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Design and Integration of Distributed Generation Systems to Dongola Distribution Grid

تصميم وتوصيل أنظمة التوليد الموزع بشبكة توزيع دنقلا

A Project Submitted In Partial Fulfillment for the Requirements of the Degree of B.Sc. (Honor) In Electrical Engineering

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الآية

قال تعالى:

﴿ إِنَّ فِي خَلْقِ السَّمَاوَاتِ وَالأَرْضِ وَاخْتِلَافِ اللَّيْلِ وَالنَّهَارِ وَالْفُلْكِ الَّتِي تَجْرِى فِي الْبَحْرِ بِمَا يَنفَعُ النَّاسَ وَمَآ أَنزَلَ اللَّهُ مِنَ السَّمَاءِ مِن مَّاءٍ فَأَحْيَا بِهِ الأَرْضَ بَعْدَ مَوْتِهَا وَبَثَّ فِيهَا مِن كُلِّ دَآبَّةٍ وَتَصْرِيفِ الرِّيَحِ وَالسَّحَابِ الْمُسَخَّرِ بَيْنَ السَّمَآءِ وَالأَرْضِ لآيَتٍ لِّقَوْمٍ يَعْقِلُونَ ﴾

صدق الله العظيم

[سورة البقرة 164]

DEDICATION

Our peace and grace from Allah be upon him.

To the utmost knowledge lighthouse, to our greatest and most honored prophet Mohamed.

To our mothers, who are the most deserving of the people with good companionship and who accompanied us with their prayers at all times, to those under their feet Paradise.

To our fathers, who taught us life and that there is no impossible if we put our trust in Allah.

To those who have demonstrated to us what is the most beauty of life our brothers.

To the people who paved our way of science and knowledge all our teachers distinguished. To the taste of the most beauty moments with them and our friends.

ACKNOWLEDGEMENT

First and above all, we praise God, the almighty for providing us this opportunity, and granting us the capability to proceed successfully. Grateful for this opportunity, then all thanks and appreciation to our supervisor Dr. **Salah Aldeen Gasim Mohammed** for his patience and valuable advises in assisting us to complete this work.

Lastly thanks to everyone who helped us in this research, starting with all the employees in the General Administration of Renewable Energies, especially Engineer **Mona** and Engineer **Tariq Taj Al-Asfia** to all those who guided, helped and pray for us, without them we wouldn’t be able to reach this far.

ABSTRACT

There is a large and rapid increase in the demand for electricity which causes a lack of electricity supply from centralized generation. Centralized generation is characterized by several challenges including that a high power loss in both transmission and distribution lines, high maintain and operation costs and high emissions which increase the different pollution due to exhaust from fossil-fired gas or coal boilers plants. These limitations in terms of efficiency and environmental impacts have given rise to Distributed Generation (DG) options for researchers and policy makers.

Distributed Generation refers to any electric power production technology that is integrated within distribution systems, close to the point of use. DGs are connected to the medium or low voltage grid. There are several technologies of DG in the market. Some are conventional such as the diesel generators and some are new technologies such as renewable energies. Renewable energy is that clean, unpolluted, environmental friendly type of energy which is obtained from natural resources that exist every day and always well as earth exists, such as sun light and wind.

This project develops a study of the design of PV and wind DG systems to be implemented in Dongola Distribution grid at 11 kV. The study aims to find the parameters of the PV and the wind DG systems such that it can function correctly. In addition, it investigates the impact of integrating these DG systems directly with the existing grid.

In order to prove the design validity of the proposed system, models and simulations in PVSYST and ETAP programs will be established for a practical distribution grid. Real loads, solar and wind energies data will be used in the simulation models for more realistic design. The results obtained from the analysis will be presented, tabulated, and discussed throughout this work.

المستخلص

هناك زيادة كبيرة وسريعة في الطلب على الكهرباء مما يؤدي إلى نقص إمدادات الكهرباء من التوليد المركزي. يواجه التوليد المركزي العديد من التحديات بما في ذلك فقدان الطاقة العالية في كل من خطوط النقل والتوزيع ، وارتفاع تكاليف الصيانة والتشغيل والانبعاثات العالية التي تزيد من التلوث المختلف بسبب العادم من الغازات التي تعمل بالحرق الأحفوري أو محطات غلايات الفحم. أدت هذه القيود من حيث الكفاءة والتأثيرات البيئية إلى ظهور خيارات الجيل الموزع للباحثين وصانعي السياسات.

يشير مصطلح "التوليد الموزع "إلى أي تقنية إنتاج طاقة كهربائية مدمجة في أنظمة التوزيع ، بالقرب من نقطة الاستخدام وتكون متصلة بشبكة الجهد المتوسط أو المنخفض .هناك العديد من تقنيات التوليد الموزع في السوق,بعضها تقليدي مثل مولدات الديزل وبعضها تقنيات جديدة مثل الطاقات المتجددة . الطاقة المتجددة هي تلك الطاقة النظيفة غير الملوثة والصديقة للبيئة والتي يتم الحصول عليها من الموارد الطبيعية الموجودة كل يوم ودائمًا كما توجد الأرض ، مثل ضوء الشمس والرياح.

يقوم هذا المشروع بتطوير دراسة لتصميم أنظمة الطاقة الكهروضوئية وطاقة الرياح ليتم تنفيذها في شبكة توزيع دنقلا عند مستوى جهد 11 كيلو فولت .تهدف الدراسة إلى إيجاد معلمات الأنظمة الكهروضوئية وأنظمة التوليد الموزع للرياح بحيث تعمل بشكل صحيح .بالإضافة إلى ذلك ، فإنه يدرس تأثير دمج أنظمة التوليد الموزع مباشرة مع الشبكة الحالية.

من أجل إثبات صحة تصميم النظام المقترح ، سيتم إنشاء نماذج ومحاكاة في برامج PVSYST و ETAPلشبكة توزيع عملية .سيتم استخدام بيانات الأحمال الحقيقية والطاقة الشمسية وطاقة الرياح في نماذج المحاكاة لتصميم أكثر واقعية .سيتم عرض النتائج التي تم الحصول عليها من التحليل وجدولتها ومناقشتها خلال هذا العمل.

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LIST OF ABBREVIATIONS

Abbreviation	**Meaning**
DG	Distributed Generation
PV	Photovoltaic
IEEE	The Institute of Electrical and Electronics Engineers
DER	Distributed Energy Resources
PCU	Power Conditioning Unit
DC	Direct Current
AC	Alternating Current
SCIG	Squirrel Cage Induction Generator
WRIG	Wound Rotor Induction Generator
WRSG	Wound Rotor Generator
PMSG	Permanent Magnet Generator
DFIG	Doubly Fed Induction Generator
DFAG	Doubly Fed Asynchronous Generator
PVSYST	Photovoltaic System
ETAP	ElectricalTransient Analyzer Program
MPPT	Maximum Power Point Tracker
SG	Synchronous Generator
PU	Per Unit

LIST OF SYMBOLS

Symbols	**Meaning**
P	Active power
Q	Reactive power
N_{pv}	Number of PV panel
S_{array}	Area occupied by the PV modules
P_{design}	Power plant design capacity
S_{pv}	Product of multiplying the length [m] by the width [m] of the PV module selected.
$P_{\mathrm{M,STC}}$	PV module power rating
$V_{i,max}$	DC input maximum MPP voltage
$V_{i,min}$	DC input minimum MPP voltage
$V_{M,max}$	Maximum MPP voltage
$I_{DC,max}$	Maximum continuous current
$I_{M,max}$	Maximum MPP current
$N_{p,max}$	Number of PV modules connected in parallel
$N_{s,max}$	Number of PV modules in series
N_i	Number of necessary inverters
$P_{installed}$	Total installed capacity in the PV power plant
$N_{\mathrm{pv,final}}$	Total number of inverters
$S_{\mathrm{array,final}}$	Final area occupied by the PV modules
P	Turbine power coefficient
ρ	Air density
A	Rotor swept area
V	Mean wind speed
$\mathrm{C}p$	Power transmission coefficient

T_p	Total annual power produced
W	Wind turbine rated power
C	capacity factor

CHAPTER ONE

INTRODUCTION

1.1 Overview

Electricity has become the heart for the sustainable development of the town and nation's economy. Sudan electric power system has been increasing from time to time in terms of demand. The power generated mostly depend on hydropower with 70% share and thermal power with nearly 26% of the plants. These power plants are not sufficient to satisfy the people fundamental services of the country. Certain fundamental services that should be provided to particular community are electricity, water supply, communication, transportation, health care and education. Thus, supply of reliable electricity is prerequisite to cater this all services.

Provision of electric energy for consumers is mostly based on having centralized generation, which involves use of conventional generators. Then, the generated electricity is transmitted via a transmission line to sub stations where the voltage is step down before the electricity is distributed for energy consumption. However, the centralized generation is characterized by the following challenges including transmission and distribution losses and high cost of fossil fuels. Therefore, the Distributed Generators (DGs) have been adopted to overcome these challenges.

Distributed generation is one of the new trends in power systems used to support the increased energy demand. DG can be defined as the strategic use of small generation throughout the electricity utilities service area at or near the premises of utility customers and interconnected to the distribution or subtransmission system to lower the cost of service. DG systems offer solution to many of challenges like increased transmission and distribution costs, deregulation trends and heightened environmental concerns.

Technologies considered particularly, suited to DG systems are: Photovoltaic (PV) systems, wind turbine, micro-turbines, small hydro plants, biomass, reciprocating engines, gas turbines, fuel cells and batteries. With a country like Sudan that has vast areas of fertile land, abundance of minerals, water, winds and sunshine, many types of these energies become a valid option. PV and wind turbines are examples of renewable energy consumables as they need no fossil fuel to operate, PV utilizes the sun and wind turbines operate by the aid of wind.

Utilizing renewable resources is one of the new trends to generate useful energy in the form of electrical power. It is the major form of energy production required in the world nowadays. When mentioning renewable energy, PV and wind turbines have to be considered as they are the major renewable energy technologies. A PV system is a system consisting of large arrays that are formed of a number of solar cells, which are used in converting the solar energy to electricity. Solar cells are made of semiconducting materials such as silicon used to generate electricity by the aid of photons supplied to it by the sun.

Wind turbine is also one of the rapidly increasing technologies and its applications are also increasing in a vigorous manner .Wind turbines depend on the wind thus it has no emissions that are harmful to the environment; the only pollution form generated by large wind turbines is noise. Due to the economics of size, a large number of wind turbines are built in the same location, grouped together and interconnected together to medium voltage power collection systems. This group of wind turbines is now called a wind farm.

Wind turbines and PVs can be used as a DGs that is interconnected to the utility network. From the economical point of view, the technology of wind turbines edges the PV technology when used as a DG in distribution networks due to the higher initial costs of PV systems. But on the other hand, when considering the performance point of view, PV systems could overcome the technology of wind turbines if it is not an inverter type wind turbine, as inverter based DGs have less impacts on distribution networks. Anyway the penetration of a DG into an existing distribution network has a lot of impacts on the network but its advantages outweighs the drawbacks which forces the essential use of DGs.

1.2 Problem Statement

The centralized generation is characterized by several challenges including that the long distance between the generation and the load lead to losses in both transmission and distribution lines that reduces efficiency. Also, there is lack in electricity supply that reduces the reliability on the grid. There is a large and rapid increase in the demand for electricity. In addition, there is a gradual decline of non-renewable sources of energy (fossil fuels, gas, etc.), as these types of non-renewable energy sources will exhaust one day.

On other hand, centralized generation requires costly management of large infrastructures including high cost of installation and maintenance, high fixed operation and high expense for unserved energy. Also, these enormous plants are susceptible to unreliability and instability under unforeseeable events, and are often vulnerable to attacks. Furthermore, environmental impact of generation facilities in the city centers thus caused high emissions, which increase the different pollution due to exhaust from fossil-fired gas or coal boilers, or nuclear boilers plants.

1.3 Aim and Objectives

This project aims at designing and modeling a grid-connected PV/wind power generation systems to meet a certain part of the load requirement of a local grid, reduce losses and increase system reliability. The project also aims at determining the effect of connecting a PV/wind station to Dongola distribution system. The objectives those are set to fulfill the above aims are:

1) To design and modelling a 30MW PV power plant.

2) To design and modelling a 30MW wind power plant.
3) To determine percentages of PV/Wind share for least power loss.
4) To study the impact of connecting the PV/Wind systems to Dongola distribution system on the voltage profile and total power loss.

1.4 Methodology

The data had been collected for the proposed location from the Sudanese Electricity Distribution Company Ltd, General administration of renewable energies, the ministry of electricity and Dams report and recently published papers in the area.

Both simulation and analytical methods were used for designing the system. PVSYST software Simulation is used to perform the design of the PV power plant by determining the total number of PV modules, inverters and their arrangements. Analytical methods are used to design the wind power plant by calculating type and size of the wind turbine.

Simulation methods were used by ETAP and PVSYST softwares to determine the higher percentage between PV/Wind systems in the final DG system design based on comparison in voltage profile, total losses, load flow and yearly power supply. ETAP software is used to study the impact of this connection on voltage profile, total losses and load flow for the final system.

1.5 Project Layout

The rest of this project report is organized as following:

Chapter two described and explained PV/wind systems and their components, including the electric power grid, and distributed generation. This chapter reviewed distributed generation resource technologies, solar energy, photovoltaic system, and wind turbine. Impact of DG on power system grids is also reviewed.

Chapter three showed a full description of the methods used for PV and wind systems design and energy calculations. Power system studies is also described.

Chapter four presented the results of the design for the PV/wind power plants, percentages of PV/Wind share for least power loss and their connection to the Dongola distribution network impacts.

Chapter five concluded the work have been done and provided future recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter reviews available literature on distributed generation. Different types of renewable energy sources are reviewed but only certain technologies are applied in this project. Section 2.2 considers definition of the electric power grid. Section 2.3 provides a brief description of distributed generation and in section 2.4 a brief description of the different technologies of distributed generation are explained. Section 2.5 and 2.6 describe solar energy, the photovoltaic system and its modules technologies in detail. Also Section 2.7 describes wind energy and the types of turbines in detail. Finally, Section 2.8 reviews the impact of the distributed generation connected to the grid system.

2.2 The Electric Power Grid

An electric grid or power grid is an interconnected network for delivering electricity from producers to consumers. Moreover, today's power system is a complex interconnected network Figure 2.1 can be subdivided into major parts:

- Generating stations that produce electric power.
- Transmission that carry power from distance sources to demand centers.
- Distribution lines that connect individual consumers.

Electric power is currently generated via large central generators located in remote areas .The purpose of the overhead transmission network is to transfer electric energy from generating units at various locations to the distribution network. The distribution network is a medium to low voltage network that is connected to a high voltage transmission network through "step down" transformers each transformer feeds power to a number of feeders to which customers are connected either directly or through a distribution transformer which further steps down the voltage to the utilization level [1].

The most important goal in power system operation and planning is to continually provide reliable electric energy to customers. Meanwhile, the system must optimize the available resources to minimize the total system production cost subject to all kinds of constraints. Existing electrical energy distribution system in most of the countries is mainly dependent on the centralized generating plants. These plants are installed at distant locations from the load centers. Although these plants are able to fulfill the demand of the consumers but in some cases, during peak hours, generation of centralized power plant may be insufficient to fulfill the whole demand and here come the importance of DG, a DG can fulfill the extra demand during peak hours [2].

