is 11.33kV, it is possible to shift down the voltage profile by reducing the voltage set-point of the transformer's AVC at Mellieħa DC to 11.1kV with a bandwidth of 1.5%. In this manner, the 11kV busbar voltage of Mellieħa DC is allowed to vary between 10.93kV and 11.267kV. Thus, in such scenario the transformer will perform a tap-change to reduce the voltage in the 11kV busbar of Mellieħa DC, whilst shifting the voltage at the PCC down to 11.35kV. The shift in the voltage profile due to the lowering of the AVC's voltage set-point at Mellieħa DC is shown in Figure 6.19. Disconnection of the wind farm during maximum load demand, with the 11kV busbar of Mellieħa DC regulated within the bandwidth of

11.1kV, does not cause the voltage in the 11kV and LV circuits to drop below the permitted limits.

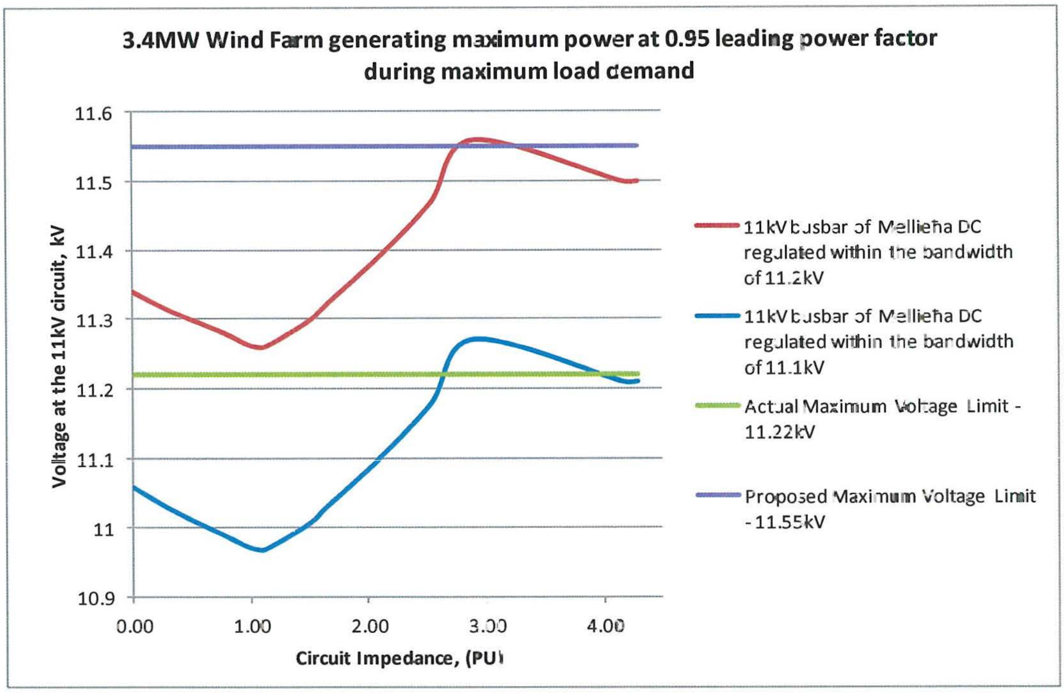


Figure 6.19 - Impact from the 3.4MW wind farm on the voltage profile of the 11kV circuit with the 11kV busbar voltage of Mellieħa DC regulated at 11.2kV and 11.1kV

A larger wind farm can be installed when connected with the cable section between Fiddien Booster and Rabat tas-Salib substations. The cable in this section is a 185mm^2 aluminium cable, rated at 5.7MVA. Thus a 5.1MW wind farm consisting of six 850kW wind turbines can be installed. Such wind farm can produce a higher energy yield, but at the expense of a higher connection cost. The connection will require one or two 185mm^2 aluminium cables between the wind turbine substations and the WFCSR with an approximate length of 2.6km buried in the ground together with the associated earthing and communication cables. This connection reduces the impedance between the PCC and Mellieħa DC to 1.84pu.

From the analysis, it was determined that the 11kV busbar voltage of Mellieħa DC needs to be regulated within the 1.5% bandwidth of 11.1kV in order to mitigate the impact on the steady-state voltage rise of the circuit from the wind farm especially when it generates maximum power during minimum load demand.

Apart from reducing the target voltage at Mellieħa DC, the generated power needs to be reduced to 4.75MW at 0.95 leading power factor in order for the voltage in the 11kV circuit to be retained below 11.55kV in such scenario. As the 5.1MW wind farm generates maximum power at 0.95 leading power factor during peak load demand, with the 11kV busbar of Mellieħa DC regulated at 11.2kV and 11.1kV, the resulting voltage magnitudes at PCC are 11.52kV and 11.24kV respectively. The voltage profiles of the 11kV circuit resulting from the two voltage set-points at Mellieħa DC are shown in Figure 6.20.

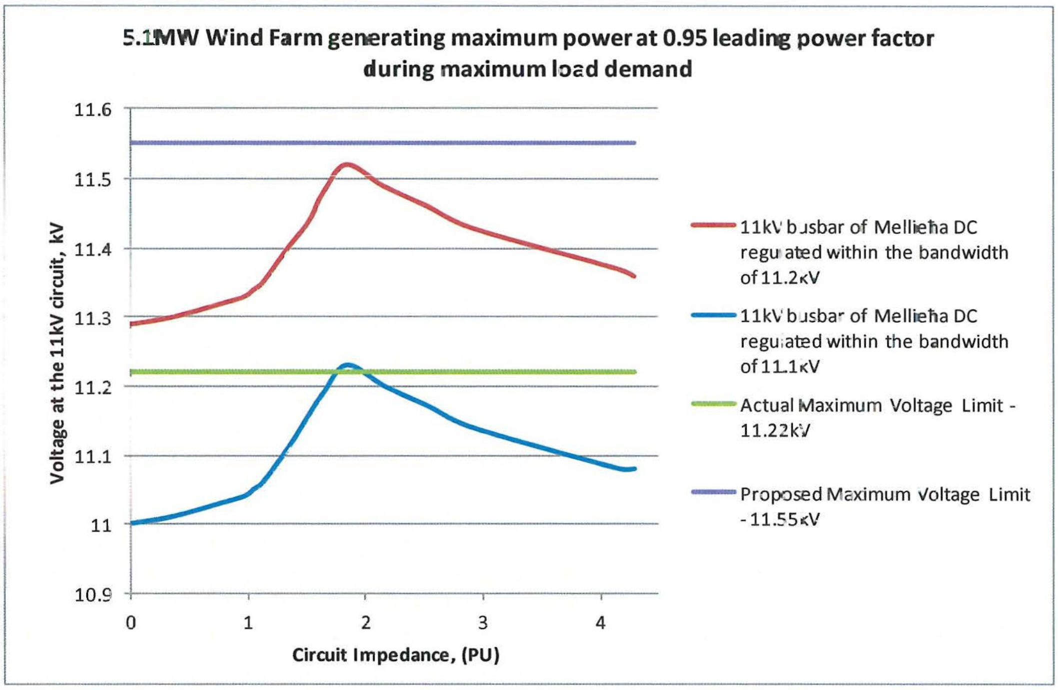


Figure 6.20 - Impact from the 5.1MW wind farm on the voltage profile of the 11kV circuit with the 11kV busbar voltage of Mellieħa DC regulated at 11.2kV and 11.1kV

CHAPTER 7

CONCLUSIONS

The dissertation mainly focuses on the impact of voltage rise in the electricity network caused by medium-scale wind farms integrated with the 11kV network. Two typical wind farm sites, one in Gozo and the other in Malta, were chosen on the basis that the sites offer a good wind resource potential, and are located in rural areas at a significant distance from the source of 11kV supply. The dissertation is split into three parts. The first part describes a typical electrical wind farm design which can be implemented in such medium-scale wind farms. The proposed wind farm layout and configuration was utilised to model the wind farm in the IPSA+ software. The second and third part of the dissertation focus on the prospective wind farm sites at Kerċem in Gozo and Baħrija in Malta. The site characteristics and constraints were described and used to identify a more precise location. The possible wind farm connection points with the 11kV network were determined. This was followed by a load flow analysis using IPSA+ program for each connection possibility. The analysis was carried out for several worst case scenarios, where the resulting steady-state voltage profiles determine whether the permitted voltage limits are exceeded. The study also investigate different ways to mitigate the voltage rise in the network.

7.1 Summary

7.1.1 Wind Farm Electrical Design

The wind turbines considered in this dissertation are the Gamesa G58 rated at 850kW, having a three-blade rotor with a diameter of 58m and a possible hub height ranging between 44m and 71m. The wind turbine converts kinetic energy into electrical energy via a four pole DFIG at a rated stator voltage of 690V and frequency of 50Hz. The variable speed generator can control the active and reactive power. The power factor can vary between 0.95 leading to 0.95 lagging. The wind turbine has a cut-in and cut-out speed of 3 and 23m/s respectively. Each wind turbine is connected to an outdoor pre-fabricated substation, consisting of a 690V switchboard, 690V/11kV 1000kVA transformer, and an 11kV RMU. The wind turbine substations are looped through 11kV cables installed between the RMUs. The wind farm is either installed as a radial or ring circuit, connected with the WFCSR. The PCC is identified at the CB in the WFCSR, which serves as an isolating point between the wind farm and the grid. The protection system of the wind farm consists of four zones. These zones are responsible for the protection of:

- the generator and its pendant LV cables;
- the 690V cables between the tower base and the wind turbine substation;
- the wind turbine transformer; and
- the 11kV cables between PCC and the wind turbine substations.

7.1.2 Wind Farm at Kerċem, Gozo

Mott MacDonald identified an unconstrained site at Gozo having a good wind resource potential, called Qasam Ben Borġ. The average site wind speed at a height of 50m above the ground is 6.65m/s. The site is characterised by areas of high landscape sensitivity, Natura 2000 SAC sites, natural valleys, the touristic area of Xlendi and archaeological sites. The site is served through minor roads passing through small villages making it impossible for large vehicles transporting the wind turbines components to get through. Considering such constraints, the Qasam Ben Borġ site has been reduced to a small site in Kerċem.

The wind farm in this site can be connected with the grid via two options. The cheapest connection is through an overhead line connected to the utility's overhead line feeding Kerċem VOR Beacon TC. The other connection is through underground cables connected with the network section between Kerċem tat-Taljana and Kerċem substations, however the connection cost is higher than the former one. These two connections limit the wind farm size to a maximum of 3.4MW, due to the 95mm^2 aluminium cables installed in the existing 11kV circuit, rated at 3.9MVA.

The first option causes the voltage at the PCC to rise slightly above the 5% of the nominal voltage, during maximum generation at 0.95 leading power factor and minimum load demand. In such scenario, the steady-state voltage is reduced by limiting the real power generated to 3.15MW. As the load in the circuit increases, the real power generated by the wind farm can be increased towards its maximum capacity while shifting the power factor towards unity or operate in lagging mode, in order to reduce the losses in the 11kV circuit.

The impedance between the PCC and Qala DC can be reduced by connecting the wind farm between Kerċem tat-Taljana and Kerċem substations. Thus, the voltage rise in the circuit is reduced. In fact, the resulting voltage at the PCC is less than 11.55kV, as the wind farm generates maximum power at 0.95 leading power factor during minimum load demand in the circuit. The costs for this connection are higher as it involves the installation of one or two 95mm^2 aluminium cables buried in the ground for an approximate length of 1850m.

A larger wind farm can be integrated in this section of the circuit by replacing the existing 95mm^2 aluminium cable by a 185mm^2 aluminium cable. This means that about 1800m length of cable needs to be replaced. The additional cost required to reinforce the network is compensated by the increased revenue generated from a 5.1MW instead of a 3.4MW wind farm. However, as the 5.1MW wind farm generates maximum power during minimum load demand, the high net power flow into the primary substation causes the voltage at certain nodes in the 11kV circuit to rise above the 5% of the nominal voltage. The voltage at the PCC was reduced to below the 11.55kV by limiting the real power generation to 4.25MW, while absorbing reactive power at a power factor of 0.95. In order to keep the voltage in the LV busbars of several nodes below the upper limit of 440V, the fixed tap-changer of the transformers are set at the minimum tap position. As load in the circuit increases, the real power generated by the wind farm can increase while shifting its operating power factor towards unity or lagging mode.