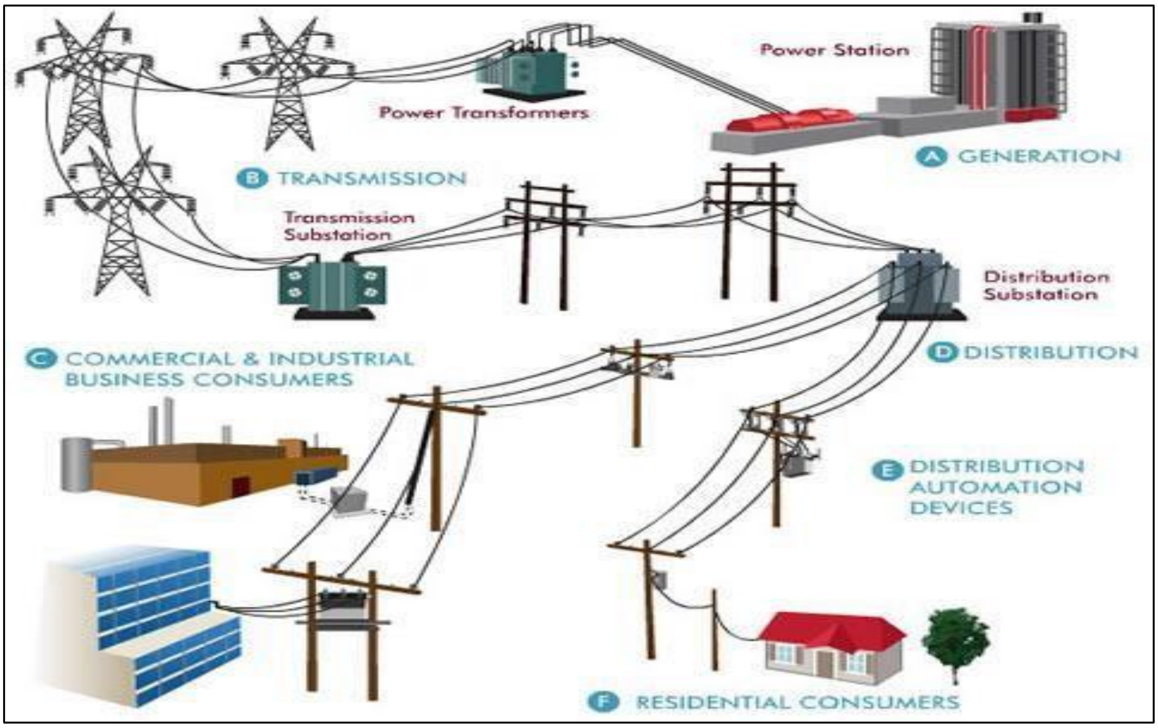


Figure 2.1: The electric power grid

2.3 Distributed Generation

Distributed Generation is not a new concept. A number of utility consumers have been using DG for decades. Over the last 20 years, the DG market has been somewhat turbulent. In the late 1990s, new Regulations/subsidies, such as net metering, renewable portfolio requirements and the development of new DG technologies. A power system with distributed generation, which is expected in the future, is shown in Figure 2.2.

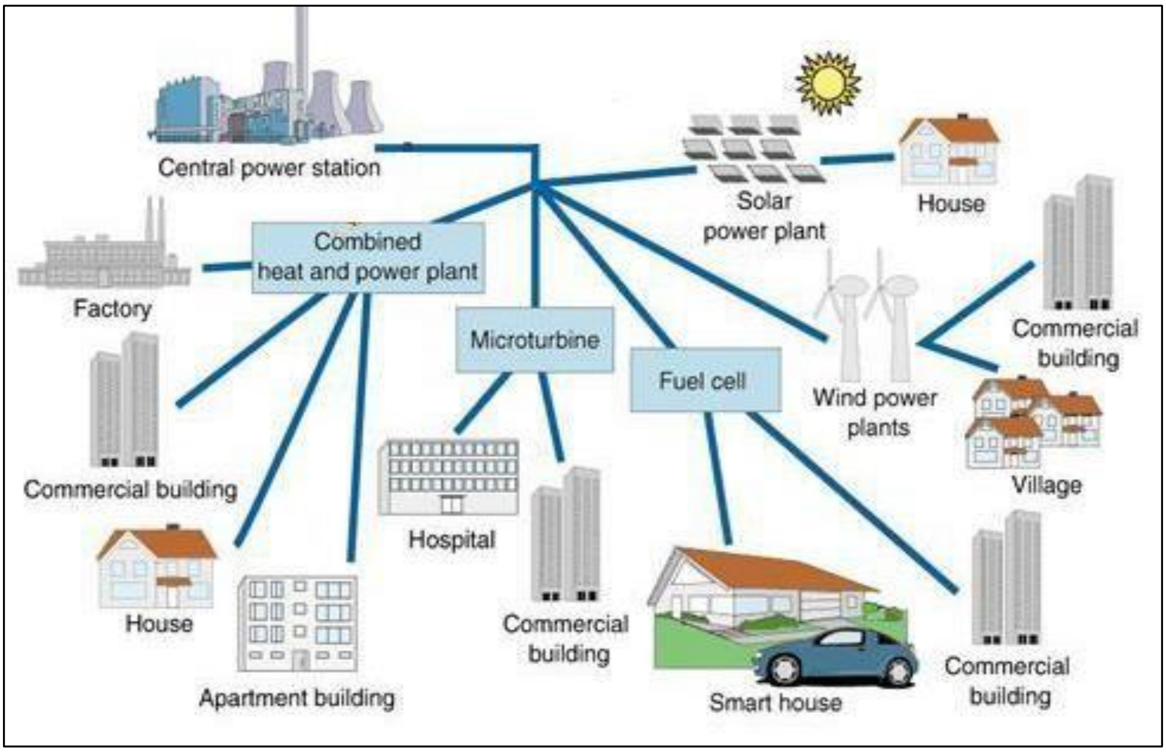


Figure 2.2: Power system with distributed generation

2.3.1 Concept

The term distributed generation or DG refers to any electric power production technology that is integrated within distribution systems, close to the point of use. DGs are connected to the medium or low voltage grid and it is a concept that existed years before. In the earlier days, energy was provided by steam, hydraulics, direct heating, cooling, light and the energy was produced near the device [3].

2.3.2 Definitions

Generally DG is defined on the basis of its size and its location but some countries define DG as having some basic characteristic (for example, using renewable, cogeneration, being non-dispatchable, etc.). The literature definitions for DG are not consistent but different terms and definitions are used for DG. Nevertheless, the following definition is generally agreed in the literature for DG:

- A simple definition has been provided by the European Commission as “a source of electric power connected to the distribution network or the customer side” [3].
- Also the International Council on Large Electricity Systems (CIGRE) has a Working Group on DG. It defined DG as “all generation units with a maximum capacity of 100MW usually connected to the distribution network that are neither centrally planned nor dispatched” [3].
- The Institute of Electrical and Electronics Engineers Inc. (IEEE) has defined DG as “the generating of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system” [3].

Further-more, in the literature, terms such as embedded generation, dispersed generation, distributed energy resources (DER) and decentralized generation, have also been used in the context of DG. The term dispersed generation is usually referred to a distributed power generation unit regardless of the technology and whether it is connected to the grid or completely independent of the grid [4]. Some categories that define the size of the generation unit are presented in Table 2.1.

Table 2.1: Size of the DG

Type	**Size**
Micro distributed generation	1 Watt < 5KW
Small distributed generation	5KW < 5MW
Medium distributed generation	5MW < 50MW
Large distributed generation	50MW < 300MW

2.4 Distributed Generation Resource Technologies

There are several technologies of DG in the market. Some are conventional such as the diesel generators, some are new technologies such as the micro-turbines and renewable energies, and some of the major DG technologies are:

2.4.1 Gas turbines

Gas turbines or power generation based on gas turbine technologies is common with very large generation capacities. Sizes of gas turbines vary from small gas turbines of 500KW and reaching the capacity of huge gas stations of 50MW. Gas turbines are very common due to low costs of their maintenance in addition to higher efficiency achieved due to the high ability for heat recovery. Gas turbines are the most favorite type for almost all distributed generation requirements [5].

2.4.2 Micro turbines

Micro turbines extend gas turbine technology to units of small size. It is a mechanism that uses the flow of a gas, to convert thermal energy into mechanical energy. The output voltage from micro-turbines cannot be connected directly to the power grid or utility, it has to be transferred to Direct Current (DC) and then converted back to Alternating Current (AC) in order to have the nominal voltage and frequency of the utility. The main advantage of micro-turbines is the clean operation with low emissions produced and good efficiency. On the other hand, its disadvantages are the high maintenance cost and the lack of experience in this field [6].

2.4.3 Fuel cell

The fuel cell is a device used to generate electric power and provide thermal energy from chemical energy through electrochemical processes. It supplies electricity by combining hydrogen and oxygen electrochemically without combustion. However, while the battery is a storage device for energy that is eventually used up and/or must be recharged. A single cell provides less than one volt, so a series of fuel cells are normally "stacked" one on another to increase the power output.

The basic fuel cell has two electrodes separated by an electrolyte. One of the electrodes (the anode) is supplied with the fuel (for example, hydrogen or natural gas). The second electrode (the cathode) is supplied with oxygen by simply pumping air in. fuel cells have their own advantages including high power efficiency and performance under variable loading values. Their emissions are very small and they cause no noise. A fuel cell also produces heat and water along with electricity but it has a high running cost, which is its major disadvantage [7].

2.4.4 Renewable energies

Green power is a new clean energy from renewable re-sources like; sun (solar energy system), wind (wind turbine), and water (small hydro-plants). Its electricity price is still higher than that of power generated from conventional oil sources.

2.5 Solar Energy

The sun is probably the most important source of renewable energy available today. Traditionally, the sun has provided energy for practically all living creatures on earth, through the process of photosynthesis. The solar energy is a highly familiar alternative clean energy type and solar energy is that energy which we get from the sun in form of radiation. Its convenient method to produce electricity and it has its own advantage and disadvantage, the advantages of solar systems are:

1. The main and most important advantage of solar systems is that their source of energy is infinite, charge free, and accessible all the time.

2. Solar energy is clean and environment friend, it is safe and cause minimal pollution.

3. Solar systems are the perfect choice to be implemented in remote areas as they are cheap and reliable compared to the creation of public grids infrastructures.

The most important drawback of solar energy resides in its initial costs if compared to other large-scale electrical power sources. However, in the last 10 years the costs of the solar energy have decreased to about 50% due to the use of new technologies in their production and development. In addition, another drawback of solar systems is the variable output power that is a function of the solar irradiation and temperature [8]. Solar energy can be used in two types of system; those that convert solar energy to DC power (photovoltaic technology) and those that convert solar energy to heat and steam to run turbines.

2.6 Photovoltaics System

Photovoltaic is the method of generating electrical power by converting solar radiation into direct current electricity using semiconductors and an effect called the photovoltaic effect. To generate electricity and make use of it using the photovoltaic effect, you will need an electrical device that does the conversion process of light into electricity called the photovoltaic cell; also, it called the solar cell [8].

2.6.1 PV cell

PV cells or solar cells, convert sunlight directly into electricity using the photovoltaic effect. These cells absorb solar energy from the sunlight where the light photons force cell electrons to flow and convert it to dc electricity that can be used directly in feeding some types of DC loads or converted through different converter types to feed other DC and AC loads. A typical silicon PV cell is composed of a thin wafer consisting of an ultra-thin layer of phosphorusdoped (N-type) silicon on top of a thicker layer of boron-doped (P-type) silicon, an electrical field is created near the top surface of the cell where these two materials are in contact, called the P-N junction [9].

PV cells are made from semiconductor materials, such as silicon and can be assembled into flat plate systems that can be mounted on rooftops or other sunny areas. They generate electricity with no moving parts, operate quietly with no emissions and require little maintenance . On the other hand, they need large spaces and the initial cost is high. When sunlight strikes the surface of a PV cell, this electrical field provides momentum and direction to lightstimulated electrons, resulting in a flow of current when the solar cell is connected to an electrical load as shown in Figure 2.3.

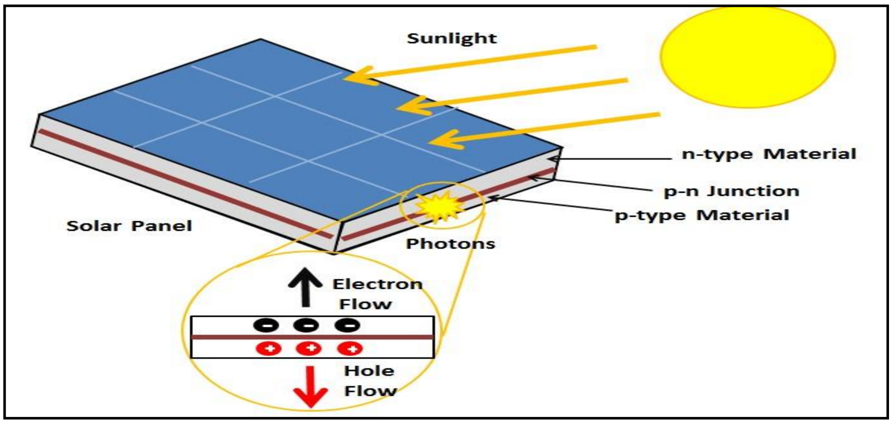


Figure 2.3: Photovoltaic effect

2.6.2 PV modules

For technical reasons, cells are connected to form a module or panel and modules are connected in series or in parallel to form an array to generate the required power and suitable voltage level as shown in Figure 2.4. PV module are available in the form of small rooftop residential systems (less than 10KW), medium- sized systems in the range of 10 to 100KW, and larger systems greater than 100KW connected to utility distribution feeders [8].

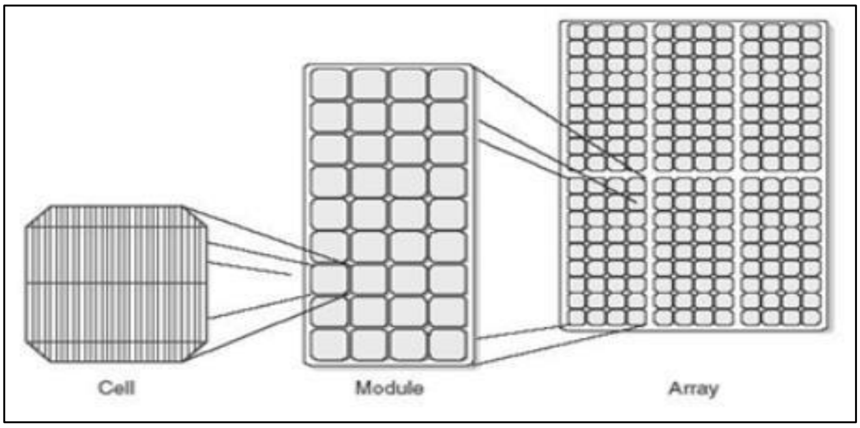


Figure 2.4: PV (cell-module-array)

2.6.3 PV modules technologies

There are many different PV modules technologies, nowadays research institutions are making efforts to discover new materials and designs with which the performance of the solar cells can be improved. The two major families of solar cells dominating the market are silicon crystalline and thinfilm technology.

a) Silicon crystalline

The first generation of PV modules exiting were silicon crystalline structure modules and it’s still the most used PV module technology .In the family of silicon crystalline structure can be found mono crystalline photovoltaic cells and poly-crystalline photovoltaic [10].

- Mono-crystalline

This is the oldest and most developed of the PV modules. Mono-crystalline panels as the name suggests are created from a single continuous crystal structure. A Mono-crystalline panel can be identified from the solar cells, which all appear as a single flat color. The manufacturing process required to produce monocrystalline silicon is complicated, resulting in slightly higher costs than other technologies. Figure 2.5 shows the mono-crystalline PV cell [10].