The main problem is encountered when the wind farm is disconnected during maximum load demand. The voltage drop resulting along the 11kV circuit added with the voltage drop across the transformers being set at the minimum tap position has caused a minimum voltage of about 376V in the LV busbars. Thus, a voltage drop higher than 4.2% in the LV circuits, causes a total voltage drop higher than 10% at the LV consumer terminals, hence exceeding the permitted limits stipulated in the network code. This situation is expected to improve with the commissioning of the proposed Xewkija DC, as the impedance between the PCC and the DC reduced significantly while the load is decreased as it is being shared between two DCs. Thus, as the 5.1MW wind farm generates maximum power at 0.95 leading power factor, the resulting voltage rise at the PCC is less than 5% of the nominal voltage. This does not force the necessity to set the substation transformers in the vicinity of the wind farm at the minimum tap position. Hence, as wind farm is disconnected, the voltage drop in the 11kV and LV circuits to does not exceed the permitted tolerance.

7.1.3 Wind Farm at Wied Rini l/o Baħrija, Malta

The site at Wied Rini l/o Baħrija offers a good wind resource potential, with an average wind speed between 7 and 7.5m/s at 45m above ground level [8]. The site is far-off from the residential settlement and is easily accessible from existing roads. The site is characterised by a wind monitoring station and disused telecommunication lattice towers. Environmental and planning constraints such as protected areas including Natura 2000 areas, AEI, AVHLS and AHLS may limit the size of a wind farm.

The cheapest connection with the grid is by connecting the wind farm between Mtaħleb Wied Rini Relay Stn and Rabat l-Andrijiet substations. The 95mm^2 aluminium cable between these two substation is passing through the site, however the cable capacity limits the wind farm size to 3.4MW, hence four 850kW wind turbines can be installed. The high impedance between PCC and Mellieħa DC, will cause the voltage in certain nodes of the 11kV circuit to exceed the 5% voltage rise from the nominal voltage, when the wind farm is generating maximum power during minimum load demand. Thus in such scenario, the voltage level was reduced to within acceptable limits by limiting the real power generation to 2.55MW, operating the wind farm at 0.95 leading power factor, and regulating the 11kV busbar voltage within the 1.5% bandwidth of 11.1kV instead of the normal 11.2kV. As the load increases, the real power generation of the wind farm can increase, with the power factor controlled to operate in the vicinity of unity or lagging mode, without exceeding the 5% voltage rise in the 11kV circuit. The voltage drop along the feeder resulting from the disconnection of the wind farm will not cause the voltage in the 11kV and LV circuit to fall below the permitted limits.

A larger wind farm can be integrated with the 11kV network if it is connected to the existing 185mm^2 cable section between Fiddien Booster and Rabat tas-Salib substations. However this involves the installation of one or two, 185mm^2 aluminium cables along with the fibre optic and earthing cables for an approximate length of 2.6km buried in the ground between the wind farm and the PCC. Such connection makes it possible to integrate a wind farm up to 5.1MW having six 850kW wind turbines. This connection reduces the impedance between the PCC and the primary substation, thus it is possible to generate more power during maximum net power flow in the circuit. During minimum load demand in the circuit, the generated real power of the wind farm has to be reduced to 4.75MW while absorbing reactive power at a power factor of 0.95, in order to maintain the steady-state voltage in the circuit within permitted limits.

7.2 Mitigation Measures

From the analysis carried out on typical medium-sized wind farms connected with the 11kV network in the Maltese islands, it resulted that the major constraints encountered are:

- the effect of voltage rise;
- the voltage drop in the LV circuits when the wind farm is disconnected; and
- the current carrying capacity limitations of the existing network cables.

7.2.1 Effect of Voltage Rise

As wind farm sites are typically located in rural areas at a distance from load centres, the cable route length between the DC and the wind farm is quite significant. This implies a high impedance in the circuit between the PCC and the DC. Such impedance causes the steady-state voltage to rise especially during a high net power flow through the circuit, which normally occurs during periods of high power generation and minimum load demand.

One of the main issues noted during the load flow analysis of the various wind farm connection options and their respective scenarios for both sites is that the voltage at the 11kV busbar of the DC exceeds the upper voltage limit of 11.22kV. In view that the 11kV busbar voltage of the DC is regulated within the 1.5% bandwidth of 11.2kV, the voltage is allowed to vary between 11.03kV and 11.37kV, equivalent to a maximum voltage rise of 3.36% of the nominal voltage, before the transformer is forced to change its tap position. This constraint, limits the integration of distributed generation connected with the 11kV network. In fact EMC has requested MRA in April of 2013 to approve an amendment in the network code which will tolerate a voltage rise in the 11kV voltage level up to a maximum of 5%, equivalent to an upper voltage limit of 11.55kV [22]. Voltage rise in the 11kV network exceeding the 5% of the nominal voltage is not permitted as this will stress the insulation of the network components, leading to accelerated ageing of the equipment. Furthermore, such voltage rise in the 11kV circuit may cause the voltage in the LV circuits to exceed the permitted 10% tolerance and this may damage consumers' equipment.

The impact of voltage rise in the network is mitigated through the following measures:

- Power factor control of the wind farm;
- Reducing the regulated voltage set-point of the 11kV busbar at the DC;
- Reducing the impedance between the PCC and the DC;
- Limiting the generated power of the wind farm; and
- Operating 11kV circuits in parallel.

One way of regulating the voltage at the PCC is by controlling the operating power factor of the wind farm. The voltage can be reduced by operating the wind farm at leading power factor, implying that the reactive power is absorbed by the DFIGs. However from the analysis carried out, results show that by operating the wind farm at unity or lagging power factor, the losses in the circuit are reduced.

The voltage in the network can be also reduced by regulating the 11kV busbar of the DC within the 1.5% bandwidth of 11.1kV instead of 11.2kV. Thus the voltage at the 11kV busbar is allowed to vary between 10.93kV and 11.27kV. This will allow a greater distributed generation penetration in the circuit. Setting the AVC of the transformer at a target voltage lower than 11.1kV is not technically possible as this will cause a considerable voltage drop along the other 11kV feeders supplied from the same busbar.

The voltage rise in the circuit can be minimised by reducing the impedance between the PCC and the traditional source. This can be achieved by connecting the wind farm at a point closer to the DC. For both sites considered in this analysis, it was noted that as the PCC is brought closer to the conventional source, the cross sectional area of the cables in the 11kV network increases, thus making it possible to integrate a larger wind farm. Thus the additional cost required to connect the wind farm with the grid may be compensated by the extra revenue generated by the wind farm.

During circumstances of high net power flow between the wind farm and the conventional source, the voltage magnitudes in the circuit nodes may still exceed the permitted limits. This may occur when the wind farm generates high power during low load demand, which is typical during the night. If the voltage is not reduced to acceptable levels by absorbing the maximum possible reactive power, the real power generated by the wind farm has to be reduced to a specific amount, such that the voltage at the PCC is reduced to a permitted level. Thus the wind farm has to regulate the voltage at PCC by varying the operating power factor and limiting the real power generation when necessary. The probability of high power generation during low load scenarios has to be analysed in order to determine the cost of power curtailment, and hence the economic feasibility of such wind farm development.

Operation of 11kV circuits in parallel will also reduce the net power flow into the DC, hence minimising the voltage rise in the network. However, this needs to be carefully investigated in order to ensure that load sharing between the two feeders will not overload any part of the circuit. Since the power flow is bi-directional, the protection system in the circuit has to incorporate directional relays in order to operate successfully in case of a fault in the circuit.

7.2.2 Voltage Drop in the LV Circuit following the Disconnection of the Wind Farm

The Gamesa G58 wind turbines have a cut-in and cut-out speeds of 3 and 23m/s respectively. Thus, as the wind speed is outside these limits, the wind turbines are disconnected. Other circumstances for wind farm disconnection are during faults either in the wind farm or in the network. For faults in the 11kV circuit, the wind farm is disconnected through island detection relays based on techniques such as ROCOF, or Vector Shift.

As wind farms are located in rural areas far-off from the traditional source, the fixed tap-changers of the substation transformers, especially those in the vicinity of the wind farm, are set at the minimum tap position in order to counteract the significant voltage rise in the circuit. The maximum voltage permitted on the

11kV side, 11.55kV, is transformed to 432V with the transformer set at the minimum tap position at no-load. Conversely, the minimum permitted voltage, 10.45kV, corresponds to 390V in the LV busbar when the transformer is set at the minimum tap position at no-load. Assuming, a 6% voltage drop along the LV lines this results in a voltage at the consumer end of 367V which is close to the permitted voltage drop limit of 10%. The feeder analysed for the proposed wind farm at Gozo, experiences a significant voltage drop in the 11kV circuit during peak load demand, with voltage reaching 10.25kV at the remote end of the circuit. This excessive voltage drop is mainly experienced in the summer season during the high peak load. Consequently, the voltage in the LV busbars reach a minimum voltage of 376V. Subsequently, the resulting voltage at the consumer end may fall below the permitted lower limit, if the voltage drop along the LV circuits exceeds the 4.2%.

The voltage drop resulting in the LV circuits following the disconnection of a distributed generator connected with the 11kV circuit can be mitigated by:

- Reducing the load in the 11kV circuit;
- Increasing the regulated voltage set-point of the DC's transformer during wind farm disconnection;
- Better load sharing between the LV feeders and balancing of phases;
- Reduction of LV lines impedance;
- Reinforcing the LV system by the installation of new LV feeders;
- Commissioning of new substations to reduce the load in the LV feeders; and
- Replacing substation transformers with ones equipped with OLTC.

Reduction of load from the 11kV feeder will reduce the voltage drop during wind farm disconnection. The drawback of such measure is that when the wind farm generates high power, this will increase the net power flow into the conventional source. Consequently, this will increase the voltage in the circuit which may exceed the permitted upper limit especially during minimum load demand. Thus, such load reduction in the 11kV circuit has to be done with caution.

In the analysis of the wind farm at Wied Rini, it was noted that greater distributed generation penetration is permitted in the 11kV network with the reduction of the set voltage of the DC's 11kV busbar to 11.1kV with a bandwidth of 1.5%. However, this can create a voltage drop problem in heavily loaded feeders during peak load demand when the wind farm is disconnected. The voltage drop can be reduced by setting the AVC set voltage of the DC's 11kV busbar back to 11.2kV as the wind farm is disconnected. This will then be set back to 11.1kV as soon as the wind farm synchronises with the grid. The DCs in the network are all equipped with a SCADA system which continuously monitors the DC while providing the network operators with the facility to make certain operations remotely. Thus, it will be possible for the network operators to change the AVC set-point remotely, if the load in the circuit exceeds a certain amount.

Another method to reduce the voltage drop in the LV circuits is by balancing the load equally between the three phases of the LV feeders, and by sharing the load between the LV feeders. The voltage drop along the LV feeders can be further minimised by reducing the line impedance. This can be achieved by having parallel lines split from the main line; and by replacing heavily loaded lines with lines having a greater cross-sectional area, and hence less impedance.

Installation of new LV feeders will assist in reducing the voltage drop. New feeders reduce the load and the impedance from other feeders, thus reducing the I^2R losses and hence the voltage drop along the LV circuits. Long LV circuits may be shortened by the commissioning of new substations. The new feeders from these substations will reduce the length and also the load from the other feeders. Thus the voltage drop in the LV circuits is reduced.

Another option to control the voltage level of the LV circuits, is by replacing the substation transformers by others equipped with OLTC. This provides the benefits of better voltage regulation while ensuring that the voltage level at the customer end is within the permitted limits. This is rather a costly option, therefore it has to be carried out at least on substations located in the vicinity of the wind farm experiencing a wide voltage range in their 11kV busbars.

7.2.3 Network Cables' Capacity Limitations

In view that in conventional electricity networks, power in the distribution circuit flows in one direction, from source to load, the cable cross-sectional area tends to decrease as one moves away from the source. Thus, in rural areas, where wind farms are typically installed, the cables passing by the site limits the wind farm size that can be possibly connected. In both sites analysed in this dissertation, 95mm^2 aluminium cables are installed in the vicinity of the wind farm. Such cables limit the wind farm size to 3.4MW. A larger wind farm is possibly integrated with the grid either by replacing the existing cables with ones having a higher power rating, or by connecting the wind farm at a point closer to the DC. A PCC closer to the DC will reduce the impedance. Thus, the increased net power flow into the primary substation caused from increased distributed generation, is compensated by the reduced impedance. The increased connection cost may be economically feasible because of the increased generated revenue.

7.3 Dissertation Limitations

The analyses was based on load data provided by EMC. Peak load data from each substation are recorded during periods of peak power generation. However, this will not necessary coincide with the peak load demand of the 11kV feeder under study. On the other hand, minimum load data for each substation are not usually recorded. Thus, minimum load readings of the 11kV feeders under consideration are recorded from the SCADA system. The approximate load for each substation was determined by sharing the total feeder load proportionally among the substations according to the ratio of typical substation load to the total feeder load. EMC is currently implementing a smart metering system where the substations' total load demand together with the consumers' load demand will be remotely monitored by the utility. Such system will enable a more accurate maximum and minimum load recordings for the substation in the network. Hence, network operators can accurately carry out load flow analysis to better plan the network reinforcements, while taking into account future load growth and distributed generation penetration in the network.

7.4 Further Work

In this dissertation, the impacts on the steady-state voltage of the network from the integration of wind farms were investigated. Mitigation measures for such negative impacts were also outlined. In view of the EU's roadmap towards low carbon economy by 2050 [29], renewable energy targets are expected to be more stringent in the coming decades. The expected increase in the penetration of distributed generation in the coming years requires further investigation. Apart from wind energy, high penetrations of solar and wave energy are expected to be integrated with the electricity network. Thus it is being suggested that the following areas of study will be investigated:

- Distributed Generation integrated with parallel 11kV circuits. Their impacts on the grid in relation with the steady-state voltage and protection system coordination.
- Investigation of the dynamic behaviour of the network due to the variable nature of renewable energy sources.
- Advantages of energy storage in relation to the dynamic behaviour of the grid.
- Integration of dispatchable renewable generators during islanding of the grid.
- Investigation on the impacts of distributed generation on the power quality of the network.
- Feasibility analysis of renewable generators connected with the 11kV network considering the connection costs, network reinforcement costs, power curtailment costs, maintenance costs, outage time and generated revenue.

APPENDICES

Appendix A 850KW DFIG Parameters

DFIG Steady State Parameters	Value (pu)
Stator resistance in pu	0.027
Rotor resistance referred to the stator in pu	0.021
Stator reactance in pu	0.125
Rotor reactance referred to the stator in pu	0.204
Magnetising reactance in pu	11.403

Table A.1 - Steady-state parameters of the 850kW DFIG

Appendix B Proposed Wind Farm at Kerċem, Gozo

B.1 Wind Farm Connected with the Grid as in Option 1

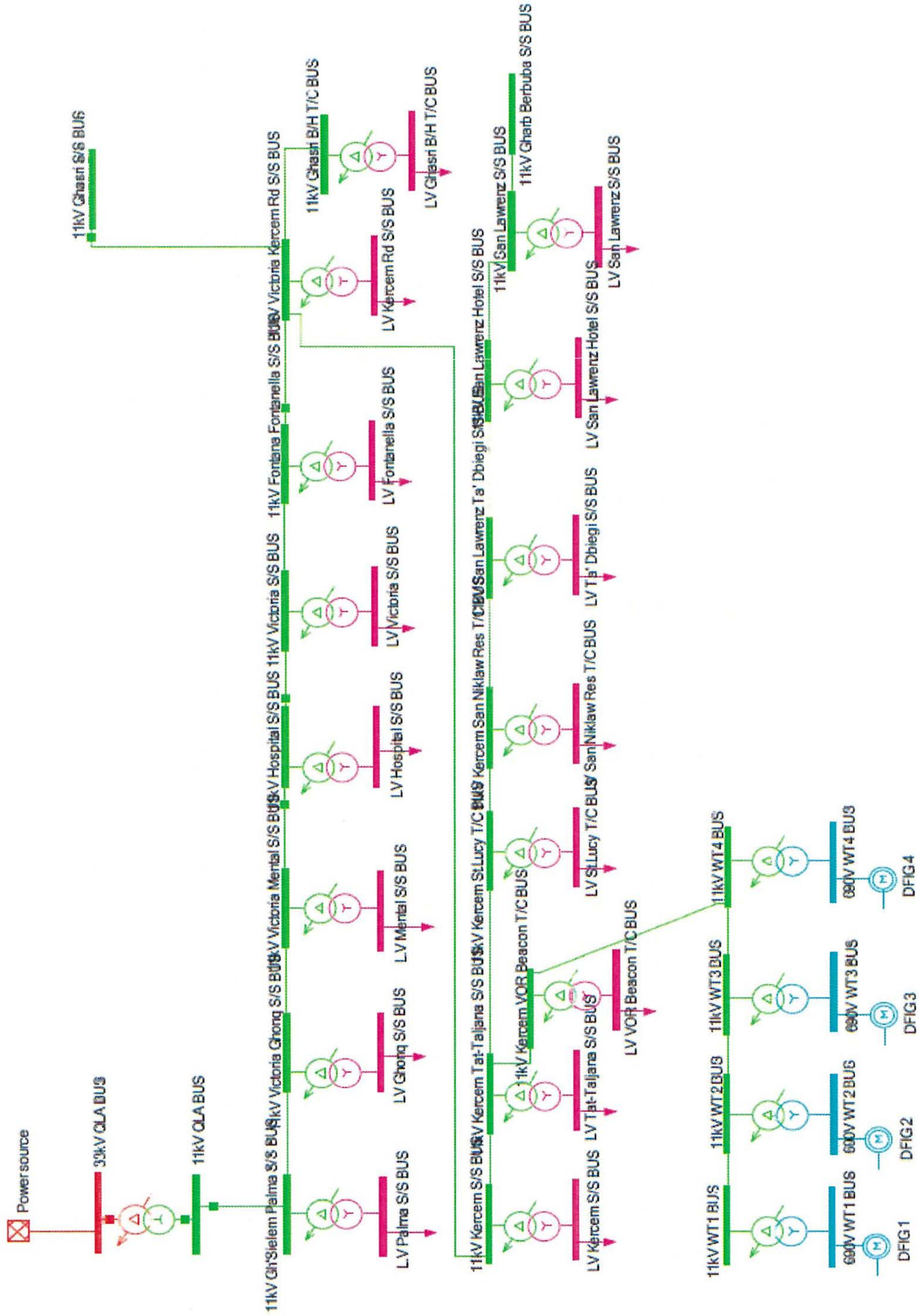


Figure B.1- Snapshot from IPSA+ of the modelled Kerċem wind farm for connection option 1

B.1.1 Steady-State Voltage Results for Scenario A in Option 1

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Qala D.C	11.15	/	-1	11.26	/	-1
Ghajnsielem Palma	11.18	429	-1	11.33	434	-1
Victoria Ghonq	11.27	432	-1	11.5	430	-2
Victoria Mental	11.28	432	-1	11.51	431	-2
Victoria Hospital	11.3	433	-1	11.53	432	-2
Victoria	11.32	434	-1	11.57	433	-2
Fontana Fontanella	11.34	435	-1	11.59	434	-2
Victoria Kercem Rd.	11.37	436	-1	11.64	436	-2
Ghasri B/H	11.37	436	-1	11.64	436	-2
Kercem	11.43	438	-1	11.71	439	-2
Kercem Tat-Taljana	11.49	430	-2	11.79	441	-2
Kercem VOR Beacon	11.58	433	-2	11.94	447	-2
Kercem St.Lucy	11.48	430	-2	11.79	441	-2
Kercem San Niklaw Res.	11.48	429	-2	11.78	441	-2
San Lawrenz Ta' Dbiegi	11.48	429	-2	11.78	441	-2
San Lawrenz Hotel	11.48	429	-2	11.78	441	-2
San Lawrenz	11.48	429	-2	11.78	441	-2

Table B.1.1 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario A in Option 1

B.1.2 Steady-State Voltage Results for Scenario B in Option 1

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Qala D.C	11.15	/	-1	11.26	/	-1
Ghajnsielem Palma	11.18	429	-1	11.32	434	-1
Victoria Ghonq	11.26	432	-1	11.47	429	-2
Victoria Mental	11.27	432	-1	11.48	429	-2
Victoria Hospital	11.28	432	-1	11.5	430	-2
Victoria	11.3	433	-1	11.53	431	-2
Fontana Fontanella	11.32	434	-1	11.56	432	-2
Victoria Kercem Rd.	11.35	435	-1	11.6	434	-2
Ghasri B/H	11.35	435	-1	11.6	434	-2
Kercem	11.4	437	-1	11.67	437	-2
Kercem Tat-Taljana	11.46	429	-2	11.74	439	-2
Kercem VOR Beacon	11.55	432	-2	11.88	444	-2
Kercem St.Lucy	11.46	429	-2	11.74	439	-2
Kercem San Niklaw Res.	11.45	428	-2	11.73	439	-2
San Lawrenz Ta' Dbiegi	11.45	428	-2	11.73	439	-2
San Lawrenz Hotel	11.45	428	-2	11.73	439	-2
San Lawrenz	11.45	428	-2	11.73	439	-2

Table B.1.2 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario B in Option 1

B.1.3 Steady-State Voltage Results for Scenario C in Option 1

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage on the 11kV busbar (kV)	Voltage on the 400V busbar (V)	Transformer Tap Position
Qala D.C	11.35	/	0	11.18	/	-1
Ghajnsielem Palma	11.26	429	-1	11.13	423	-1
Victoria Ghonq	11.07	421	-1	11.02	419	-1
Victoria Mental	11.06	419	-1	11.01	418	-1
Victoria Hospital	11.04	419	-1	11	418	-1
Victoria	11.03	418	-1	11.01	417	-1
Fontana Fontanella	11.02	421	-1	11.01	420	-1
Victoria Kercem Rd.	11.02	415	-1	11.03	415	-1
Ghasri B/H	11.01	416	-1	11.02	416	-1
Kercem	11.05	418	-1	11.08	419	-1
Kercem Tat-Taljana	11.1	409	-2	11.14	411	-2
Kercem VOR Beacon	11.19	413	-2	11.29	416	-2
Kercem St.Lucy	11.09	409	-2	11.14	410	-2
Kercem San Niklaw Res.	11.09	408	-2	11.13	410	-2
San Lawrenz Ta' Dbiegi	11.08	414	-2	11.12	416	-2
San Lawrenz Hotel	11.08	414	-2	11.12	416	-2
San Lawrenz	11.08	414	-2	11.12	416	-2

Table B.1.3 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario C in Option 1

B.1.4 Steady-State Voltage Results for Scenario D in Option 1

Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Qala D.C	11.12	/	-1
Ghajnsielem Palma	10.94	416	-1
Victoria Ghonq	10.53	400	-1
Victoria Mental	10.5	398	-1
Victoria Hospital	10.46	397	-1
Victoria	10.41	394	-1
Fontana Fontanella	10.38	396	-1
Victoria Kercem Rd.	10.33	388	-1
Ghasri B/H	10.32	389	-1
Kercem	10.29	389	-1
Kercem Tat-Taljana	10.27	378	-2
Kercem VOR Beacon	10.26	377	-2
Kercem St.Lucy	10.26	377	-2
Kercem San Niklaw Res.	10.25	376	-2
San Lawrenz Ta' Dbiegi	10.25	383	-2
San Lawrenz Hotel	10.25	383	-2
San Lawrenz	10.25	383	-2

Table B.1.4 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario D in Option 1