- Poly-crystalline

Also known as multicrystalline cells, poly-crystalline silicon cells are made from cells cut from an ingot of melted and recrystallized silicon. They are generally cheaper to produce than mono-crystalline cells, due to the simpler manufacturing process, but they tend to be slightly less efficient. Figure 2.5 shows poly-crystalline PV cell [10].

b) Thin film technology

Related to the effort to make PV technology less costly, and hence to make more economically viable projects, appears a new technology called thin-film solar cells [9]. Wolf and Lofersky discovered that by decreasing the cell thickness, open circuit voltage increases due to reduced saturation current and decreasing the geometry factor [10].

Thin-film technology consist on thin layers of a semiconductor material applied to a solid backing material. Using this technology, the amount of required material is reduced without compromising the lifespan of the photovoltaic cell or being hazardous for the environment. Additionally, the cost of production is also reduced due to the photovoltaic materials used are cheaper than those used for crystalline structures. Figure 2.5 shows solar module types. Moreover, in Table 2.2 show a comparison between various PV module types.

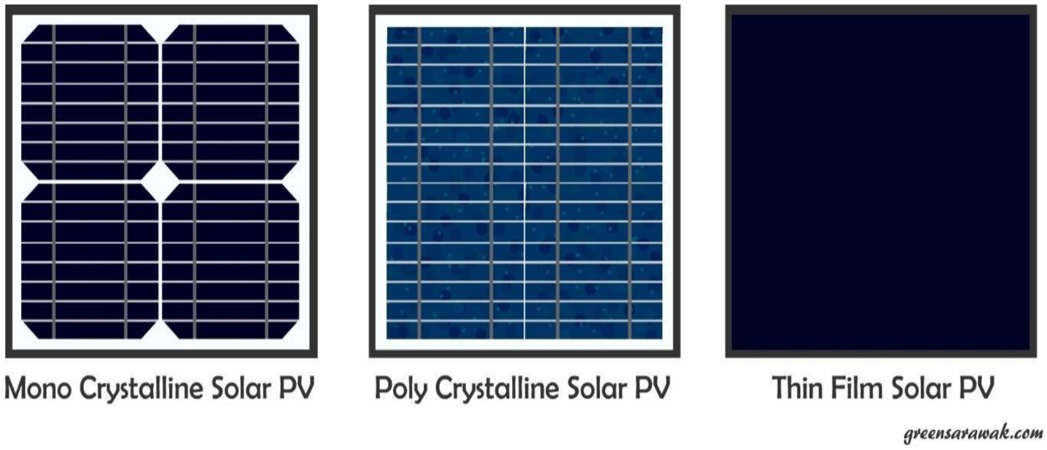


Figure 2.5: Solar module types

Table 2.2: Comparison between various PV module types

Type	Mono-Crystalline	Poly-Crystalline	Thin-Film
Efficiency	High efficiency performance (14-18%) cell efficiency	Lower efficiency (12-14%) cell efficiency	(5-6%) cell efficiency
Life Time	25 - 30 years	20 - 25 years	15 - 20 years
Cost	Higher cost	Lower cost	Lower cost
Area	Require least area for a given power	Require less area for a given power	Require large area for a given power

2.6.4 PV inverters

The PV inverter is the key element of grid-connected PV power systems. The main function is to convert the DC power generated by PV panels into grid-synchronized AC power. The input voltage, output voltage, frequency and overall power handing depend on the design of the specific device or circuitry, the inverter does not produce any power; the power is provided by the DC source.

Considering the classification based on the mode of operation, inverters can be classified into two broad categories:

i. Stand-alone inverters

It used in isolated systems where the inverter draws its DC energy from batteries charged by PV arrays. Many stand-alone inverters also incorporate integral battery chargers to recharge the battery from an AC source, when available.

ii. Grid-tie inverters

It used in the utility connection where it supply AC power which is synchronized in frequency, phase angle and voltage amplitude with the utility specifications, grid-tie inverters are designed to shut down automatically upon loss of utility supply, for safety reasons. They do not provide backup power during utility outages [11]. Inverters are also classified according to configuration topology by their connections between the PV modules and utility grid into two types of inverters; these are multiple string inverter and central inverter.

iii. Multi-string inverters

Multi string inverter topology is presented in Figure 2.6. Each group of panels or strings are connected together and fed to a suitable DC-AC inverter. The group of inverters are then connected individually and separately to the grid.

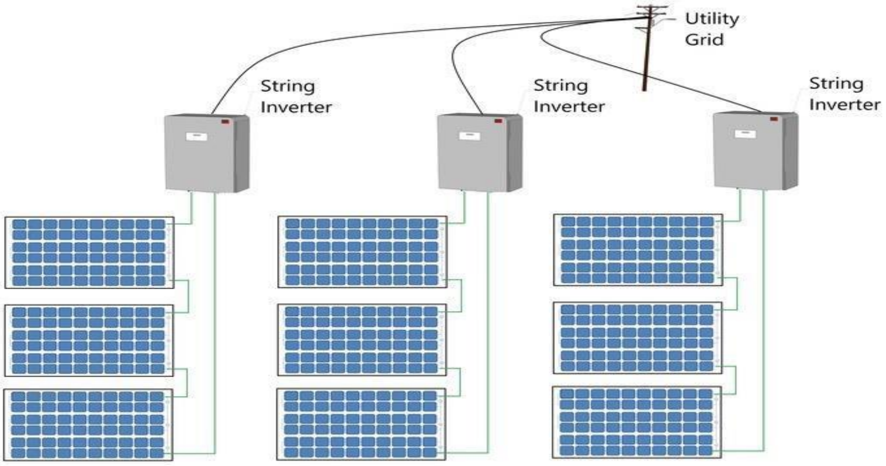


Figure 2.6: Multi-string inverters

The main advantage of this topology is the use of small size and rating inverters instead of using one large inverter in central topology. It also requires less maintenance in general than the other topology. The failure of one inverter in a string system causes the failure of a part of the system and not the whole system. Over more, the maintenance required will be considered for that one inverter and not for the whole system. However, the initial cost of string inverter based system is higher than the central inverter [8].

iv. Central inverter

Central inverters are the most used in power stations. Figure 2.7 shows the topology of the central inverter. Multiple PV strings are combined in a one DC box out of which one connection is fed to a high rated inverter. The DC connection of multiple strings implies that their tilt angle and generated power are the same. Central inverter requires less space and less initial costs compared to string inverters. However, the failure of the inverter causes the failure of the whole system [8].

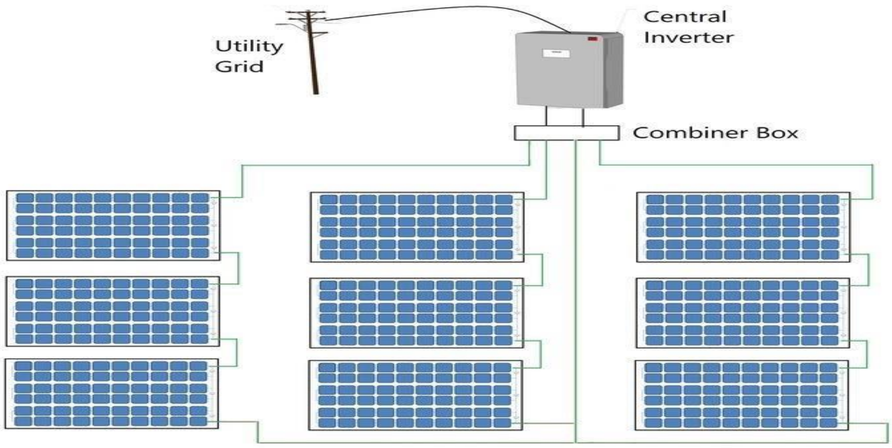


Figure 2.7: Central inverter

2.6.5 Grid-connected solar PV systems

Grid-connected or utility-interactive PV systems are designed to operate in parallel with and interconnected with the electric utility grid as shown in Figure 2.8. The primary component in grid-connected PV systems is the inverter, or Power Conditioning Unit (PCU). The PCU converts the DC power produced by the PV array into AC power consistent with the voltage and power quality requirements of the utility grid. Then automatically stops supplying power to the grid when the utility grid is not energized, the transformer is used to boost the voltage level that produced from the PV system to the distribution system level [12].

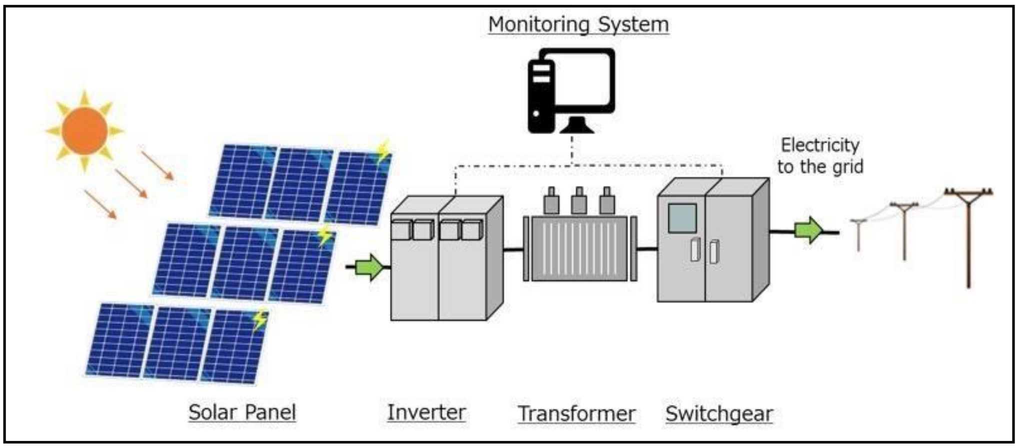


Figure 2.8: Grid connected solar PV system

2.7 Wind Turbine

When air flows then it is having some kinetic energy with it, which is known as wind energy. This kinetic energy is converted into mechanical energy by the wind turbine. Wind turbines can be manufactured in two basics groups: the horizontal- axis and the vertical-axis design. A horizontal axis machine has its blades rotating on an axis parallel to the ground, while vertical axis machine has its blades rotating on an axis perpendicular to the ground. There are several available designs for both and each type has certain advantages and disadvantages. However, Horizontal axis wind turbine is the most used wind turbine now days [13].

2.7.1 Wind turbines components

Modern wind energy systems consist of the following components Figure 2.9 [13]:

1. Tower: On which the wind turbine is mounted, the tower is tall in order to harness the wind at a greater velocity and to be free of turbulence caused by interference from obstacles such as trees, hills, and buildings.

2. Blades: Modern turbines typically use three blades. The blades need to be light and strong in order to be aerodynamically efficient and to withstand prolonged used in high winds.
3. Nacelle: This is the main structure of the turbine and the main turbine components are housed in this fiberglass structure.
4. Rotor: That is turned by the wind.
5. Generator: The generator is housed in the nacelle and converts the mechanical energy from the rotor to electrical energy.
6. Gearbox: This is housed in the nacelle although “direct drive” designs that do not require one are available. The gearbox converts the low-speed, hightorque rotation of the rotor to high-speed rotation (approximately 1500rpm) with low-torque for input to the generator.

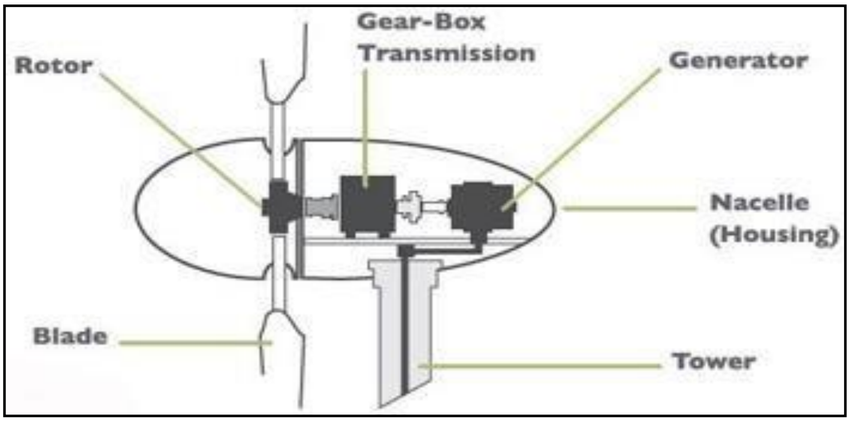


Figure 2.9: Wind turbine

2.7.2 Wind turbine operation

Wind turbines produce electricity by using the power of the wind to drive an electrical generator. Wind passes over the blades, generating lift and exerting a turning force. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases the rotational speed to that which is appropriate for the generator, which uses magnetic fields to convert the rotational energy into electrical energy. The power output goes to a transformer, which converts the electricity from the generator at around 700 to the appropriate voltage for the power collection system, typically 33KV [14].

2.7.3 Types of wind turbine

Wind turbine is having two types. One is fixed speed wind turbine and another one is variable wind turbine. Variable speed wind turbines are most used wind turbines now a days due to its advantages. It is characteristic of fixed-speed wind turbines that they are equipped with an induction generator that is directly connected to the grid, with a soft-starter and a capacitor bank for reducing reactive power compensation. They are designed to achieve maximum efficiency at one particular wind speed.

The fixed-speed wind turbine has the advantage of being simple, robust and reliable and well-proven. Moreover, the cost of its electrical parts is low. Its disadvantages are an uncontrollable reactive power consumption, mechanical stress and limited power quality control. Owing to its fixed-speed operation, all fluctuations in the wind speed are further transmitted as fluctuations in the mechanical torque and then as fluctuations in the electrical power on the grid.

Variable-speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. It has more complicated electrical system than that of a fixed-speed wind turbine. It is typically equipped with an induction or synchronous generator and connected to the grid through a power converter. The power converter controls the generator speed. The advantages of variable-speed wind turbines are an increased energy capture, improved power quality and reduced mechanical stress on the wind turbine. The disadvantages are losses in power electronics, the use of more components and the increased cost of equipment because of the power electronics [14].

2.7.4 Types of generators used in wind turbine system

Any types of three-phase generator can connect to with a wind turbine. Today, the demand for grid-compatible electric current can be met by connecting frequency converters, even if the generator supplies AC of variable frequency or DC. Several different types of generators, which are used in wind turbines, are as follows: Asynchronous (induction) generator and synchronous generator. Squirrel Cage Induction Generator (SCIG) and Wound Rotor Induction Generator (WRIG) are comes under asynchronous generators. Wound Rotor Generator (WRSG) and Permanent Magnet Generator (PMSG) are comes under synchronous generator.

a) Type 1 – Fixed speed induction generator :

It is the oldest and the simplest one, it is illustrated in Figure 2.10, it consists of a conventional direct grid coupled SCIG, which is coupled to the aerodynamic rotor through a speed increasing gearbox. Turbine speed is almost fixed to the electrical grid frequency and generates when a negative slip is created (shaft speed exceeds grid frequency). Because induction generators absorb a lot of reactive power when generating active power, type 1 generators are usually equipped with reactive power compensators (capacitors are often added in parallel to generate magnetizing currents) in the case of large wind turbines or weak grids and improving the power factor of the system[15].

In the case of a fault, SCIGs without any reactive power compensation system can lead to voltage instability on the grid. The wind turbine rotor may speed up, for instance, when a fault occurs, owing to the imbalance between the electrical and mechanical torque. Thus, when the fault is cleared, SCIGs draw a large amount of reactive power from the grid, which leads to a further decrease in voltage.