B.2 Wind Farm Connected with the Grid as in Option 2

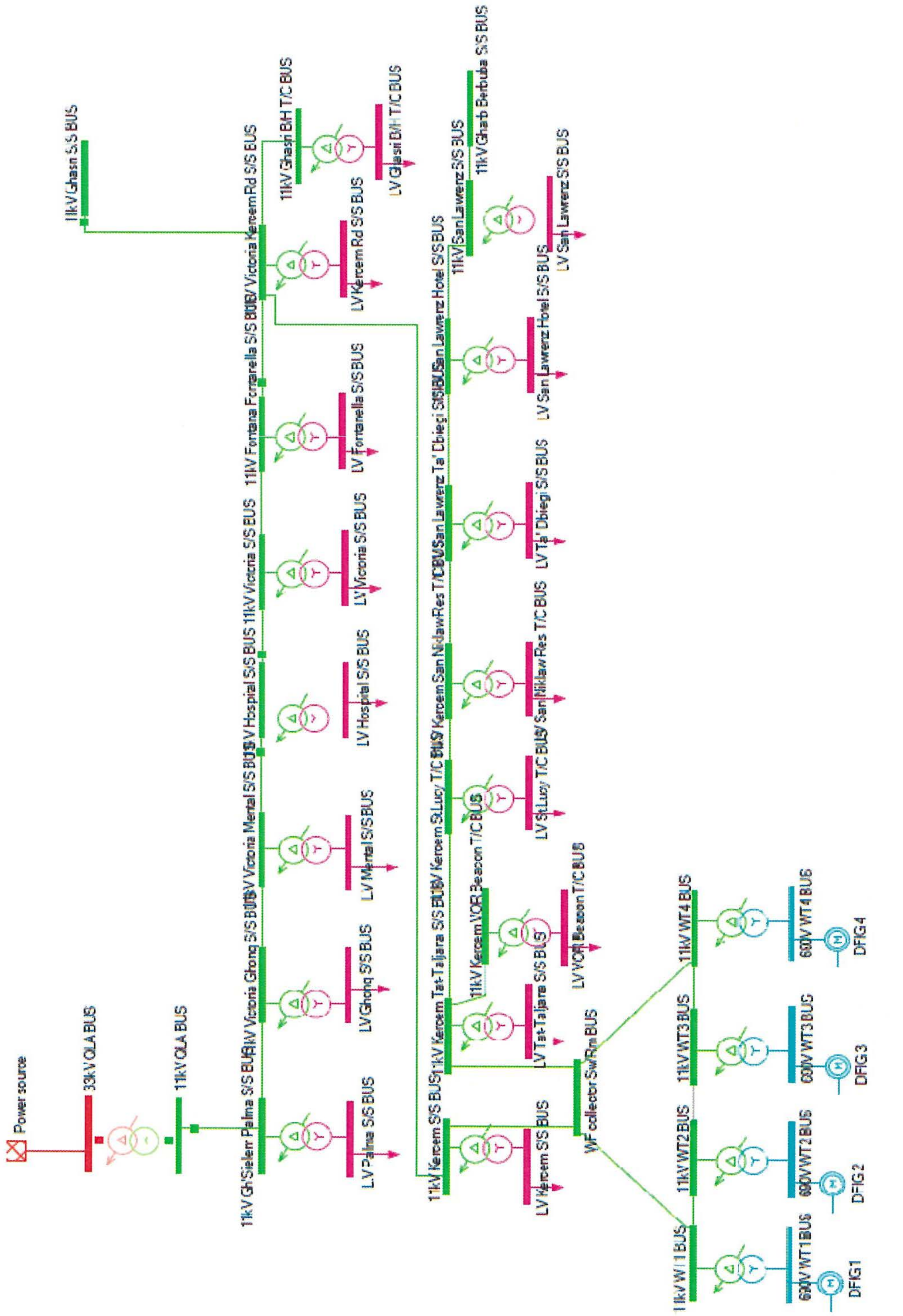


Figure B.2 - Snapshot from IPSA+ of the modelled Kerċem wind farm for connection option 2

B.2.1 Steady-State Voltage Results for Scenario A in Option 2

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Qala D.C	11.15	/	-1	11.26	/	-1
Ghajnsielem Palma	11.19	429	-1	11.33	434	-1
Victoria Ghonq	11.28	432	-1	11.5	430	-2
Victoria Mental	11.29	433	-1	11.52	431	-2
Victoria Hospital	11.3	433	-1	11.54	432	-2
Victoria	11.33	434	-1	11.57	433	-2
Fontana Fontanella	11.35	435	-1	11.6	434	-2
Victoria Kercem Rd.	11.38	436	-1	11.65	436	-2
Ghasri B/H	11.38	436	-1	11.65	436	-2
Kercem	11.44	439	-1	11.72	439	-2
Wind Farm Collector Switch-Room	11.52	/	/	11.82	/	/
Kercem Tat-Taljana	11.52	431	-2	11.82	442	-2
Kercem VOR Beacon	11.51	431	-2	11.81	442	-2
Kercem St.Lucy	11.51	431	-2	11.81	442	-2
Kercem San Niklaw Res.	11.51	430	-2	11.81	442	-2
San Lawrenz Ta' Dbiegi	11.5	430	-2	11.81	442	-2
San Lawrenz Hotel	11.5	430	-2	11.8	442	-2
San Lawrenz	11.5	430	-2	11.8	442	-2

Table B.2.1 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario A in Option 2

B.2.2 Steady-State Voltage Results for Scenario B in Option 2

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Qala D.C	11.35	/	0	11.18	/	-1
Ghajnsielem Palma	11.26	429	-1	11.13	423	-1
Victoria Ghonq	11.08	421	-1	11.02	419	-1
Victoria Mental	11.06	420	-1	11.02	418	-1
Victoria Hospital	11.05	419	-1	11.01	418	-1
Victoria	11.04	419	-1	11.01	418	-1
Fontana Fontanella	11.03	421	-1	11.02	421	-1
Victoria Kercem Rd.	11.03	415	-1	11.04	416	-1
Ghasri B/H	11.03	417	-1	11.03	417	-1
Kercem	11.07	419	-1	11.09	420	-1
Wind Farm Collector Switch-Room	11.12	/	/	11.16	/	/
Kercem Tat-Taljana	11.12	410	-2	11.16	412	-2
Kercem VOR Beacon	11.12	410	-2	11.15	411	-2
Kercem St.Lucy	11.12	410	-2	11.16	411	-2
Kercem San Niklaw Res.	11.11	409	-2	11.15	410	-2
San Lawrenz Ta' Dbiegi	11.11	415	-2	11.14	416	-2
San Lawrenz Hotel	11.11	415	-2	11.14	416	-2
San Lawrenz	11.11	415	-2	11.14	416	-2

Table B.2.2 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario B in Option 2

B.2.3 Steady-State Voltage Results for Scenario C in Option 2

Substation Name	Voltage on the 11kV busbar (kV)	Voltage on the 400V busbar (V)	Transformer Tap Position (%)
Qala D.C	11.12	/	-1
Ghajnsielem Palma	10.94	416	-1
Victoria Ghonq	10.53	400	-1
Victoria Mental	10.51	398	-1
Victoria Hospital	10.46	397	-1
Victoria	10.42	394	-1
Fontana Fontanella	10.38	396	-1
Victoria Kercem Rd.	10.33	388	-1
Ghasri B/H	10.33	389	-1
Kercem	10.3	389	-1
Wind Farm Collector Switch-Room	10.27	/	/
Kercem Tat-Taljana	10.26	377	-2
Kercem VOR Beacon	10.25	377	-2
Kercem St.Lucy	10.25	377	-2
Kercem San Niklaw Res.	10.25	376	-2
San Lawrenz Ta' Dbiegi	10.24	382	-2
San Lawrenz Hotel	10.24	382	-2
San Lawrenz	10.24	382	-2

Table B.2.3 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario C in Option 2

B.3 Wind Farm Connected with the Grid as in Option 3

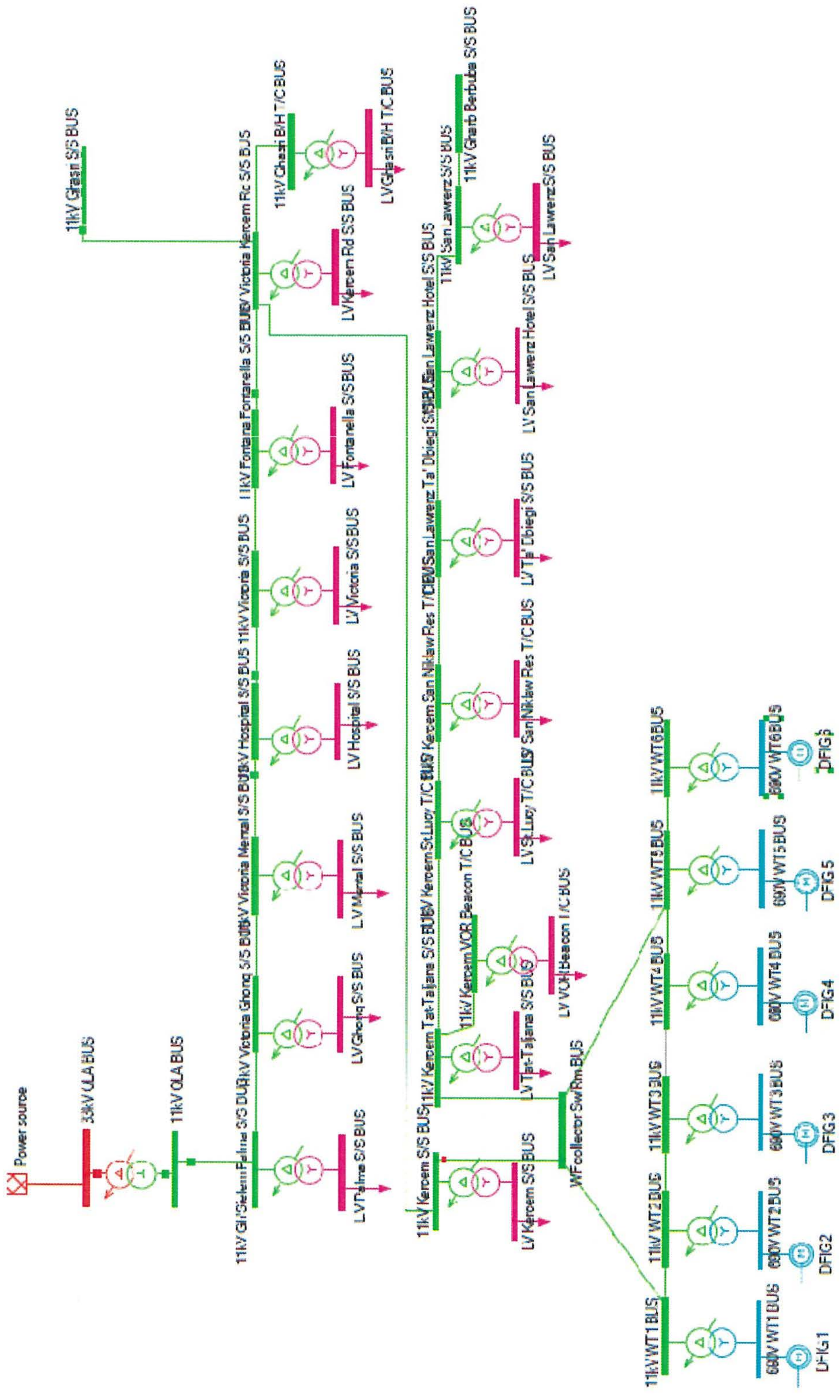


Figure B.3 - Snapshot from IPSA+ of the modelled Kerċem wind farm for connection option 3

B.3.1 Steady-State Voltage Results for Scenario A in Option 3

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Qala D.C	11.12	/	-1	11.28	/	-1
Ghajnsielem Palma	11.19	429	-1	11.4	437	-1
Victoria Ghonq	11.37	425	-2	11.7	438	-2
Victoria Mental	11.39	426	-2	11.72	439	-2
Victoria Hospital	11.41	427	-2	11.76	440	-2
Victoria	11.45	428	-2	11.82	442	-2
Fontana Fontanella	11.48	430	-2	11.86	444	-2
Victoria Kercem Rd.	11.54	432	-2	11.94	447	-2
Ghasri B/H	11.54	432	-2	11.94	447	-2
Kercem	11.59	434	-2	12.02	450	-2
Wind Farm Collector Switch-Room	11.65	/	/	12.1	/	/
Kercem Tat-Taljana	11.65	436	-2	12.1	453	-2
Kercem VOR Beacon	11.65	436	-2	12.1	453	-2
Kercem St.Lucy	11.65	436	-2	12.1	453	-2
Kercem San Niklaw Res.	11.64	436	-2	12.1	453	-2
San Lawrenz Ta' Dbiegi	11.64	436	-2	12.09	453	-2
San Lawrenz Hotel	11.64	436	-2	12.09	453	-2
San Lawrenz	11.64	436	-2	12.09	453	-2

Table B.3.1 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario A in Option 3

B.3.2 Steady-State Voltage Results for Scenario B in Option 3

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Qala D.C	11.13	/	-1	11.27	/	-1
Ghajnsielem Palma	11.19	429	-1	11.37	436	-1
Victoria Ghonq	11.33	424	-2	11.6	434	-2
Victoria Mental	11.34	424	-2	11.62	435	-2
Victoria Hospital	11.36	425	-2	11.65	436	-2
Victoria	11.39	426	-2	11.7	438	-2
Fontana Fontanella	11.42	427	-2	11.73	439	-2
Victoria Kercem Rd.	11.46	429	-2	11.8	442	-2
Ghasri B/H	11.46	429	-2	11.8	441	-2
Kercem	11.51	431	-2	11.86	444	-2
Wind Farm Collector Switch-Room	11.55	/	/	11.93	/	/
Kercem Tat-Taljana	11.55	432	-2	11.93	447	-2
Kercem VOR Beacon	11.55	432	-2	11.93	446	-2
Kercem St.Lucy	11.55	432	-2	11.93	446	-2
Kercem San Niklaw Res.	11.55	432	-2	11.93	446	-2
San Lawrenz Ta' Dbiegi	11.54	432	-2	11.92	446	-2
San Lawrenz Hotel	11.54	432	-2	11.92	446	-2
San Lawrenz	11.54	432	-2	11.92	446	-2

Table B.3.2 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario B in Option 3

B.3.3 Steady-State Voltage Results for Scenario C in Option 3

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Qala D.C	11.32	/	0	11.2	/	-1
Ghajnsielem Palma	11.27	429	-1	11.21	427	-1
Victoria Ghonq	11.18	415	-2	11.25	418	-2
Victoria Mental	11.17	414	-2	11.25	417	-2
Victoria Hospital	11.17	414	-2	11.26	417	-2
Victoria	11.17	414	-2	11.28	418	-2
Fontana Fontanella	11.19	417	-2	11.31	422	-2
Victoria Kercem Rd.	11.21	412	-2	11.36	417	-2
Ghasri B/H	11.2	413	-2	11.35	419	-2
Kercem	11.24	415	-2	11.42	422	-2
Wind Farm Collector Switch-Room	11.29	/	/	11.5	/	/
Kercem Tat-Taljana	11.29	417	-2	11.49	424	-2
Kercem VOR Beacon	11.28	416	-2	11.49	424	-2
Kercem St.Lucy	11.28	416	-2	11.49	424	-2
Kercem San Niklaw Res.	11.28	415	-2	11.48	423	-2
San Lawrenz Ta' Dbiegi	11.27	421	-2	11.48	429	-2
San Lawrenz Hotel	11.27	421	-2	11.48	429	-2
San Lawrenz	11.27	421	-2	11.48	429	-2

Table B.3.3 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario C in Option 3

B.3.4 Steady-State Voltage Results for Scenario D in Option 3

Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Qala D.C	11.12	/	-1
Ghajnsielem Palma	10.94	416	-1
Victoria Ghonq	10.53	391	-2
Victoria Mental	10.51	388	-2
Victoria Hospital	10.46	387	-2
Victoria	10.42	385	-2
Fontana Fontanella	10.38	387	-2
Victoria Kercem Rd.	10.33	378	-2
Ghasri B/H	10.33	380	-2
Kercem	10.31	379	-2
Wind Farm Collector Switch-Room	10.29	/	/
Kercem Tat-Taljana	10.28	378	-2
Kercem VOR Beacon	10.27	378	-2
Kercem St.Lucy	10.28	378	-2
Kercem San Niklaw Res.	10.27	377	-2
San Lawrenz Ta' Dbiegi	10.27	383	-2
San Lawrenz Hotel	10.26	383	-2
San Lawrenz	10.26	383	-2

Table B.3.4 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario D in Option 3

B.4 Wind Farm Connected with the Grid as in Option 4

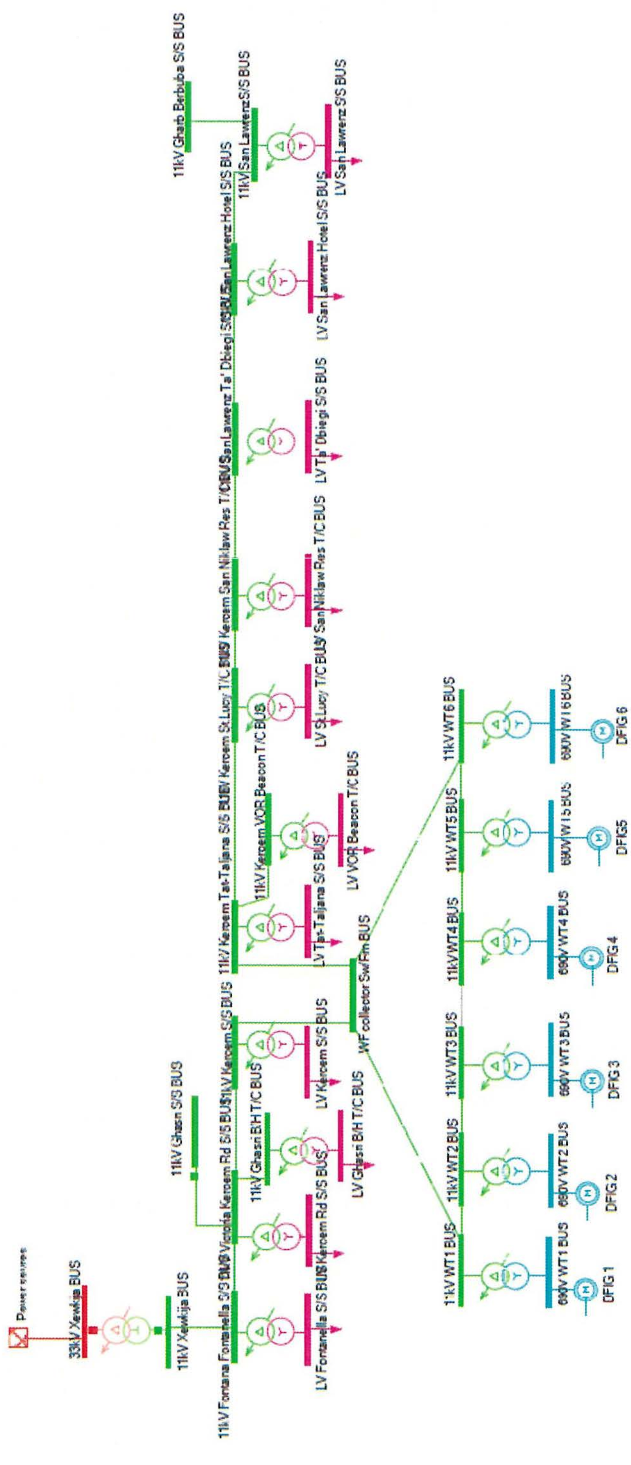


Figure B.4 - Snapshot from IPSA+ of the modelled Kerċem wind farm for Connection Option 4

B.4.1 Steady-State Voltage Results for Scenario A in Option 4

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Xewkija D.C	11.12	/	-1	11.29	/	-1
Fontana Fontanella	11.26	432	-1	11.49	430	-2
Victoria Kercem Rd.	11.32	434	-1	11.57	433	-2
Ghasri B/H	11.32	434	-1	11.57	433	-2
Kercem	11.37	436	-1	11.65	436	-2
Wind Farm Collector Switch-Room	11.42	/	/	11.71	/	/
Kercem Tat-Taljana	11.42	438	-1	11.71	438	-2
Kercem VOR Beacon	11.42	438	-1	11.71	438	-2
Kercem St.Lucy	11.42	437	-1	11.71	438	-2
Kercem San Niklaw Res.	11.41	437	-1	11.7	438	-2
San Lawrenz Ta' Dbiegi	11.41	437	-1	11.7	438	-2
San Lawrenz Hotel	11.41	437	-1	11.7	438	-2
San Lawrenz	11.41	437	-1	11.7	438	-2

Table B.4.1 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario A in Option 4

B.4.2 Steady-State Voltage Results for Scenario B in Option 4

Substation Name	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
	Voltage on the 11kV busbar (kV)	Voltage on the 400V busbar (V)	Transformer Tap Position (%)	Voltage on the 11kV busbar (kV)	Voltage on the 400V busbar (V)	Transformer Tap Position (%)
Xewkija D.C	11.36	/	0	11.25	/	-1
Fontana Fontanella	11.4	436	-1	11.35	434	-1
Victoria Kercem Rd.	11.42	431	-1	11.4	430	-1
Ghasri B/H	11.42	432	-1	11.39	431	-1
Kercem	11.46	434	-1	11.46	434	-1
Wind Farm Collector Switch-Room	11.5	/	/	11.52	/	/
Kercem Tat-Taljana	11.49	435	-1	11.5	436	-1
Kercem VOR Beacon	11.48	434	-1	11.5	435	-1
Kercem St.Lucy	11.49	434	-1	11.5	435	-1
Kercem San Niklaw Res.	11.48	434	-1	11.49	434	-1
San Lawrenz Ta' Dbiegi	11.48	439	-1	11.49	440	-1
San Lawrenz Hotel	11.47	439	-1	11.49	440	-1
San Lawrenz	11.47	439	-1	11.49	440	-1

Table B.4.2 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario B in Option 4

B.4.3 Steady-State Voltage Results for Scenario C in Option 4

Substation Name	Voltage on the 11kV busbar (kV)	Voltage on the 400V busbar (V)	Transformer Tap Position (%)
Xewkija D.C	11.17	/	+2.5
Fontana Fontanella	11.04	421	+2.5
Victoria Kercem Rd.	10.99	414	+2.5
Ghasri B/H	10.98	415	+2.5
Kercem	10.96	415	+2.5
Wind Farm Collector Switch-Room	10.95	/	/
Kercem Tat-Taljana	10.94	413	+2.5
Kercem VOR Beacon	10.93	413	+2.5
Kercem St.Lucy	10.93	413	+2.5
Kercem San Niklaw Res.	10.93	412	+2.5
San Lawrenz Ta' Dbiegi	10.92	418	+2.5
San Lawrenz Hotel	10.92	418	+2.5
San Lawrenz	10.92	418	+2.5

Table B.4.3 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario C in Option 4

Appendix C Proposed Wind Farm at Wied Rini, Malta

C.1 Wind Farm Connected with the Grid as in Option 1

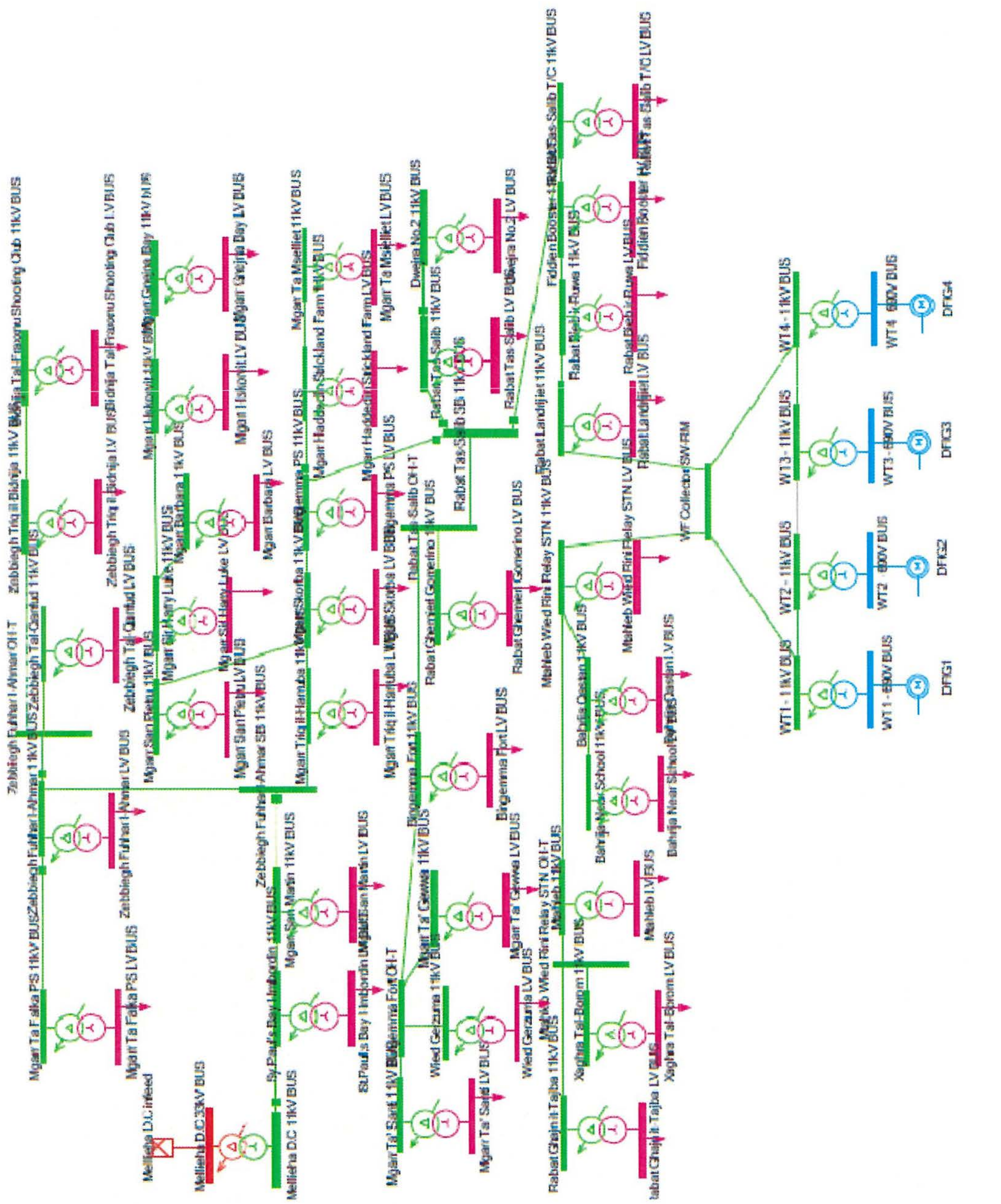


Figure C.1 - Snapshot from IPSA+ of the modelled Wied Rini wind farm for Connection Option 1