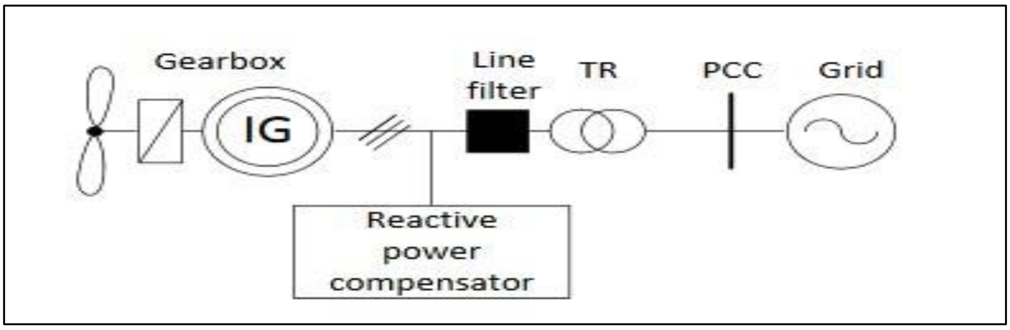


Figure 2.10: Type 1 SCIG

b) Type 2 – Variable-slip induction generator:

The slip feature allows generator to have a variable slip and to choose the optimum slip, resulting in smaller fluctuations in torque and power output. The variable slip is a very simple, reliable and cost effective way to achieve load reductions. Type 2 is similar to type 1 with regards to the machines stator circuit, but is equipped with a variable resistor in the wound rotor circuit. The advantages of this no need for slip rings and an improved operating speed range compared with the SCIG. However, it still requires a reactive power compensation system. The disadvantages include the speed range is typically limited to 0–10%,poor control of active and reactive power is achieved and the slip power is dissipated in the variable resistance as losses. The SCIG is shown in Figure 2.11.

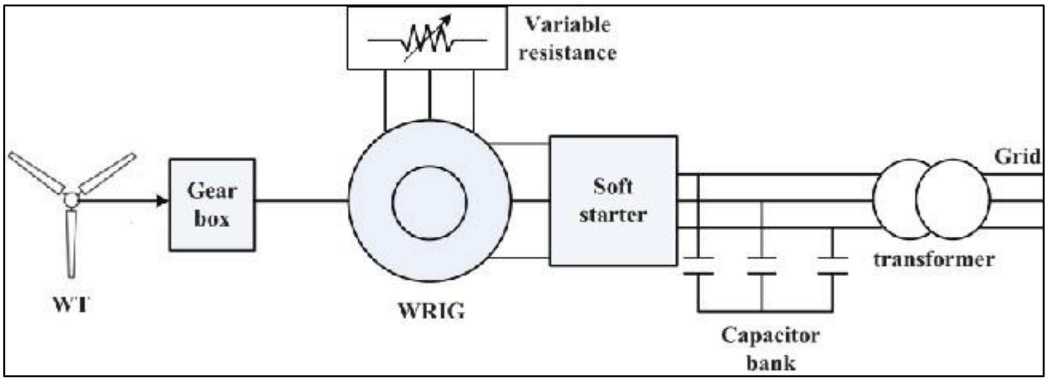


Figure 2.11: Type 2 WRIG

c) Type 3 – Doubly fed induction generator :

Type 3 turbine, known commonly as the Doubly Fed Induction Generator (DFIG) or Doubly Fed Asynchronous Generator (DFAG), DFIG wind turbines combine the designs of type 1 and type 2 with advances in power electronics. Variable frequency ac excitation is now added (instead of simply resistance) to the rotor circuit.

The additional rotor excitation is supplied via slip rings by a current regulated, voltage-source converter, which can adjust the rotor currents magnitude and phase nearly instantaneously. This rotor-side converter is connected back-to-back with a grid side converter, which exchanges power directly with the grid. See Figure 2.12. A small amount power injected into the rotor circuit can effect a large control of power in the stator circuit. This is a major advantage of the DFIG , a great deal of control of the output is available with the presence of a set of converters that typically are only 30% of the rating of the machine.

In addition to the real power that is delivered to the grid from the generator’s stator circuit, power is delivered to the grid through the grid connected inverter when the generator is moving faster than synchronous speed. When the generator is moving slower than synchronous speed, real power flows from the grid, through both converters, and from rotor to stator. These two modes, made possible by the four-quadrant nature of the two converters, allows a much wider speed range, both above and below synchronous speed by up to 50%, although narrower ranges are more common.

The greatest advantage of the DFIG, is that it offers the benefits of separate real and reactive power control, much like a traditional synchronous generator, while being able to run asynchronously. The torque producing components of the rotor flux can be made to respond fast enough that the machine remains under relative control, even during significant grid disturbances. Indeed, while more expensive than the Type 1 or 2 machines, the Type 3 is becoming popular due to its advantages.

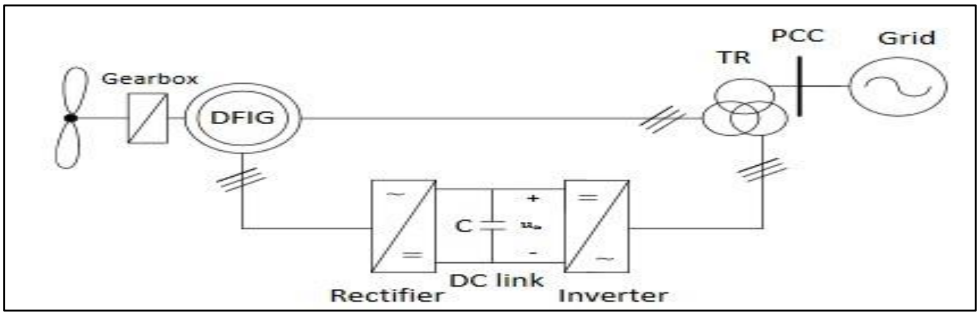


Figure 2.12: Type 3 DFIG

d) Type 4 – Full-power conversion WTG:

The Type 4 turbine offers a great deal of flexibility in design and operation as the output of the rotating machine is sent to the grid through a full scale back-to-back frequency converter, which means all the power output goes to the electrical grid through the converter as shown in Figure 2.13. The generator may be a synchronous generator with wound rotors, a permanent magnet generator or a SCIG. Similar to the characteristic of the type 3 wind generator, a type 4 generator can provide a much greater range of speed variation as well as reactive power and voltage control capability. Its output current can be adjusted to zero, hence limiting the short circuit current contribution to the grid [16].

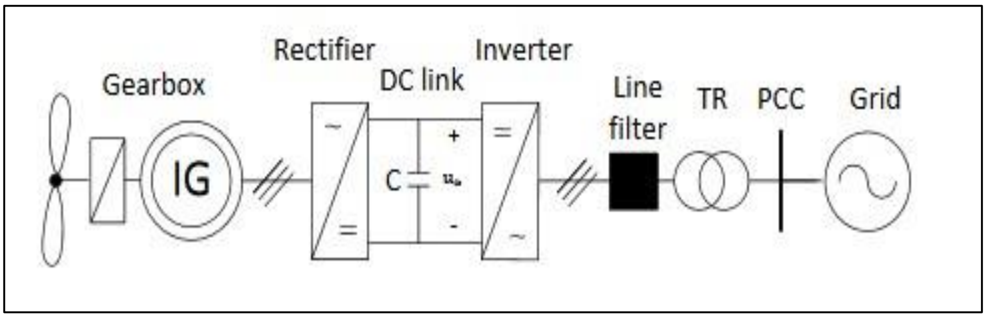


Figure 2.13: Type 4 full power

2.7.5 Converters for wind turbine generator systems

In the last two decades, different converter topologies have been investigated for power conditioning of wind turbine generator systems. All the proposed converters have some advantages and some disadvantages. Only diode rectifier based unidirectional converter and back-to-back bidirectional converter topologies are commonly used in the commercial wind turbine generator systems.

2.8 Impact of DG on Power System Grids

The distribution network was originally designed to transfer power from the transmission network and distribute it to the loads. It was not designed to have generators directly connected to it. The distribution network topology, control, and protection are all designed assuming that power is flowing in one direction, from transmission to loads. The connection of DGs to the feeders of the distribution network can cause the power flow to be bi-directional instead of unidirectional affecting the network performance and stability in a number of ways [17]. A short overview of the most important problems associated with the connection of DGs to the utility grid is described below.

2.8.1 Impact on voltage regulation

Voltage regulation is the degree of control or stability of the R.M.S voltage at the load. It is often specified in relation to other parameters, such as input-voltage changes, load changes, or temperature changes [17]. The connection of DG may result changes in voltage profile along a feeder by changing the direction and magnitude of real and reactive power flows. Nevertheless, DG impact on voltage regulation can be positive or negative depending on distribution system and distributed generator characteristics as well as DG location [18].

During normal operation conditions, without DG, voltage received at the load terminals is lower than the voltage at the primary of the transformer. The connection of DG can cause a reverse power flow, maybe even raising the voltage somewhat, and the voltage received at the customer's site could be higher than on the primary side of the distribution transformer.

2.8.2 Impact of DG on power losses

One of the major impacts of Distributed generation is on the losses in a feeder. Locating the DG units is an important criterion that has to be analyzed to be able to achieve a better reliability of the system with reduced losses. According to [18], locating DG units to minimize losses is similar to locating capacitor banks to reduce losses.

The main difference between both situations is that DG may contribute with active power and reactive power (P and Q). On the other hand, capacitor banks only contribute with reactive power flow. Mainly, generators in the system operate with a power factor range between 0.85 lagging and unity. The optimum location of DG can be obtained using load flow analysis software, which is able to investigate the suitable location of DG within the system in order to reduce the losses.

CHAPTER THREE

METHODOLGY

3.1 Introduction

A large-scale grid connected PV/wind systems are designed to operate in parallel and synchronized to the National grid via distribution system. The main system design is 50MW. Results of designing and modelling PV power plant, wind power plant, percentages of PV/Wind share for least power loss and impact of connecting the PV/Wind systems are presented, analyzed and discussed. Objectives of this study presented in two main areas. Detailed design section and power analysis studies using ETAP.

Design section starts with considering site selection and the selection of PV modules and their arrangement, inverters and power transformers in the PV system, And selecting of wind turbine and generator in the wind system. In power system analysis section load flow and voltage regulation studies were carried out. The results of power flow, busses voltages, busses angles and line losses were compared. Flow chart of the methodology is depicted below in Figure 3.1.

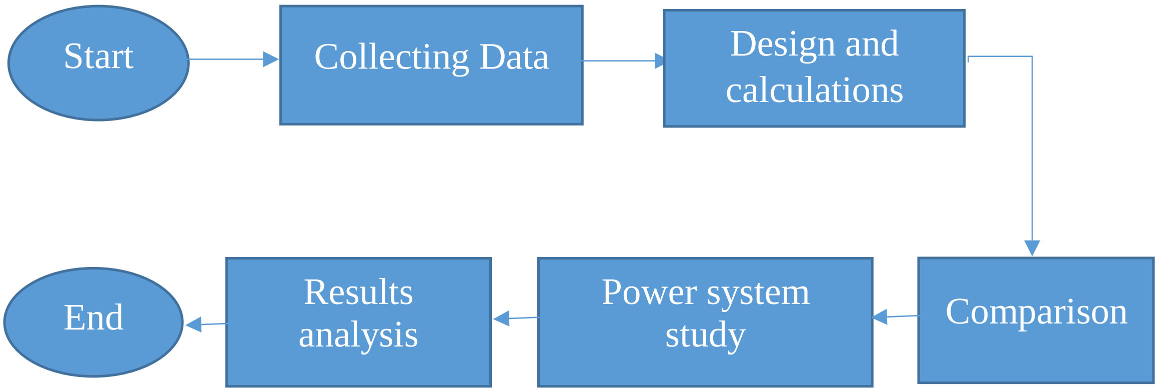


Figure 3.1: Flow chart of the system design and analysis process

3.2 Modelling and Analysis Software

In this work, two software packages have been used which are:

1) PVSYST (version 6.81): was used for sizing, simulation and data analysis of complete PV systems including solar panels and inverters. It is suitable for grid connected and stand-alone systems. It also offers an option to use any meteorological data. Furthermore, it has a large PV-components database which gives the ability to model most of the commercially available solar panels type connected to suitable inverters. The main purpose of using this software in this study is to find the total power output for different size of PV system based on the solar radiation data for that area.

2) ETAP: is the most wide-ranging analysis software that designed especially to design and apply tests of power systems. It is a comprehensive analysis platform for the design, simulation, operation, control, optimization, and automation of generation, transmission, distribution, and industrial power systems. The name ETAP stands for (Electrical Transient Analyzer Program). The main purpose of using this software in the study is to model the electrical distribution networks based on real load. Also, the software will be used to simulate the grid connected PV/wind system and apply power system analysis studies.

3.3 Site Selection

Before doing the design of the PV/wind power plant, it is necessary to select the site where the plant is going to be installed. The selection of the site is a very important issue due to the meteorological conditions. The site selected will largely determine the energy production of the PV/wind plant. Therefore, a several conditions must be met, as follows:

1. The site must has enough area and should be purchased or rented during the operational lifetime.

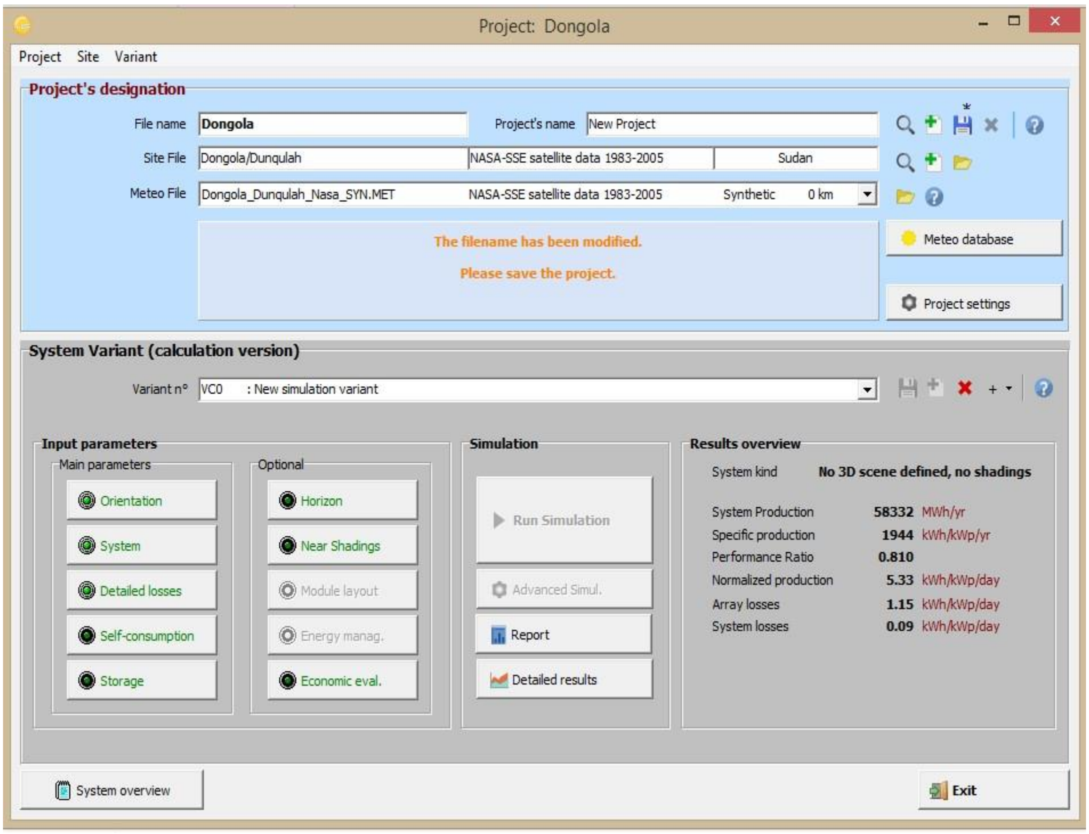
2. There are aspects related with the climate important for the development of a PV/Wind power plant project: temperature, direct normal solar radiation and wind speed value and direction.
3. The ideal situation would be a flat terrain; other configurations of the terrain could have a negative impact on the cost of the project due to more complex mounting structures. Besides, the presence of mountains near can produce undesirable shades and impede the movement of wind.
4. Environmental and social considerations.
5. The site must be as close as possible to the facilities so that the organizer of the project is implemented without barriers.
6. The site must be close to the lines of the electric grid in the case of the electricity generated will be pumped to the electric grid.
7. For large-scale PV power plants, the availability of water is an important factor. Large amounts of water are necessary for maintenance purposes (cleaning).

3.4 PV System Design

A 30MW PV system had been designed as three units each of 10MW using PVSYST program. PVSYST gives options to select site, PV modules and inverters, which are going to be used during the process of calculation. Furthermore, it is important to obtain the technical specifications of these components since they are going to be used during calculations. The steps followed during the design phase are the following:

3.4.1 Site and metrology

Location is chosen as the location of PV power plant installation from the PVSYST metrological database as shown in Figure 3.2. The nominal power of the system is set, active area and annual yield are automatically calculated. PVSYST found the optimum values depending on the location previously selected. For an optimization on annual yield, optimum tilt angle is defined.



File name: Dongola
Project's name: New Project
Site File: Dongola/Dunqulah — NASA-SSE satellite data 1983-2005 — Sudan
Meteo File: Dongola_Dunqulah_Nasa_SYN.MET — NASA-SSE satellite data 1983-2005 — Synthetic — 0 km

The filename has been modified.

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Variant n°: VC0 : New simulation variant

System kind: No 3D scene defined, no shadings
System Production: 58332 MWh/yr
Specific production: 1944 kWh/kWp/yr
Performance Ratio: 0.810
Normalized production: 5.33 kWh/kWp/day
Array losses: 1.15 kWh/kWp/day
System losses: 0.09 kWh/kWp/day

Figure 3.2: Selecting the site in PVSYST

3.4.2 Selection of PV modules

PV modules those selected from the PVSYST library based on some criterions related to their efficiency, price, warranty, life period, and brand quality. The selection must consider these considerations in order to guarantee the best performance, highest benefit, reliability at suitable prices. The first decision is to choose between mono-crystalline and poly-crystalline modules. The choice must consider the price and efficiency as the first criterions as the other criterions are approximately the same.

Depending on the module technology selected for the PV plant PVSYST calculate the required number of PV panel (N_{pv}) and area occupied by the PV modules (S_{array}) based on the following equations:

$$N_{pv} = \frac{P_{design} \cdot 10^6}{P_{M,STC}} \qquad (3.1)$$

Where,

P_{design} [MW] is the power plant design capacity

$P_{\text{M,STC}}$ [W] is the PV module power rating

$$S_{pv} = length \cdot width \tag{3.2}$$

Where,

$S_{PV}[m^2]$ is the product of multiplying the length [m] by the width [m] of the PV module selected.

For calculating the total area occupied by the PV array, S_{array} $[Km^2]$, the following formula is used:

$$\mathrm{S}_{array} = S_{pv} \cdot N_{PV} \cdot 10^{-\mathbf{6}} \tag{3.3}$$

The calculation of the number of PV modules in series and parallel depends on the specifications of the inverter selected. The equations used for the calculation of the maximum number of PV modules in series per inverter is:

$$V_{mid} = \frac{V_{i,max} + V_{i,min}}{2} \tag{3.4}$$

$$N_{s,max} = floor\left(\frac{V_{mid}}{V_{M,max}}\right) \tag{3.5}$$

Where, the specifications of the inverter are:

$V_{i,max}$ [V] is the DC input maximum MPP voltage

$V_{i,min}$ [V] is the DC input minimum MPP voltage

$V_{M,max}$ [V] is maximum MPP voltage

The number of PV modules connected in parallel ($N_{p,max}$) is calculated using the values of current of the module and the current of the inverter:

$$N_{p,max} = floor\left(\frac{I_{DC,max}}{I_{M,max}}\right) \tag{3.6}$$

Where, the specification used of the inverter are:

$I_{DC,max}$ [A] is maximum continuous current.

$I_{M,max}$ [A] is maximum MPP current.

3.4.3 Selection of inverters

Inverter is a power electronic device used to invert/convert electrical energy from DC to AC. As is mentioned in chapter two, there are two types of inverters those can be used in large-scale projects; these are multiple string inverter and central inverter. Inverter type is selected from PVSYST library. The selected inverter supports Maximum Power Point Tracker (MPPT), which allows for maximum solar energy extracting. PVSYST calculates the number of necessary inverters in the system based on Equation (3.7).

$$N_i = ceil\left(\frac{N_{pv}}{N_s \cdot N_p}\right) \tag{3.7}$$

Where, it is considered Ns=$N_{s,max}$ and Np=$N_{p,max}$.

After determining the total number of inverters the final number of PV modules ($N_{\mathrm{pv,final}}$) is calculated using the following equation:

$$N_{\mathrm{pv,final}} = N_s \cdot N_p \cdot N_i \tag{3.8}$$

Then the total installed capacity in the PV power plant is also modified:

$$P_{installed} = N_{\mathrm{pv,final}} \cdot P_{\mathrm{M,STC}} \tag{3.9}$$

In addition, the area occupied by the PV modules must be recalculated. The formula is the same as the one previously explained in Equation (3.3), but in this case, the number of PV modules is definitive:

$$S_{\text{array,final}} = S_{pv} \cdot N_{\text{pv,final}} \cdot 10^{-6} \qquad (3.10)$$

3.5 Wind System Design

A 30MW wind farm was designed as three 10MW units, each unit has a number of wind turbines and transformers. The turbine selected based upon their size, wind resource, availability, reliability, warranty, spare parts availability, proximity of operation and maintenance teams. Amongst others the selection of the most suitable wind turbine size depends on several site related criteria, such as:

- Available space on site.
- Wind conditions and in particular extreme wind condition on site.
- The financing available to the project.
- The ability of the transmission or distribution grid to handle the additional energy from the project.

The most suitable wind turbine for the proposed plant was selected under wind power density, average wind speed and power requirement of the site. Wind turbine with rated power was chosen for the design in order to harness the low wind speed efficiently.

3.5.1 Wind turbine selection

The main options in a wind turbine design and construction include:

- Number of blades (commonly two or three) and blade material.
- Hub height.
- Power control via aerodynamic control (stall control) or variable-pitch blades (pitch control).

- Fixed or variable rotor speed.
- Orientation by self-aligning action (free yaw) or direct control (active yaw).
- Synchronous or asynchronous generator (with squirrel-cage rotor or wound rotor -DFIG.
- With gearbox or direct drive generator.

3.5.2 Power generated in wind system

The amount of power transferred by a wind turbine is directly proportional to the area swept out by rotors, to the density of air and the cube of the wind speed. The power P is given by Equation (3.11):

$$P = 0.5 \times A \times \rho \times Cp \times V^3 \tag{3.11}$$

Where,

P =Turbine power coefficient

ρ =Air density (Kg/m^3)

A =Rotor swept area (m^2)

V =Mean wind speed (m/s)

Cp= Power transmission coefficient which depends on the blades design and on the tip speed ratio.

The total produced energy from wind farm per year is given by Equation (3.12):

$$T_p = \text{W} \times \text{days} \times \text{hours} \times C \tag{3.12}$$

Where,

T_p=Total annual power produced [MWh].

W=Wind turbine rated power [MW].

C=capacity factor (its percentage for annual output power, normally ranged between 15-30%).

3.6 Power System Studies

The electrical power system studies for the project have been done using ETAP software. The used methodology is as shown in the flow chart of Figure 3.3.

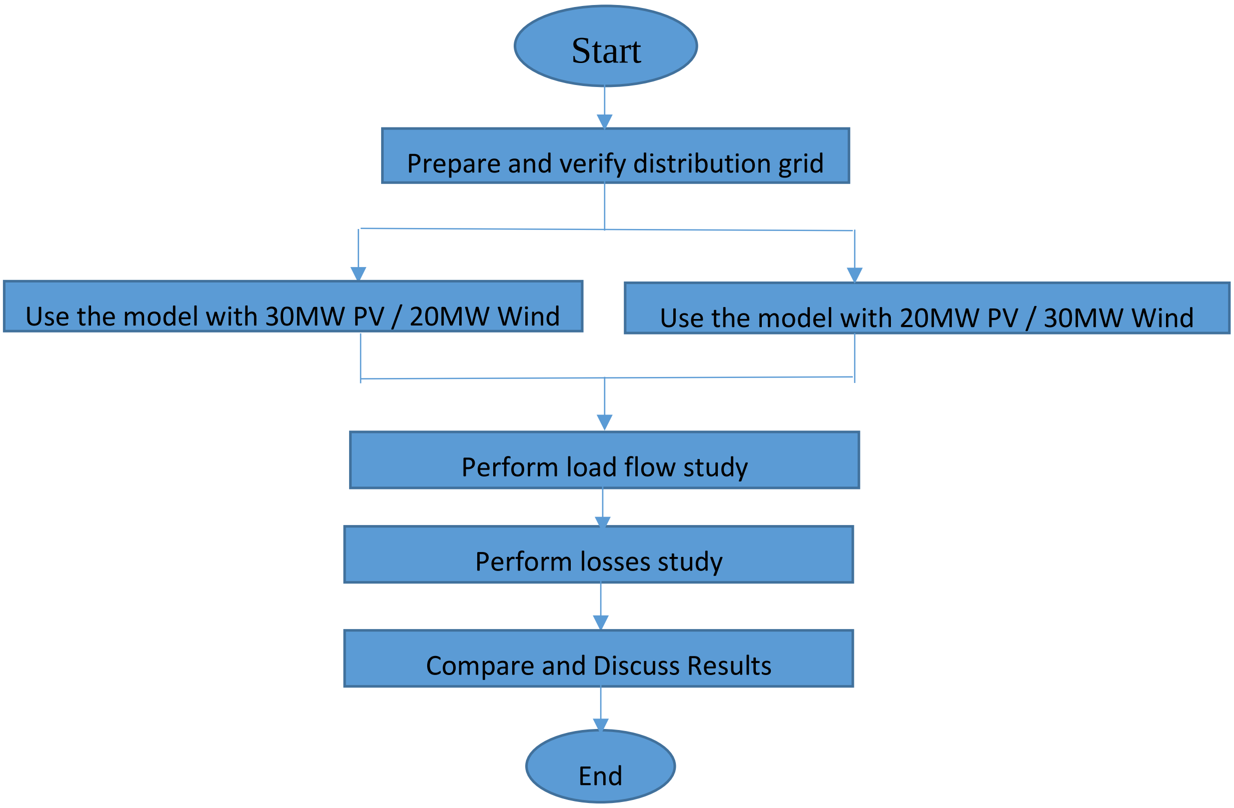


Figure 3.3: Comparison process flow chart

3.6.1 System modeling

The method used to study DG impact on the grid is to model the electrical distribution grid, PV/Wind system and their integration in ETAP software. Figure 3.4 shows the generation mix in the model from conventional Synchronous Generator (SG) and renewable-based DG. As shown in Figure 3.3 different implementation scenarios were used to perform the comparison by using ETAP and PVSYST softwares.

The first scenario is to connect 30MW PV power plant and 20MW wind power plant to the distribution grid. The second scenario is to connect 20MW PV power plant and 30MW wind power plant to the distribution grid. The result of those scenarios were compared and discussed on the basses of voltage regulation, losses, load flow and the daily power supply to determine the PV/Wind power percentages in the final system.

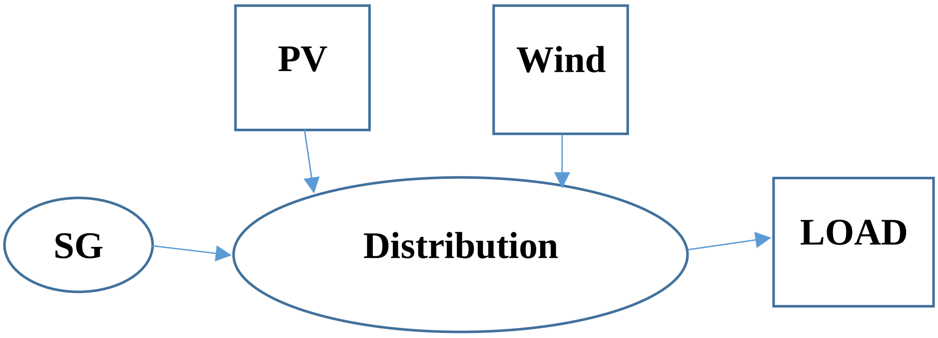


Figure 3.4: System block diagram

3.6.2 Load flow study and analysis using ETAP

The Load flow analysis in ETAP is based mainly on numerical solutions of systems of differential equations. ETAP software uses the buses voltages, flow of current and power in the system, and branches power factor to perform load flow analysis. The purpose of load flow analysis in ETAP is to build an extensive idea about the behavior of the power system under different supply and load conditions. It helps electrical power systems planners to design and test the performance of their systems prior to their installation and during their real time operation. It is also used to detect and forecast possible faults or power flow problems to propose the suitable solutions and ETAP has multiple choices to define the display options based on the user’s needs and requirements from load flow analysis.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of designing PV and wind systems, determine the percentages share of each system and studying the impact of the integration for these systems to Dongola distribution system.

4.2 Case Study

The purpose of this study is to design PV and wind systems integrated to the distribution system at Dongola city to provide the city with an additional electrical power and support the Sudanese National grid, also to study and discuss the impacts on the power system. Site location, climatology and electrical data are mentioned.

4.2.1 Site location

The PV/Wind system is located in Dongola city in the northern part of the Republic of Sudan, which is located approximately 460Km north-northwest of the Sudanese capital of Khartoum and 300Km south of the border to Egypt. The city of Dongola is the capital and largest city of the Northern state in Sudan, located on the banks of the Nile which indicated by the red borders. More details in Appendix A.

4.2.2 Site climatology

The climate conditions in Dongola region are mostly arid desert-like with a minimal chance of precipitation in the period between July to September. Temperatures do not vary greatly with the season; the most significant climate variables are rainfall and the length of the dry season. Temperatures are highest at the end of the dry season when clear skies and dry air allow them to soar. The Dongola region, with its short rainy season, has hot daytime temperatures year round with an average of 25°C to 35°C and peak temperatures of over 50°C. Lows occur during wintertime with a minimum 10°C and mean temperature of around 20°C. Irradiation of North-west Sudan is one of the highest in Africa with up to 2,900KWh/m^2 per year as shown in Table 4.1. Dongola itself has slightly lower irradiation due to frequent air soiling and higher air humidity caused by the river Nile. For more details See Appendix B.

Table 4.1: Irradiation in Dongola

Interval Beginning	GlobHor KWh/m^2.mth	DiffHor KWh/m^2.mth
Jan	149.4	51.45
Feb	160.7	45.51
Mar	205.2	53.9
Apr	216.9	57.33
May	227.2	61.05
Jun	226.8	55.8
Jul	222.3	61.54
Aug	214.5	64.93
Sep	192.9	59.48
Oct	183.2	51.95
Nov	154.2	49.65
Dec	137.9	46.97
Year	2291.2	659.56

4.2.3 Site electrical grid

Dongola network draws electricity from the utility grid via a high voltage transmission substation 220/33KV consists of two 100MVA power transformers. This substation built in 2006 within the frame of the Merowe dam. The distribution system feeds the load via two 33/11KV substations, substation I has two transformers with ratings of 20MVA and 10MVA, substation II has two transformers with rating 20MVA each. The system total connected load is 70MW, which had been taken from the full load capacity of the transformers. The single line diagram is showed in Figure 4.1.