C.1.1 Steady-State Voltage Results for Scenario A in Option 1

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Mellieha D.C	11.09	/	-1	11.31	/	-1
St.Paul's Bay l-Imbordin	11.14	438	0	11.40	427	-2
Mgarr San Martin	11.20	430	-1	11.51	431	-2
Zebbiegh Fuhhar l-Ahmar	11.23	431	-1	11.56	433	-2
Zebbiegh Tal-Qanfud	11.23	431	-1	11.56	433	-2
Zebbiegh Triq il-Bidnija	11.23	431	-1	11.56	433	-2
Bidnija Tal-Fraxxnu Shooting Club	11.23	431	-1	11.56	433	-2
Mgarr Ta' Falka	11,23	431	-1	11.56	433	-2
Mgarr Triq il-Harruba	11.25	431	-1	11.58	434	-2
Mgarr Skorba	11.26	432	-1	11.61	435	-2
Mgarr San Pietru	11.25	432	-1	11.60	434	-2
Mgarr Sir Harry Luke	11.25	432	-1	11.59	434	-2
Mgarr Barbara	11.25	432	-1	11.59	434	-2
Mgarr l-Iskorvit	11.25	431	-1	11.59	434	-2
Mgarr Gnejna	11.25	431	-1	11.59	434	-2

Bay						
Bingemma PS	11.31	434	-1	11.67	437	-2
Mgarr Haddedin Strickland Farm	11.30	432	-1	11.67	436	-2
Mgarr Ta' Mselliet	11.30	433	-1	11.67	437	-2
Rabat Tas-Salib	11.34	435	-1	11.73	439	-2
Dwejra No.2	11.34	435	-1	11.73	439	-2
Rabat Ghemieri Gomerino	11.34	435	-1	11.73	439	-2
Bingemma Fort	11.34	435	-1	11.72	439	-2
Mgarr Ta' Gewwa	11.39	435	-1	11.72	439	-2
Wied Gerzuma	11.39	435	-1	11.72	439	-2
Mgarr Ta' Santi	11.34	434	-1	11.72	438	-2
Rabat Tas-Salib T/C	11.37	436	-1	11.77	440	-2
Fiddien Booster	11.42	438	-1	11.83	443	-2
Rabat Bieb ir-Ruwa	11.48	430	-2	11.93	447	-2
Rabat l-Andrijiet	11.58	433	-2	12.06	452	-2
Wind Farm Collector Sw/Rm	11.68	/	/	12.18	/	/
Mtahleb Wied Rini Relay Stn	11.68	437	-2	12.18	456	-2
Bahrija Qastan	11.67	437	-2	12.17	456	-2
Bahrija Near School	11.67	437	-2	12.17	456	-2
Mtahleb	11.68	437	-2	12.18	456	-2
Xaghra tal-Borom	11.68	436	-2	12.18	455	-2
Rabat	11.68	436	-2	12.18	455	-2

Ghajn it-Tajba		

Table C.1.1 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario A in Option 1

C.1.2 Steady-State Voltage Results for Scenario B in Option 1

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Mellieha D.C	11.09	/	-1	11.05	/	-2
St.Paul's Bay l-Imbordin	11.14	438	0	11.14	427	-1
Mgarr San Martin	11.20	430	-1	11.25	431	-1
Zebbiegh Fuhhar l-Ahmar	11.23	431	-1	11.30	434	-1
Zebbiegh Tal-Qanfud	11.23	431	-1	11.30	433	-1
Zebbiegh Triq il-Bidnija	11.23	431	-1	11.30	433	-1
Bidnija Tal-Fraxxnu Shooting Club	11.23	431	-1	11.30	433	-1
Mgarr Ta' Falka	11,23	431	-1	11.30	433	-1
Mgarr Triq il-Harruba	11.25	431	-1	11.32	434	-1
Mgarr Skorba	11.26	432	-1	11.34	435	-1
Mgarr San Pietru	11.25	432	-1	11.34	424	-2
Mgarr Sir Harry	11.25	432	-1	11.33	424	-2

Luke						
Mgarr Barbara	11.25	432	-1	11.33	424	-2
Mgarr l-Iskorvit	11.25	431	-1	11.33	424	-2
Mgarr Gnejna Bay	11.25	431	-1	11.33	424	-2
Bingemma PS	11.31	434	-1	11.41	438	-1
Mgarr Haddedin Strickland Farm	11.30	432	-1	11.41	426	-2
Mgarr Ta' Mselliet	11.30	433	-1	11.41	427	-2
Rabat Tas-Salib	11.34	435	-1	11.47	429	-2
Dwejra No.2	11.34	435	-1	11.47	429	-2
Rabat Ghemieri Gomerino	11.34	435	-1	11.47	440	-1
Bingemma Fort	11.34	435	-1	11.47	440	-1
Mgarr Ta' Gewwa	11.39	435	-1	11.46	440	-1
Wied Gerzuma	11.39	435	-1	11.46	429	-2
Mgarr Ta' Santi	11.34	434	-1	11.46	439	-1
Rabat Tas-Salib T/C	11.37	436	-1	11.51	431	-2
Fiddien Booster	11.42	438	-1	11.57	433	-2
Rabat Bieb ir-Ruwa	11.48	430	-2	11.68	437	-2
Rabat l-Andrijiet	11.58	433	-2	11.81	442	-2
Wind Farm Collector Sw/Rm	11.68	/	/	11.93	/	/
Mtahleb Wied Rini Relay Stn	11.68	437	-2	11.93	447	-2
Bahrija Qastan	11.67	437	-2	11.92	446	-2

Bahrija Near School	11.67	437	-2	11.92	446	-2
Mtahleb	11.68	437	-2	11.93	447	-2
Xaghra tal-Borom	11.68	436	-2	11.93	446	-2
Rabat Ghajn it-Tajba	11.68	436	-2	11.93	457	-1

Table C.1.2 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario B in Option 1

C.1.3 Steady-State Voltage Results for Scenario C in Option 1

	Wind Farm running at 0.95 leading power factor			**Wind Farm running at 0.95 lagging power factor**		
Substation Name	**Voltage in the 11kV busbar (kV)**	**Voltage in the 400V busbar (V)**	**Transformer Tap Position**	**Voltage in the 11kV busbar (kV)**	**Voltage in the 400V busbar (V)**	**Transformer Tap Position**
Mellieha D.C	11.12	/	-1	11.02	/	-2
St.Paul's Bay l-Imbordin	11.15	438	0	11.08	436	0
Mgarr San Martin	11.19	429	-1	11.16	428	-1
Zebbiegh Fuhhar l-Ahmar	11.21	430	-1	11.19	429	-1
Zebbiegh Tal-Qanfud	11.21	430	-1	11.19	429	-1
Zebbiegh Triq il-Bidnija	11.21	430	-1	11.19	429	-1
Bidnija Tal-Fraxxnu Shooting Club	11.21	430	-1	11.19	429	-1
Mgarr Ta' Falka	11.21	430	-1	11.19	429	-1
Mgarr Triq il-	11.22	430	-1	11.21	430	-1

Harruba						
Mgarr Skorba	11.23	431	-1	11.22	430	-1
Mgarr San Pietru	11.22	430	-1	11.21	430	-1
Mgarr Sir Harry Luke	11.22	430	-1	11.21	430	-1
Mgarr Barbara	11.22	430	-1	11.21	430	-1
Mgarr l-Iskorvit	11.22	430	-1	11.21	430	-1
Mgarr Gnejna Bay	11.21	430	-1	11.21	430	-1
Bingemma PS	11.26	432	-1	11.27	432	-1
Mgarr Haddedin Strickland Farm	11.26	431	-1	11.27	431	-1
Mgarr Ta' Mselliet	11.26	432	-1	11.27	432	-1
Rabat Tas-Salib	11.29	433	-1	11.31	434	-1
Dwejra No.2	11.29	433	-1	11.31	434	-1
Rabat Ghemieri Gomerino	11.28	433	-1	11.31	434	-1
Bingemma Fort	11.28	433	-1	11.31	434	-1
Mgarr Ta' Gewwa	11.28	433	-1	11.31	434	-1
Wied Gerzuma	11.28	433	-1	11.31	434	-1
Mgarr Ta' Santi	11.28	432	-1	11.31	433	-1
Rabat Tas-Salib T/C	11.31	433	-1	11.34	435	-1
Fiddien Booster	11.34	435	-1	11.39	437	-1
Rabat Bieb ir-Ruwa	11.39	426	-2	11.47	429	-2
Rabat l-Andrijiet	11.46	429	-2	11.56	433	-2
Wind Farm	11.53	/	/	11.66	/	/

Collector Sw/Rm						
Mtahleb Wied Rini Relay Stn	11.53	432	-2	11.66	436	-2
Bahrija Qastan	11.52	431	-2	11.64	436	-2
Bahrija Near School	11.52	431	-2	11.64	436	-2
Mtahleb	11.53	432	-2	11.65	436	-2
Xaghra tal-Borom	11.53	431	-2	11.65	435	-2
Rabat Ghajn it-Tajba	11.53	431	-2	11.65	435	-2

Table C.1.3 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario C in Option 1

C.1.4 Steady-State Voltage Results for Scenario D in Option 1

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Mellieha D.C	11.34	/	0	11.28	/	-1
St.Paul's Bay l-Imbordin	11.31	430	-1	11.29	429	-1
Mgarr San Martin	11.28	430	-1	11.30	431	-1
Zebbiegh Fuhhar l-Ahmar	11.26	432	-1	11.31	433	-1
Zebbiegh Tal-Qanfud	11.26	430	-1	11.30	432	-1
Zebbiegh Triq il-Bidnija	11.25	430	-1	11.30	432	-1
Bidnija Tal-Fraxxnu Shooting	11.25	430	-1	11.30	432	-1

Club						
Mgarr Ta' Falka	11.26	431	-1	11.31	432	-1
Mgarr Triq il-Harruba	11.26	431	-1	11.32	433	-1
Mgarr Skorba	11.26	431	-1	11.32	433	-1
Mgarr San Pietru	11.23	429	-1	11.29	432	-1
Mgarr Sir Harry Luke	11.22	429	-1	11.29	432	-1
Mgarr Barbara	11.22	429	-1	11.28	432	-1
Mgarr l-Iskorvit	11.22	429	-1	11.28	431	-1
Mgarr Gnejna Bay	11.22	429	-1	11.28	431	-1
Bingemma PS	11.28	431	-1	11.37	434	-1
Mgarr Haddedin Strickland Farm	11.28	430	-1	11.36	434	-1
Mgarr Ta' Mselliet	11.27	431	-1	11.36	434	-1
Rabat Tas-Salib	11.30	432	-1	11.41	436	-1
Dwejra No.2	11.30	433	-1	11.41	437	-1
Rabat Ghemieri Gomerino	11.30	431	-1	11.40	435	-1
Bingemma Fort	11.29	431	-1	11.39	435	-1
Mgarr Ta' Gewwa	11.28	431	-1	11.39	435	-1
Wied Gerzuma	11.29	433	-1	11.39	437	-1
Mgarr Ta' Santi	11.29	430	-1	11.39	434	-1
Rabat Tas-Salib T/C	11.32	422	-2	11.44	427	-2
Fiddien Booster	11.35	424	-2	11.49	429	-2
Rabat Bieb ir-	11.40	426	-2	11.58	432	-2