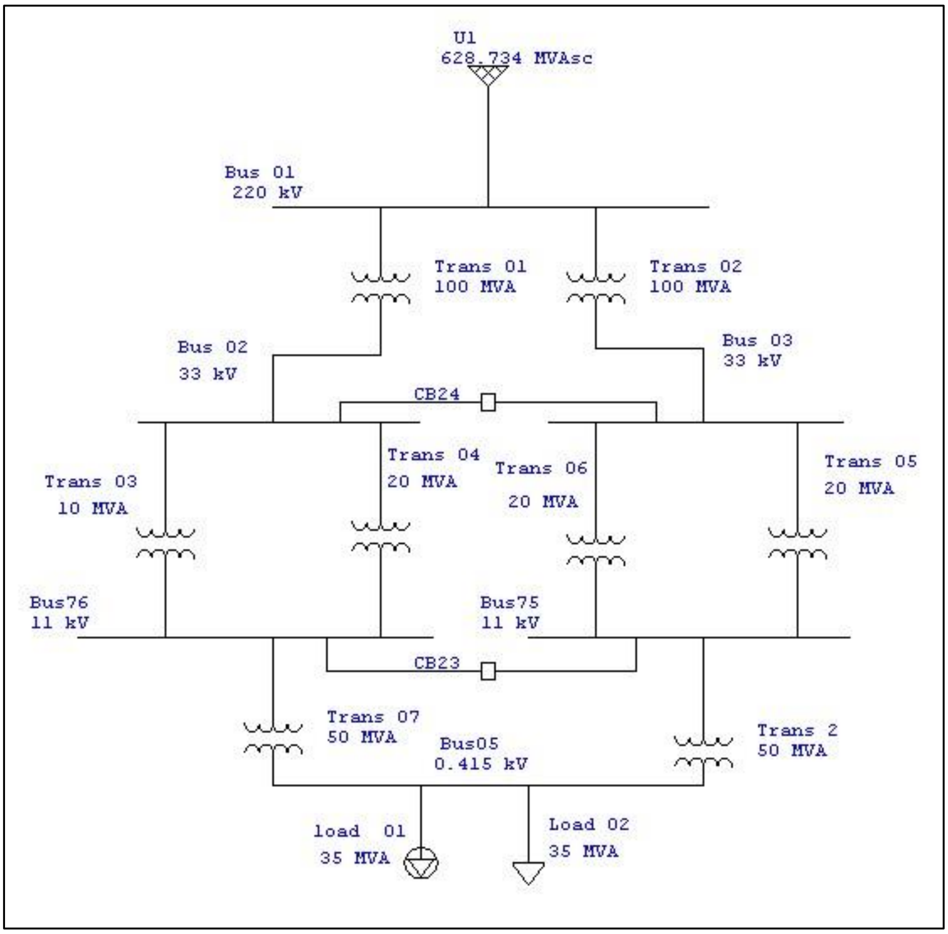


Figure 4.1: Single line diagram of Dongola distribution network

4.3 PV System Design

In order to design 30MW PV system, the system divided into three independent segments. Each segment is equipped with four inverters of 2.5MW each and grouped together to form 10MW.

4.3.1 Tilt angle

The plant has a fixed tilted PV panels field type facing south (in the Northern Hemisphere) and the optimum tilt angle is 21° and azimuth angle of 0° as shown in Figure 4.2.

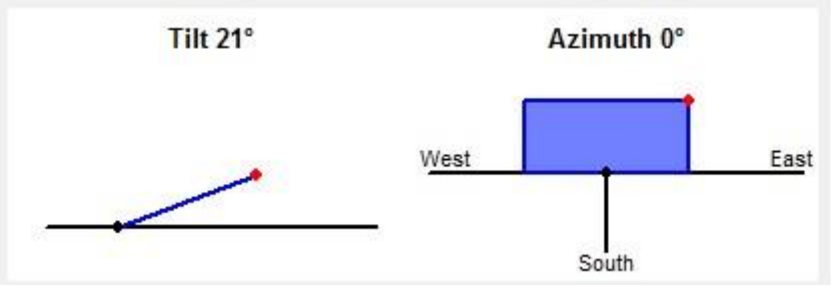


Figure 4.2: Collector plane orientation PVSYST's screen capture

4.3.2 Selected PV module

From the irradiation data, Polycrystalline Jinko Solar JKM 340PP-72-V modules of 340W_p solar panels are going to be used exemplary in the project. PV module V-I curve of the system is presented in Figure 4.3. The curves show the variations in voltage and current under different irradiation levels and fixed temperature of 45°C. More PV module specifications in Appendix C.

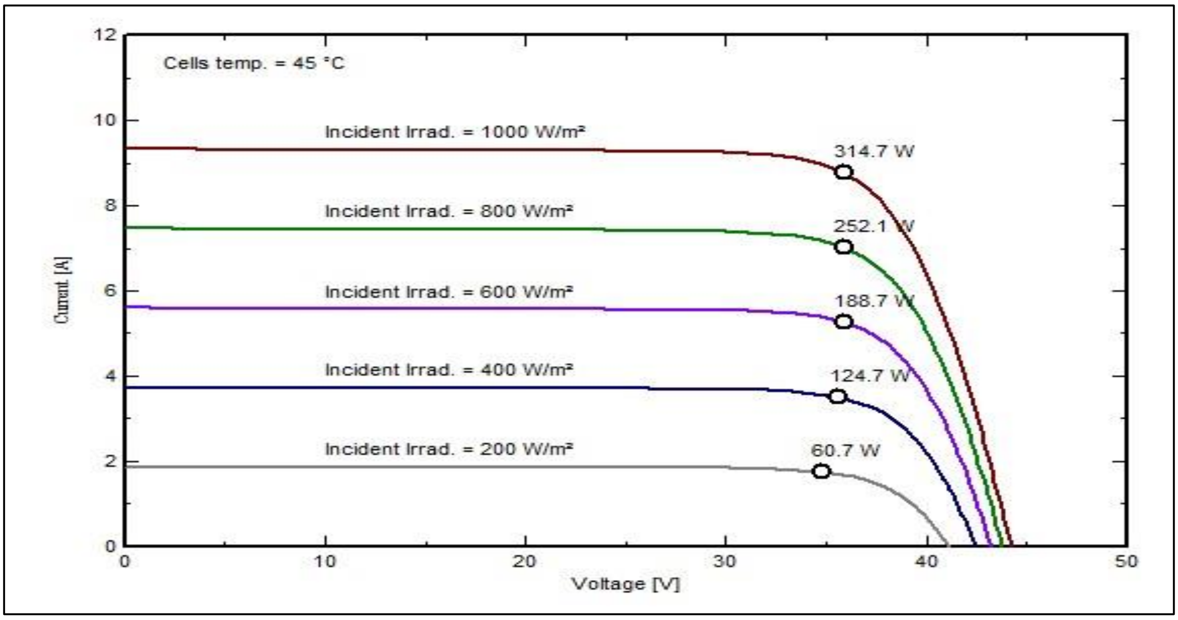


Figure 4.3: PV module V-I curve

4.3.3 Selected inverter type

Total of 12 units of SG2500HV central inverter from Sungrow, each unit with 2500KVA rating are going to be used in the project to form 30MW PV system. Number of PV modules and inverters units used are shown in Table 4.2. More details of inverter specifications in Appendix D.

Table 4.2: Total number of PV modules and inverters units

	PV Modules	Inverters
number of PV modules/inverter units per group	8148 modules	1 unit
number of PV modules/inverter units per segment	32592 modules	4 units
Total number of PV/inverter units modules	97776 modules	12 units

4.3.4 PV modules arrangements

Depending on the 340W_p modules, 291 PV arrays are connected in parallel to each single inverter; each array consists of 28 modules connected in series as shown in Table 4.3. The power generated from 30MW PV plant at 0.55KV is stepped up to 11KV with help of three step-up transformers and connected to existing 11KV lines. The ETAP model of each segment is shown in Figure 4.4.

Table 4.3: PV modules arrangements

Unit	Content	Connection
String	28 modules	Series
Group	291 strings	Parallel

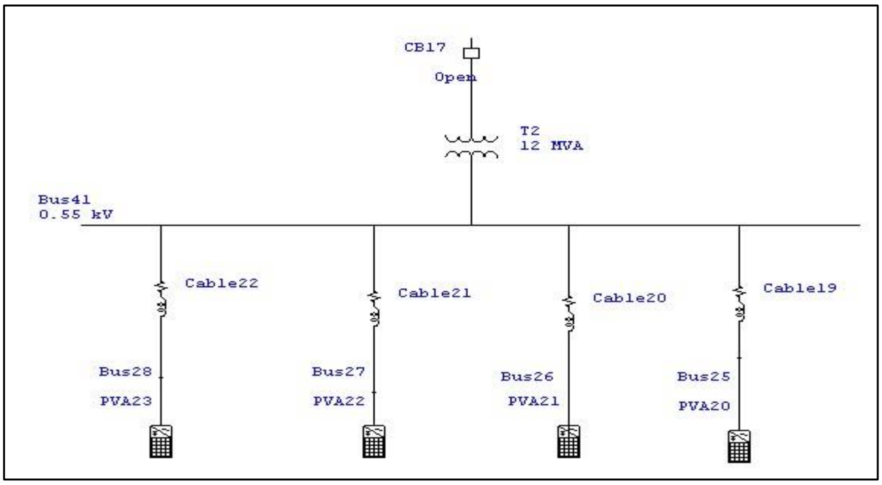


Figure 4.4: ETAP model of 10MW PV segment

4.4 Wind System Design

In order to design 30MW wind system, the system is divided into three layers, each layer designed to have 10MW installed capacity, this will be obtained by installing five-wind turbine of 2MW capacity.

4.4.1 Hub height

The preferred hub height is 90m as shall result in a good combination of energy yield and the costs for tower and foundation. The average wind speed at this height is 9m/s taken from Dongola wind speed data.

4.4.2 Selected turbine type

The wind turbine used is horizontal wind turbine with a 2MW rated power by Sany model: (SE12120) with a rotor diameter of 120m. The model cut-in speed is 2.5m/s and the rated wind speed is 8.5m/s, which gives the advantage of generating power at low wind speed. Wind turbine module specification in Appendix F.

4.4.3 Selected generator type

The selected generator is Doubly Fed Induction Generator as variable speed control; it allows the amplitude and frequency of their output voltages to be maintained at a constant value, no matter the speed of the wind blowing on the wind turbine rotor. Because of this, DFIG can be directly connected to distribution power network and remain synchronized at all times with the ac power network. Other advantages include the ability to control the power factor (e.g., to maintain the power factor at unity), while keeping the power electronics devices in the wind turbine at a moderate size.

4.4.4 Selected transformer

Each layer of wind turbine has a rated voltage of 0.69KV which stepped up to 11KV using a step-up transformer with rating of 12MVA. Figure 4.5 shows the ETAP model of the 10MW wind system.

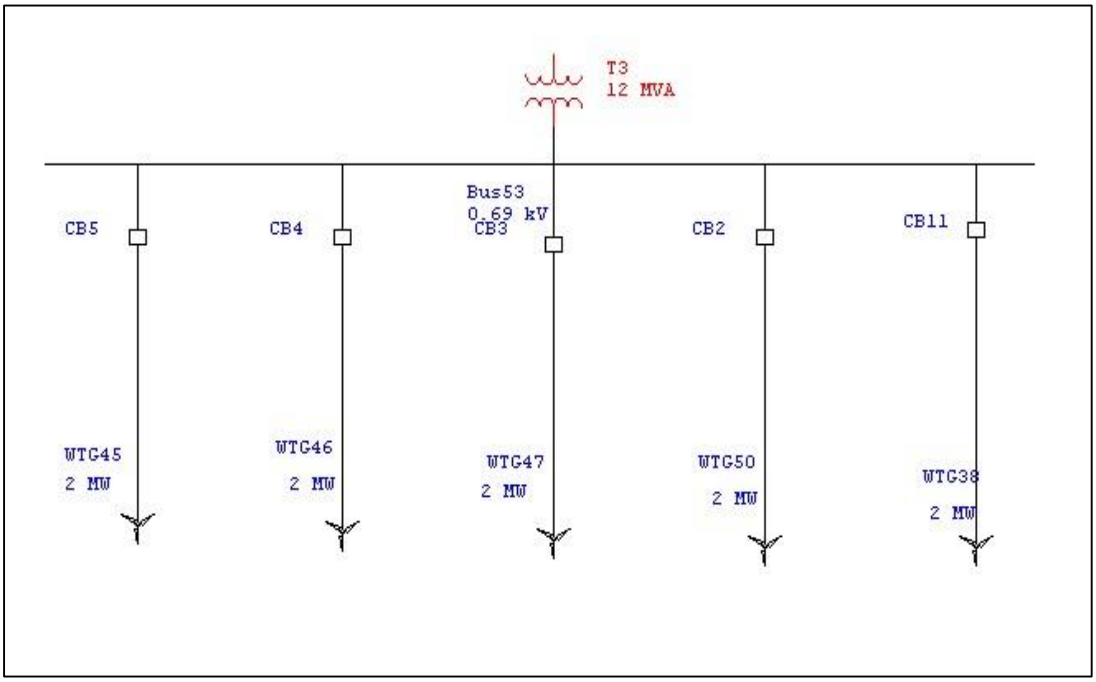


Figure 4.5: ETAP model of 10MW wind layer

4.4.5 Turbine spacing

The distance between each wind turbine is the approximate measurement of 360m in cross and 850m in wind direction as shown in Figure 4.6.

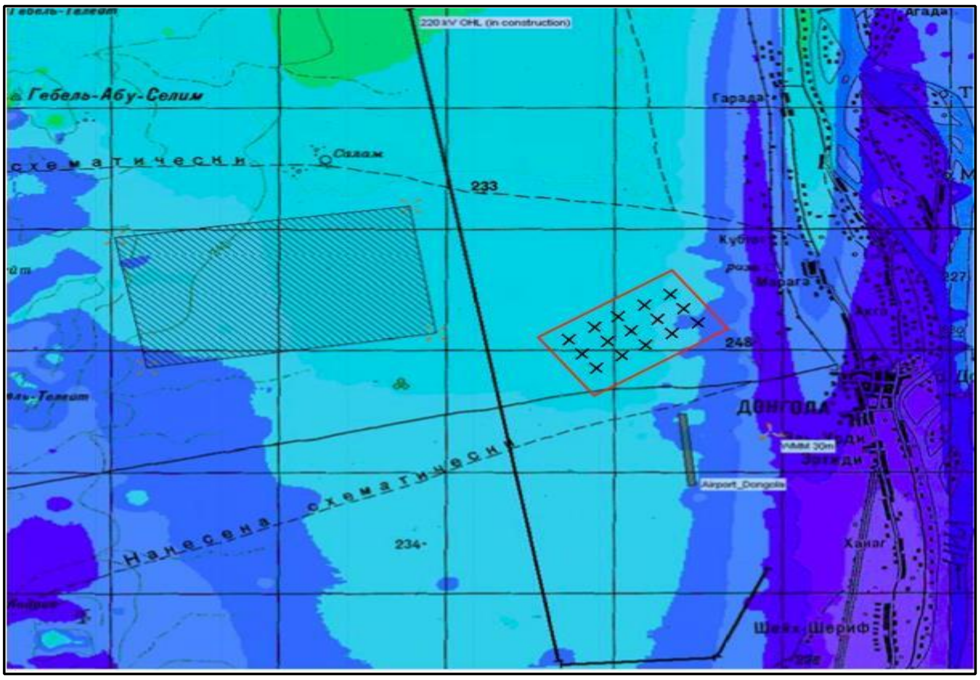


Figure 4.6: Wind system layout

4.4.6 Power generated from wind turbine

According to equation 3.11 in chapter three, the power generated from variable wind speeds is represented in Table 4.4.

Table 4.4: Power generated from the variable wind speed

Wind speed (m/s)	Power(KW)
2-3	15.5
3	41
4	197
5	428
6	755
7	1211
8	1825
9-22	2000

Power curve of a wind turbine, which gives the output power of turbine at a variable wind speeds, provides a convenient way to model the performance of wind turbines. In the first region when the wind speed is less than a threshold minimum, known as the cut-in speed 2.5m/s, the power output is zero. In the second region between the cut-in and the rated speed 8.5m/s, there is a rapid growth of power produced. In the third region, a constant output (rated 2MW) is produced until the cut-off speed 22m/s is attained. Beyond this speed, the turbine is taken out of operation to protect its components from high winds; hence, it produces zero power in this region as shown in Figure 4.7.

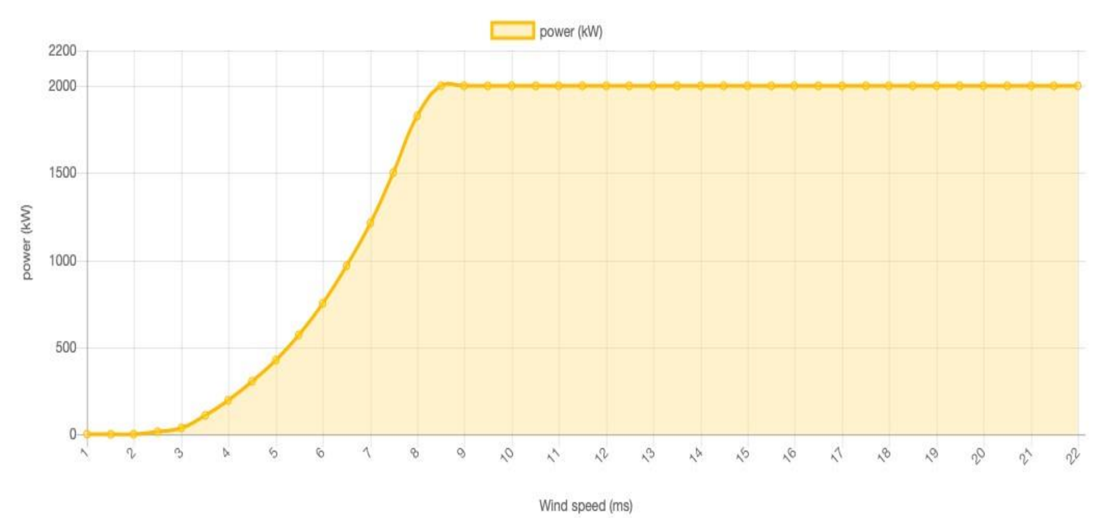


Figure 4.7: Power generated from variable wind speed

4.5 Determination the Percentages of PV/Wind Share

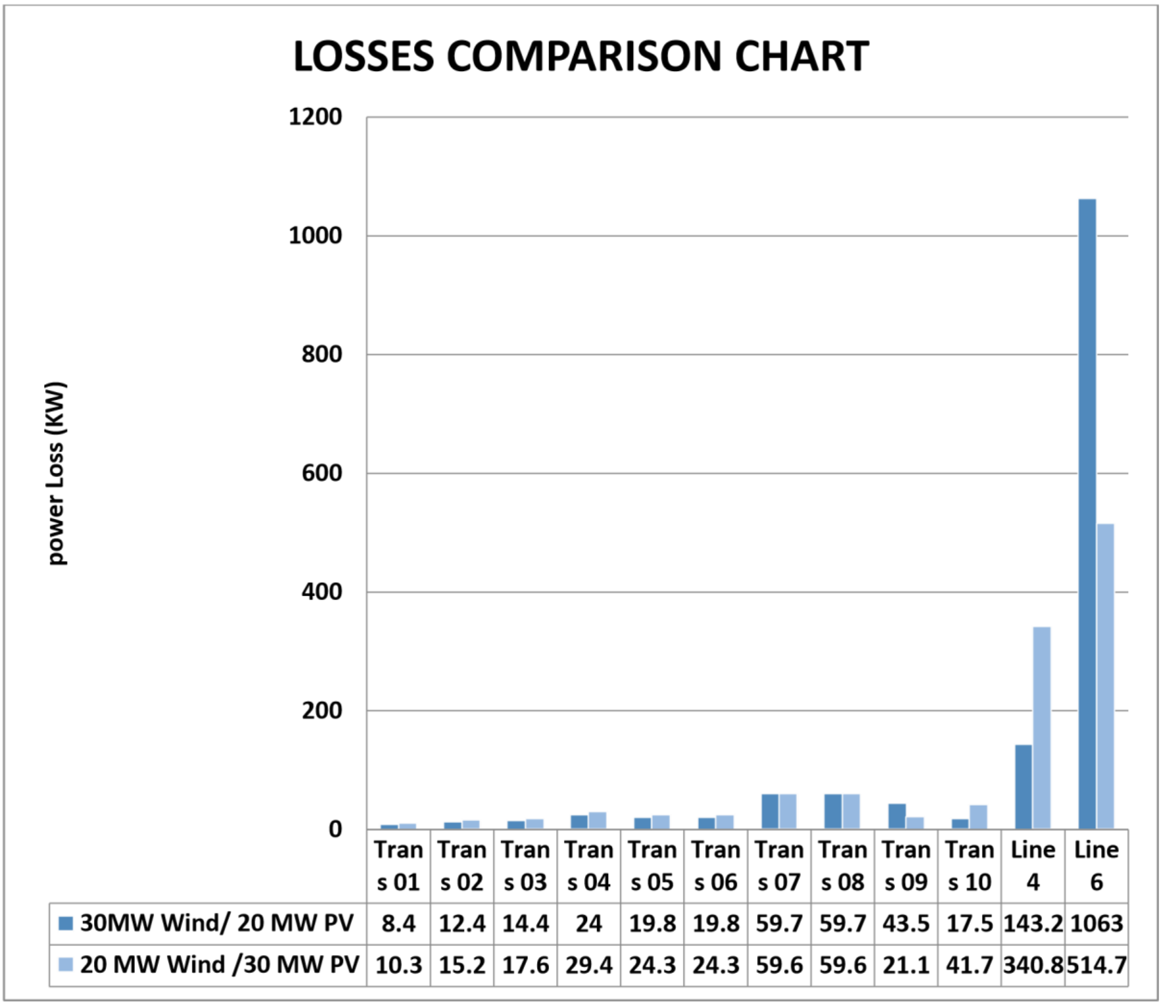
This section discusses the implementation of Dongola distribution system with different scenarios as presented in Figure 4.9 and Figure 4.10, which shown the components of Dongola distribution network in addition to the PV/wind systems model in ETAP. Those figures show the load flow results for each one of the buses and branches.

On the figure buses, voltages are in per unit (PU). It is important to mention that in Figure 4.9 the 30MW PV and 20MW wind systems are connected and the amount of absorbed power from the grid is 7112KW. The voltage on the 11KV bus 04 is 93.8% and on the 0.415KV bus 05 is 91.1%. While Figure 4.10 shows the system load flow after the connection of 20MW PV and 30MW wind systems. The voltage at bus 11KV has increased to 94.14% and on the 0.415KV bus 05 also increased to 91.71% and the absorbed power from the grid increased to 7439KW. Table 4.5 presents the comparison of the voltage regulation.

The total losses in the 30MW PV/20MW wind systems is 1270KW and 1555.3KW in 20MW PV/30MW wind systems. The amount of total losses calculated from the loss in transformers, transmission lines and the PV/Wind systems internal cables as shown in Figure 4.8.

Table 4.5: Voltage regulation comparison between the two scenarios

System/ bus bar	Bus bur 11KV	Bus bar 0.415KV
30MW PV and 20MW wind	93.8%	91.1%
20MW PV and 30MW wind	94.14%	91.71%



	Trans 01	Trans 02	Trans 03	Trans 04	Trans 05	Trans 06	Trans 07	Trans 08	Trans 09	Trans 10	Line 4	Line 6
■ 30MW Wind/ 20 MW PV	8.4	12.4	14.4	24	19.8	19.8	59.7	59.7	43.5	17.5	143.2	1063
■ 20 MW Wind /30 MW PV	10.3	15.2	17.6	29.4	24.3	24.3	59.6	59.6	21.1	41.7	340.8	514.7

Figure 4.8: Power loss comparison between the two scenarios

The transmission lines that used to carry the PV and wind power plant are the same type and size. The absorbed power from the utility grid after connecting the two systems are likely the same, that means there is no difference in the power loss in the grid before 11KV bus bar, These results show that the wind power plants has more losses than the PV power plants.

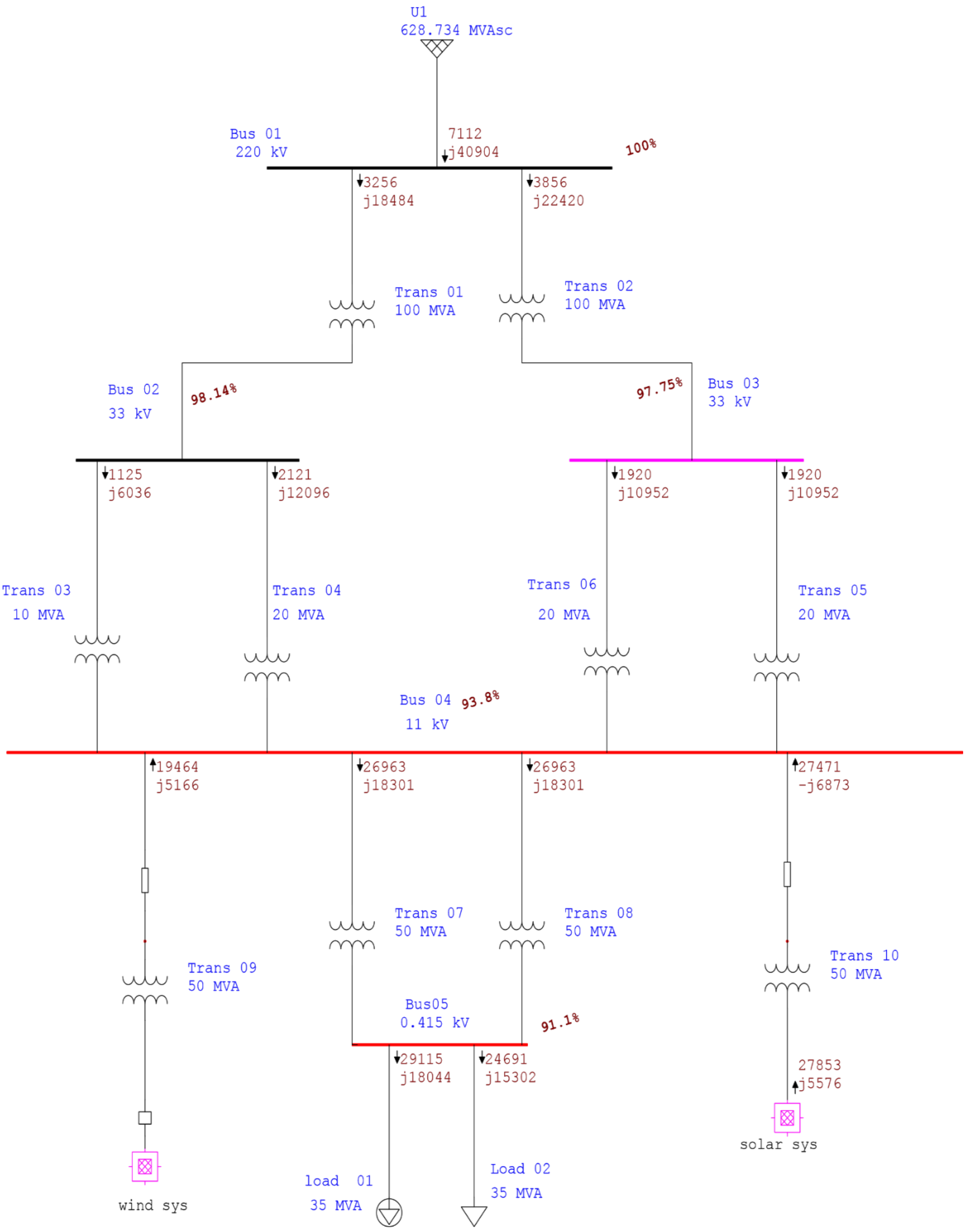


Figure 4.9: Load flow simulation with 30MW PV/20MW Wind

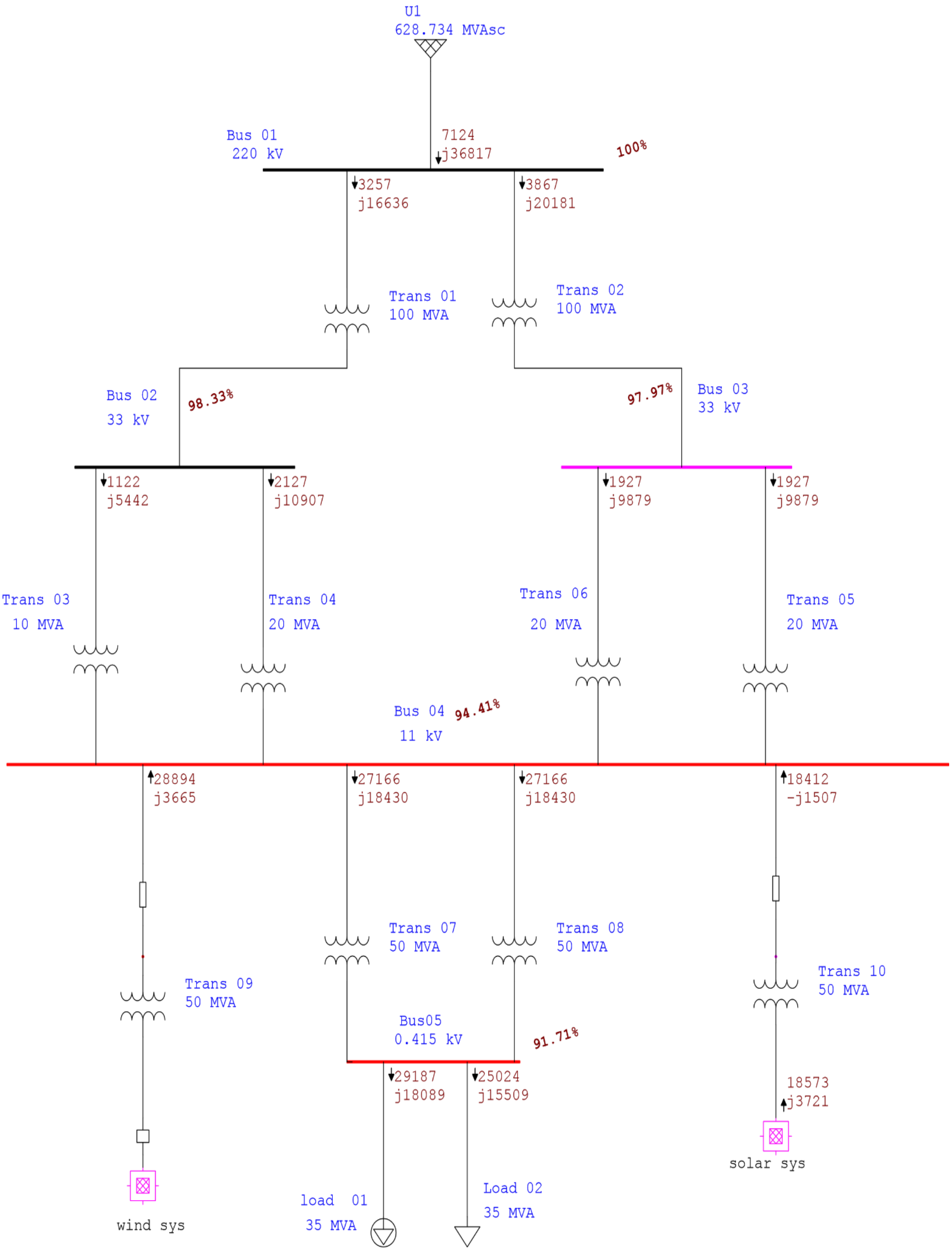


Figure 4.10: Load flow simulation with 20MW PV/30MW Wind

On other hand of annual energy production for the PV power plant obtained from PVSYST software and wind power plant obtained by the Equation (3.12) in chapter three as shown in Table 4.6, the first scenario annual produced energy is 100.355GWh and the annual produced energy by the second scenario is 103.439GWh.