Ruwa						
Rabat l-Andrijiet	11.47	428	-2	11.68	436	-2
Wind Farm Collector Sw/Rm	11.56	/	/	11.79	/	/
Mtahleb Wied Rini Relay Stn	11.56	431	-2	11.79	440	-2
Bahrija Qastan	11.50	430	-2	11.73	438	-2
Bahrija Near School	11.50	429	-2	11.73	438	-2
Mtahleb	11.55	431	-2	11.78	439	-2
Xaghra tal-Borom	11.55	430	-2	11.78	438	-2
Rabat Ghajn it-Tajba	11.55	430	-2	11.78	438	-2

Table C.1.4 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario D in Option 1

C.1.5 Steady-State Voltage Results for Scenario E in Option 1

	Wind Farm running at 0.95 leading power factor			**Wind Farm running at 0.95 lagging power factor**		
Substation Name	**Voltage in the 11kV busbar (kV)**	**Voltage in the 400V busbar (V)**	**Transformer Tap Position**	**Voltage in the 11kV busbar (kV)**	**Voltage in the 400V busbar (V)**	**Transformer Tap Position**
Mellieha D.C	11.06	/	-1	11.02	/	-2
St.Paul's Bay l-Imbordin	11.03	418	-1	11.03	418	-1
Mgarr San Martin	10.99	419	-1	11.04	421	-1
Zebbiegh Fuhhar l-Ahmar	10.97	420	-1	11.04	423	-1
Zebbiegh Tal-	10.97	419	-1	11.04	422	-1

Qanfud						
Zebbiegh Triq il-Bidnija	10.96	419	-1	11.03	422	-1
Bidnija Tal-Fraxxnu Shooting Club	10.96	419	-1	11.03	422	-1
Mgarr Ta' Falka	10.97	419	-1	11.04	422	-1
Mgarr Triq il-Harruba	10.97	419	-1	11.05	422	-1
Mgarr Skorba	10.97	419	-1	11.06	423	-1
Mgarr San Pietru	10.94	418	-1	11.02	421	-1
Mgarr Sir Harry Luke	10.93	418	-1	11.02	422	-1
Mgarr Barbara	10.93	418	-1	11.02	421	-1
Mgarr l-Iskorvit	10.93	417	-1	11.02	421	-1
Mgarr Gnejna Bay	10.93	417	-1	11.01	421	-1
Bingemma PS	10.99	420	-1	11.10	424	-1
Mgarr Haddedin Strickland Farm	10.99	419	-1	11.10	423	-1
Mgarr Ta' Mselliet	10.98	419	-1	11.09	424	-1
Rabat Tas-Salib	11.01	421	-1	11.14	426	-1
Dwejra No.2	11.01	422	-1	11.14	427	-1
Rabat Ghemieri Gomerino	11.01	420	-1	11.14	425	-1
Bingemma Fort	11.00	420	-1	11.13	425	-1
Mgarr Ta' Gewwa	10.99	420	-1	11.12	425	-1
Wied Gerzuma	11.00	421	-1	11.13	426	-1

Mgarr Ta' Santi	11.00	419	-1	11.13	424	-1
Rabat Tas-Salib T/C	11.03	411	-2	11.18	417	-2
Fiddien Booster	11.06	413	-2	11.23	420	-2
Rabat Bieb ir-Ruwa	11.11	415	-2	11.32	423	-2
Rabat l-Andrijiet	11.18	417	-2	11.42	427	-2
Wind Farm Collector Sw/Rm	11.27	/	/	11.53	/	/
Mtahleb Wied Rimi Relay Stn	11.27	421	-2	11.53	430	-2
Bahrija Qastan	11.21	419	-2	11.47	429	-2
Bahrija Near School	11.21	418	-2	11.47	428	-2
Mtahleb	11.26	420	-2	11.52	430	-2
Xaghra tal-Borom	11.26	419	-2	11.52	429	-2
Rabat Ghajn it-Tajba	11.26	419	-2	11.52	429	-2

Table C.1.5 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario E in Option 1

C.1.6 Steady-State Voltage Results for Scenario F in Option 1

Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Mellieha D.C	11.16	/	+2.5
St.Paul's Bay l-Imbordin	11.03	419	+2.5
Mgarr San Martin	10.87	415	+2.5
Zebbiegh Fuhhar l-Ahmar	10.81	414	+2.5
Zebbiegh Tal-Qanfud	10.80	413	+2.5
Zebbiegh Triq il-Bidnija	10.80	413	+2.5
Bidnija Tal-Fraxxnu Shooting	10.79	413	+2.5

Club			
Mgarr Ta' Falka	10.80	413	+2.5
Mgarr Triq il-Harruba	10.78	412	+2.5
Mgarr Skorba	10.76	411	+2.5
Mgarr San Pietru	10.73	410	+2.5
Mgarr Sir Harry Luke	10.72	410	+2.5
Mgarr Barbara	10.72	410	+2.5
Mgarr l-Iskorvit	10.72	409	+2.5
Mgarr Gnejna Bay	10.71	409	+2.5
Bingemma PS	10.72	410	+2.5
Mgarr Haddedin Strickland Farm	10.72	409	+2.5
Mgarr Ta' Mselliet	10.71	409	+2.5
Rabat Tas-Salib	10.69	409	+2.5
Dwejra No.2	10.69	409	+2.5
Rabat Ghemieri Gomerino	10.68	408	+2.5
Bingemma Fort	10.68	407	+2.5
Mgarr Ta' Gewwa	10.67	407	+2.5
Wied Gerzuma	10.68	409	+2.5
Mgarr Ta' Santi	10.68	407	+2.5
Rabat Tas-Salib T/C	10.68	398	+5
Fiddien Booster	10.66	398	+5
Rabat Bieb ir-Ruwa	10.63	397	+5
Rabat l-Andrijiet	10.59	395	+5
Wind Farm Collector Sw/Rm	10.56	/	/
Mtahleb Wied Rini Relay Stn	10.56	394	+5
Bahrija Qastan	10.49	392	+5
Bahrija Near School	10.49	391	+5
Mtahleb	10.55	393	+5
Xaghra tal-Borom	10.54	392	+5
Rabat Ghajn it-Tajba	10.54	392	+5

Table C.1.6 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario F in Option 1

C.2 Wind Farm Connected with the Grid as in Option 2

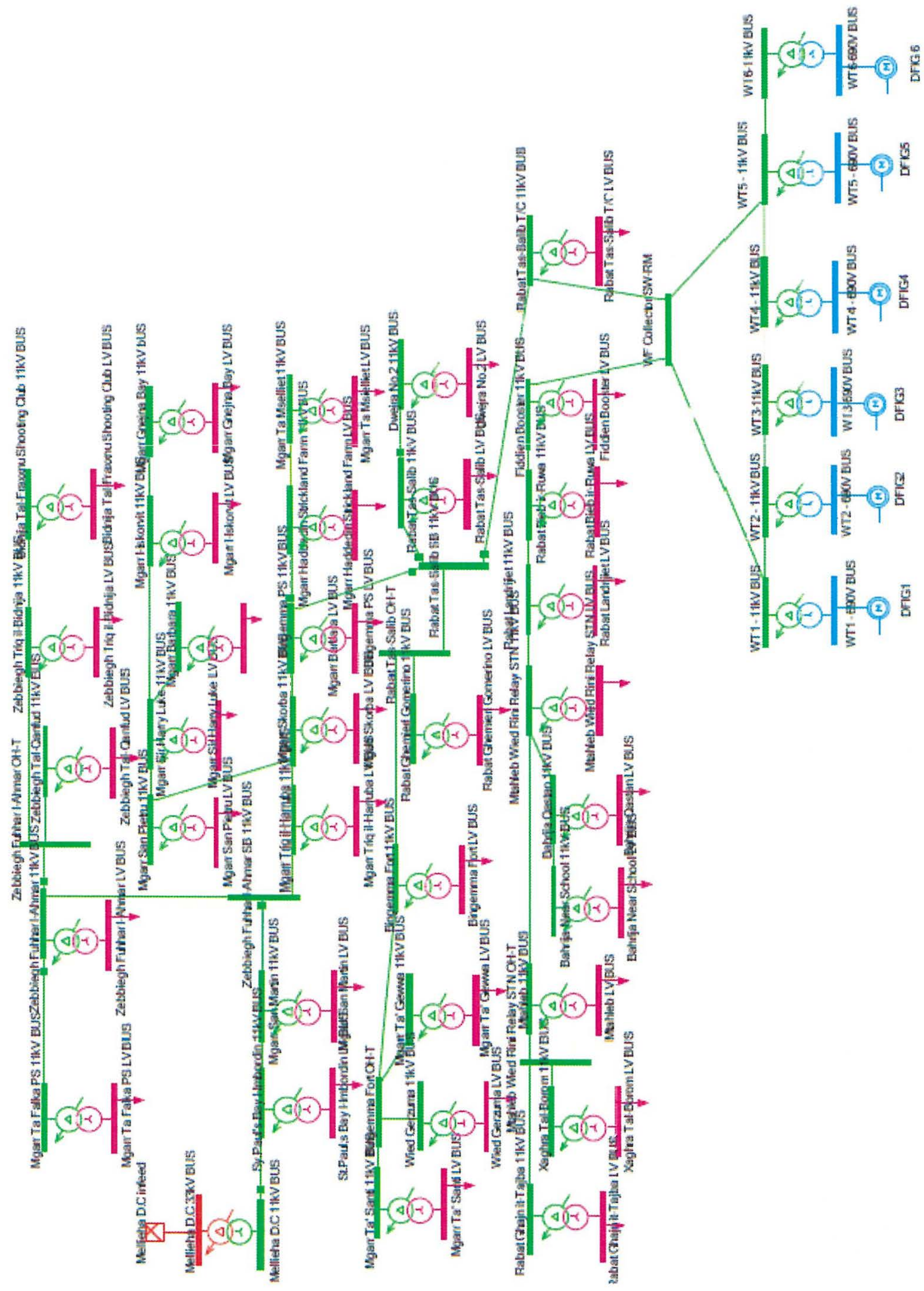


Figure C.2 - Snapshot from IPSA+ of the modelled Wied Rini wind farm for Connection Option 1

C.2.1 Steady-State Voltage Results for Scenario A in Option 2

	11kV busbar of Mellieha DC regulated within the bandwidth of 11.2kV			11kV busbar of Mellieha DC regulated within the bandwidth of 11.1kV		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Mellieha D.C	11.31	/	0	11.02	/	-1
St.Paul's Bay l-Imbordin	11.40	429	-2	11.12	439	0
Mgarr San Martin	11.52	433	-2	11.24	433	-1
Zebbiegh Fuhhar l-Ahmar	11.58	435	-2	11.29	435	-1
Zebbiegh Tal-Qanfud	11.57	435	-2	11.29	435	-1
Zebbiegh Triq il-Bidnija	11.57	435	-2	11.29	435	-1
Bidnija Tal-Fraxxnu Shooting Club	11.57	435	-2	11.29	435	-1
Mgarr Ta' Falka	11.57	435	-2	11.29	424	-2
Mgarr Triq il-Harruba	11.60	436	-2	11.32	436	-1
Mgarr Skorba	11.62	437	-2	11.34	437	-1
Mgarr San Pietru	11.61	437	-2	11.33	426	-2
Mgarr Sir Harry Luke	11.61	437	-2	11.33	426	-2
Mgarr Barbara	11.61	437	-2	11.33	426	-2
Mgarr l-Iskorvit	11.61	437	-2	11.33	426	-2
Mgarr Gnejna Bay	11.61	437	-2	11.33	426	-2
Bingemma PS	11.69	440	-2	11.41	429	-2
Mgarr Haddedin Strickland Farm	11.69	439	-2	11.41	428	-2

Mgarr Ta' Mselliet	11.69	440	-2	11.41	429	-2
Rabat Tas-Salib	11.76	442	-2	11.48	432	-2
Dwejra No.2	11.76	442	-2	11.48	431	-2
Rabat Ghemieri Gomerino	11.75	442	-2	11.47	431	-2
Bingemma Fort	11.75	442	-2	11.47	431	-2
Mgarr Ta' Gewwa	11.75	442	-2	11.47	431	-2
Wied Gerzuma	11.75	442	-2	11.47	431	-2
Mgarr Ta' Santi	11.75	441	-2	11.47	430	-2
Rabat Tas-Salib T/C	11.80	443	-2	11.52	433	-2
Fiddien Booster	11.85	446	-2	11.57	435	-2
Rabat Bieb ir-Ruwa	11.84	445	-2	11.57	435	-2
Rabat l-Andrijiet	11.84	445	-2	11.56	435	-2
Wind Farm Collector Sw/Rm	11.85	/	/	11.58	/	/
Mtahleb Wied Rini Relay Stn	11.83	445	-2	11.55	434	-2
Bahrija Qastan	11.81	444	-2	11.53	434	-2
Bahrija Near School	11.81	444	-2	11.53	434	-2
Mtahleb	11.82	445	-2	11.55	434	-2
Xaghra tal-Borom	11.82	444	-2	11.55	433	-2
Rabat Ghajn it-Tajba	11.82	444	-2	11.54	433	-2

Table C.2.1 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario A in Option 2

C.2.2 Steady-State Voltage Results for Scenario B in Option 2

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Mellieha D.C	11.04	/	-1	11.09	/	-2
St.Paul's Bay l-Imbordin	11.13	428	-1	11.23	432	-1
Mgarr San Martin	11.23	433	-1	11.40	439	-1
Zebbiegh Fuhhar l-Ahmar	11.28	435	-1	11.48	432	-2
Zebbiegh Tal-Qanfud	11.28	435	-1	11.48	431	-2
Zebbiegh Triq il-Bidnija	11.28	435	-1	11.48	431	-2
Bidnija Tal-Fraxxnu Shooting Club	11.28	435	-1	11.48	431	-2
Mgarr Ta' Falka	11.28	435	-1	11.48	432	-2
Mgarr Triq il-Harruba	11.31	436	-1	11.51	433	-2
Mgarr Skorba	11.33	436	-1	11.54	434	-2
Mgarr San Pietru	11.32	436	-1	11.54	444	-1
Mgarr Sir Harry Luke	11.32	436	-1	11.53	444	-1
Mgarr Barbara	11.32	436	-1	11.53	444	-1
Mgarr l-Iskorvit	11.32	436	-1	11.53	444	-1
Mgarr Gnejna	11.32	436	-1	11.53	444	-1

Bay						
Bingemma PS	11.40	439	-1	11.64	438	-2
Mgarr Haddedin Strickland Farm	11.39	427	-2	11.64	437	-2
Mgarr Ta' Msselliet	11.39	428	-2	11.64	438	-2
Rabat Tas-Salib	11.46	431	-2	11.72	441	-2
Dwejra No.2	11.45	431	-2	11.73	441	-2
Rabat Ghemieri Gomerino	11.45	430	-2	11.72	441	-2
Bingemma Fort	11.45	430	-2	11.72	441	-2
Mgarr Ta' Gewwa	11.45	430	-2	11.72	441	-2
Wied Gerzuma	11.45	430	-2	11.72	441	-2
Mgarr Ta' Santi	11.45	430	-2	11.72	440	-2
Rabat Tas-Salib T/C	11.49	432	-2	11.78	443	-2
Fiddien Booster	11.55	434	-2	11.86	446	-2
Rabat Bieb ir-Ruwa	11.54	434	-2	11.85	445	-2
Rabat l-Andrijiet	11.53	434	-2	11.84	445	-2
Wind Farm Collector Sw/Rm	11.55	/	/	11.86	/	/
Mtahleb Wied Rini Relay Stn	11.52	433	-2	11.83	445	-2
Bahrija Qastan	11.50	433	-2	11.81	444	-2
Bahrija Near School	11.50	433	-2	11.81	444	-2
Mtahleb	11.52	433	-2	11.83	445	-2
Xaghra tal-Borom	11.52	432	-2	11.83	444	-2

Rabat Ghajn it-Tajba	11.52	432	-2	11.83	444	-2

Table C.2.2 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario B in Option 2

C.2.3 Steady-State Voltage Results for Scenario C in Option 2

	Wind Farm running at 0.95 leading power factor			**Wind Farm running at 0.95 lagging power factor**		
Substation Name	**Voltage in the 11kV busbar (kV)**	**Voltage in the 400V busbar (V)**	**Transformer Tap Position**	**Voltage in the 11kV busbar (kV)**	**Voltage in the 400V busbar (V)**	**Transformer Tap Position**
Mellieha D.C	11.29	/	0	11.34	/	-1
St.Paul's Bay l-Imbordin	11.30	429	-1	11.41	433	-1
Mgarr San Martin	11.32	432	-1	11.50	439	-1
Zebbiegh Fuhhar l-Ahmar	11.33	424	-2	11.54	432	-2
Zebbiegh Tal-Qanfud	11.33	423	-2	11.53	431	-2
Zebbiegh Triq il-Bidnija	11.32	423	-2	11.53	430	-2
Bidnija Tal-Fraxxnu Shooting Club	11.32	422	-2	11.53	430	-2
Mgarr Ta' Falka	11.33	423	-2	11.54	431	-2
Mgarr Triq il-Harruba	11.34	423	-2	11.56	432	-2
Mgarr Skorba	11.35	424	-2	11.58	432	-2
Mgarr San Pietru	11.32	422	-2	11.55	431	-2
Mgarr Sir	11.31	422	-2	11.54	431	-2

Harry Luke						
Mgarr Barbara	11.31	422	-2	11.54	431	-2
Mgarr l-Iskorvit	11.31	422	-2	11.54	430	-2
Mgarr Gnejna Bay	11.30	422	-2	11.54	430	-2
Bingemma PS	11.40	425	-2	11.66	435	-2
Mgarr Haddedin Strickland Farm	11.39	424	-2	11.66	434	-2
Mgarr Ta' Mselliet	11.39	425	-2	11.65	435	-2
Rabat Tas-Salib	11.44	427	-2	11.74	438	-2
Dwejra No.2	11.44	428	-2	11.74	439	-2
Rabat Ghemieri Gomerino	11.44	426	-2	11.73	437	-2
Bingemma Fort	11.43	426	-2	11.72	437	-2
Mgarr Ta' Gewwa	11.42	426	-2	11.72	437	-2
Wied Gerzuma	11.43	427	-2	11.72	438	-2
Mgarr Ta' Santi	11.43	425	-2	11.72	436	-2
Rabat Tas-Salib T/C	11.48	428	-2	11.79	440	-2
Fiddien Booster	11.52	430	-2	11.85	443	-2
Rabat Bieb ir-Ruwa	11.49	429	-2	11.82	442	-2
Rabat l-Andrijiet	11.46	428	-2	11.79	440	-2
Wind Farm Collector Sw/Rm	11.52	/	/	11.86	/	/
Mtahleb Wied Rini Relay Stn	11.43	426	-2	11.76	439	-2
Bahrija	11.37	425	-2	11.70	437	-2

Qastan						
Bahrija Near School	11.36	424	-2	11.70	437	-2
Mtahleb	11.42	426	-2	11.75	438	-2
Xaghra tal-Borom	11.42	425	-2	11.75	438	-2
Rabat Ghajn it-Tajba	11.41	425	-2	11.75	438	-2

Table C.2.3 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario C in Option 2

C.2.4 Steady-State Voltage Results for Scenario D in Option 2

	Wind Farm running at 0.95 leading power factor			Wind Farm running at 0.95 lagging power factor		
Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Mellieha D.C	11.00	/	-1	11.07	/	-2
St.Paul's Bay l-Imbordin	11.01	418	-1	11.15	423	-1
Mgarr San Martin	11.03	421	-1	11.24	429	-1
Zebbiegh Fuhhar l-Ahmar	11.04	413	-2	11.28	422	-2
Zebbiegh Tal-Qanfud	11.04	412	-2	11.28	421	-2
Zebbiegh Triq il-Bidnija	11.03	412	-2	11.27	421	-2
Bidnija Tal-Fraxxnu Shooting Club	11.03	412	-2	11.27	421	-2
Mgarr Ta' Falka	11.04	412	-2	11.28	421	-2
Mgarr	11.05	412	-2	11.30	422	-2

Triq il-Harruba						
Mgarr Skorba	11.06	413	-2	11.32	423	-2
Mgarr San Pietru	11.03	411	-2	11.29	421	-2
Mgarr Sir Harry Luke	11.02	411	-2	11.28	421	-2
Mgarr Barbara	11.02	411	-2	11.28	421	-2
Mgarr l-Iskorvit	11.02	411	-2	11.28	421	-2
Mgarr Gnejna Bay	11.01	411	-2	11.28	421	-2
Bingemma PS	11.11	414	-2	11.41	425	-2
Mgarr Haddedin Strickland Farm	11.10	413	-2	11.40	425	-2
Mgarr Ta' Mselliet	11.10	414	-2	11.39	425	-2
Rabat Tas-Salib	11.16	416	-2	11.48	428	-2
Dwejra No.2	11.16	417	-2	11.48	429	-2
Rabat Ghemieri Gomerino	11.15	415	-2	11.47	428	-2
Bingemma Fort	11.14	415	-2	11.47	427	-2
Mgarr Ta' Gewwa	11.14	415	-2	11.46	427	-2
Wied Gerzuma	11.14	417	-2	11.46	429	-2
Mgarr Ta' Santi	11.14	415	-2	11.47	427	-2
Rabat Tas-Salib T/C	11.19	417	-2	11.53	430	-2
Fiddien Booster	11.23	420	-2	11.60	433	-2
Rabat Bieb ir-Ruwa	11.20	418	-2	11.57	432	-2
Rabat l-Andrijiet	11.17	417	-2	11.54	431	-2
Wind	11.24	/	/	11.60	/	/

Farm Collector Sw/Rm						
Mtahleb Wied Rini Relay Stn	11.14	416	-2	11.51	430	-2
Bahrija Qastan	11.08	414	-2	11.45	428	-2
Bahrija Near School	11.08	413	-2	11.45	427	-2
Mtahleb	11.13	415	-2	11.50	429	-2
Xaghra tal-Borom	11.13	414	-2	11.50	428	-2
Rabat Ghajn it-Tajba	11.13	414	-2	11.50	428	-2

Table C.2.4 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario D in Option 2

C.2.5 Steady-State Voltage Results for Scenario E in Option 2

Substation Name	Voltage in the 11kV busbar (kV)	Voltage in the 400V busbar (V)	Transformer Tap Position
Mellieha D.C	11.16	/	-1
St.Paul's Bay l-Imbordin	11.03	418	-1
Mgarr San Martin	10.87	415	-1
Zebbiegh Fuhhar l-Ahmar	10.81	404	-2
Zebbiegh Tal-Qanfud	10.80	403	-2
Zebbiegh Triq il-Bidnija	10.80	403	-2
Bidnija Tal-Fraxxnu Shooting Club	10.80	403	-2
Mgarr Ta' Falka	10.80	403	-2
Mgarr Triq il-Harruba	10.78	402	-2
Mgarr Skorba	10.76	401	-2
Mgarr San Pietru	10.73	400	-2
Mgarr Sir Harry Luke	10.72	400	-2
Mgarr Barbara	10.72	400	-2
Mgarr l-Iskorvit	10.72	399	-2
Mgarr Gnejna Bay	10.71	399	-2
Bingemma PS	10.72	400	-2
Mgarr Haddedin Strickland Farm	10.72	399	-2
Mgarr Ta' Msalliet	10.71	399	-2

Rabat Tas-Salib	10.69	399	-2
Dwejra No.2	10.69	400	-2
Rabat Ghemieri Gomerino	10.69	398	-2
Bingemma Fort	10.68	398	-2
Mgarr Ta' Gewwa	10.67	398	-2
Wied Gerzuma	10.68	399	-2
Mgarr Ta' Santi	10.68	397	-2
Rabat Tas-Salib T/C	10.68	398	-2
Fiddien Booster	10.66	398	-2
Rabat Bieb ir-Ruwa	10.63	397	-2
Rabat l-Andrijiet	10.59	395	-2
Wind Farm Collector Sw/Rm	10.66	/	/
Mtahleb Wied Rini Relay Stn	10.56	394	-2
Bahrija Qastan	10.49	392	-2
Bahrija Near School	10.49	391	-2
Mtahleb	10.55	393	-2
Xaghra tal-Borom	10.55	392	-2
Rabat Ghajn it-Tajba	10.55	392	-2

Table C.2.5 - Voltage magnitudes resulting at the 11kV and LV busbars for Scenario E in Option 2

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