Table 4.6: Annual energy production for renewable energy systems

System	Annual energy production	Total
30 MW PV	56.555 GWh	100.355 GWh
20 MW wind	43.8 GWh	
20MW PV	37.739 GWh	103.439 GWh
30MW wind	65.7 GWh	

As a result of the previous comparison the system with higher percentage of wind power plant is more efficient than the system with higher percentage of PV power plant.

4.6 Impact of Connecting the PV/Wind Systems

In Figure 4.11 the PV/wind power plants are disconnected. The power of the PV/Wind power plants is zero and the amount of absorbed power from the grid is 53.987MW. The voltage on the11KV bus 04 is 93.37% and on the 0.415KV bus 05 is 90.86%. Figure 4.9 shows the system load flow after connection the system. The voltage at bus 04 has increased to 93.8% and on the 0.415KV bus 05 also increased to 91.1% and the absorbed power from the grid decreased to 7112KW.

The total power loss in Dongola distribution grid before the connection of DG systems is 458.2KW and the total power loss in the transmission system is 339KW. The total power loss after the connection is increased to 1270KW in both distribution and transmission systems, while the total losses in the transmission system decreased to 121.1KW as shown in Figure 4.12.

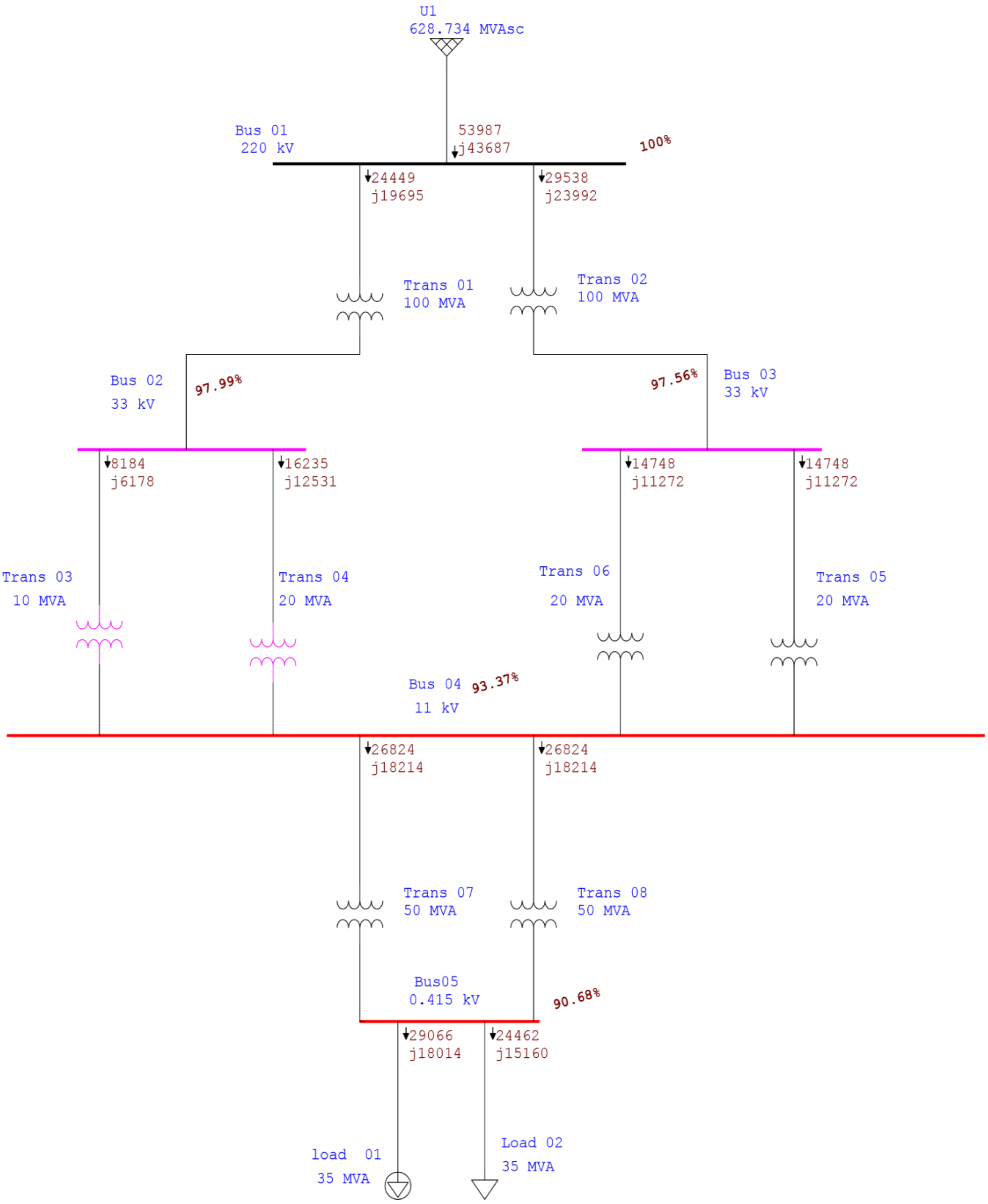


Figure 4.11: Load flow simulation with PV/Wind disconnected

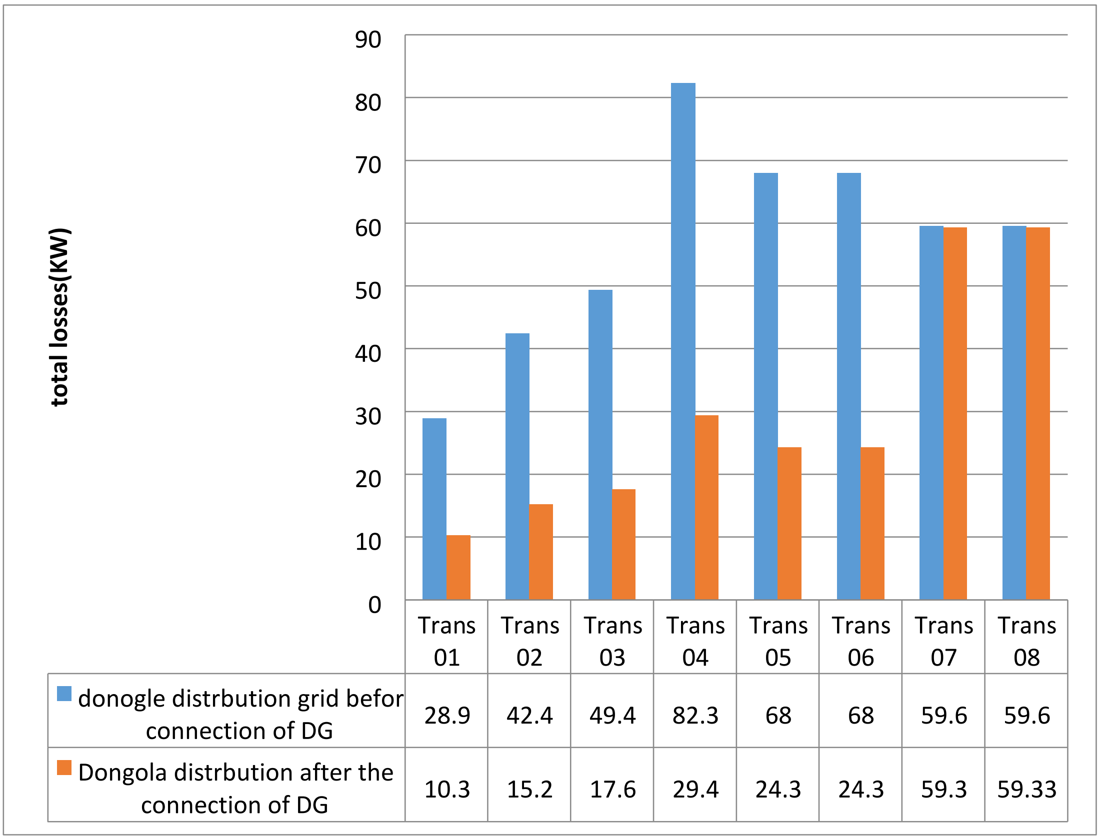


Figure 4.12: Power losses before and after connection

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Sudan is very wealthy in the solar and wind energies and gains a huge prospective for solar and wind power generation plants. These energies are variable in the nature and depends on the site. The unpredictable nature of these energies sources have great impact on the power system operation and planning. The aim of this specific work is to evaluate the effect of the integration of solar/wind power plants in Dongola distribution grid. This aim was achieved by developing the design of PV/wind systems to be implemented in 11KV busbar.

In order to verify the design validity, different simulation models using PVSYST and ETAP programs have been built and carried out. Real load and solar energy data were used in the simulation to achieve more realistic results that can help for future analysis and planning processes.

Investigation of the impact of the PV/wind plants on Dongola distribution power system in this report was carried out and some analyses were established. The first study was concerned on developing comparison between the two scenarios of PV/Wind systems on the study of load flow, voltage profile and the total amount of the losses. This study is performed in order to determine the percentage share of PV and wind power plants in the system. The second study was concerned on the study of the impact of the integration on Dongola distribution grid on load flow, voltage profile and the total amount of the losses of the system.

The obtained results from studies shown that the integration of the DGs systems to the distribution side reduce the total power loss in the transmission lines and improve the voltage profile.

5.2 Recommendations

Any scientific research cannot cover all aspects and investigates all important points at once; some points need to be reinvestigated and studied in future works. Separately from the studies applied in the course of this thesis work; that seems to be of the highest importance, further studies of the impact of the PV/Wind systems on the connected power systems and distribution grid needs to be penetrated. After the integration of PV/Wind systems, different protection and interruption systems need to be studied and introduced into the grid. Future works that are recommended in other stages of this work are:

- Further studies on the protection profile after the injection of PV/Wind systems.
- The stability of the power system grid under the effects of PV/Wind systems
- Harmonic Filters can be include to the power system, three-phase harmonics filters can be designed to achieve an optimal control strategy for harmonic problems to maintain the quality limits proposed by standards and for correcting the power factor.
- Apply this project in as many cities and villages as possible in Sudan to increase the reliability and continuity of energy supply. With the possibility of applying the concept of smart grid in the future.

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APPENDIX A

SITE LOCATION

Figure A.1: Close up view for Dongola

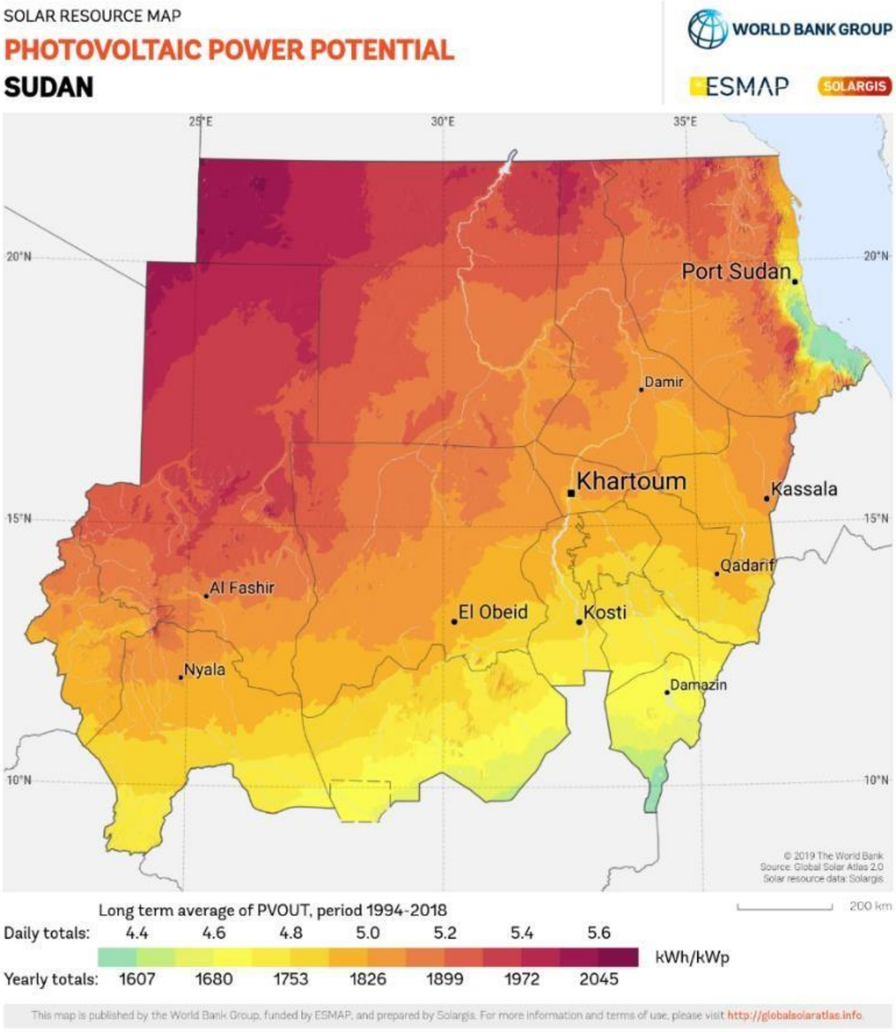


Figure A.2: Sudan horizontal irradiation map

APPENDIX B

SITE CONDITIONS

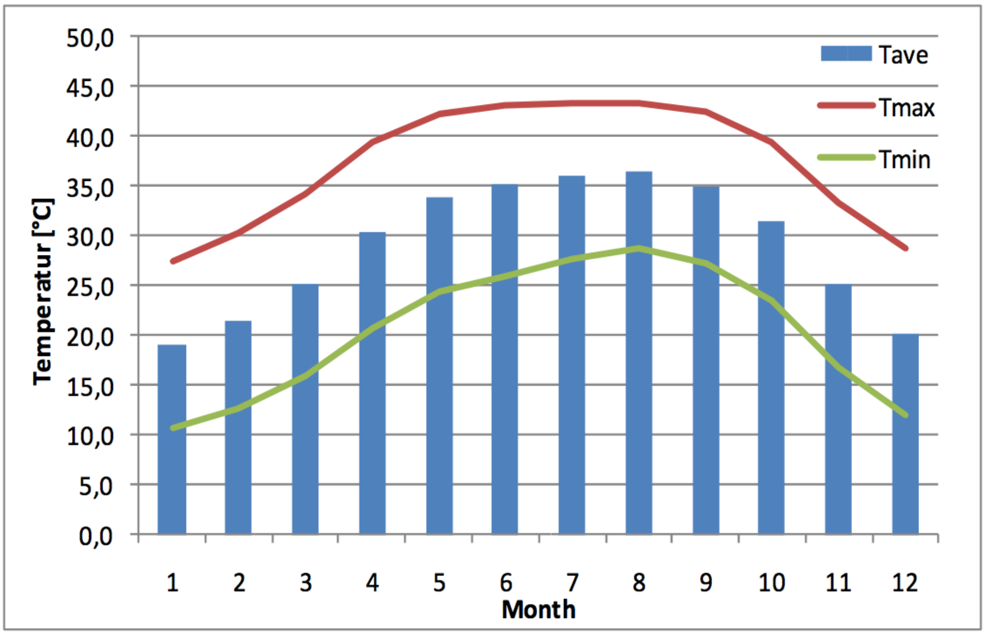


Figure B.1: Temperature conditions in Dongola

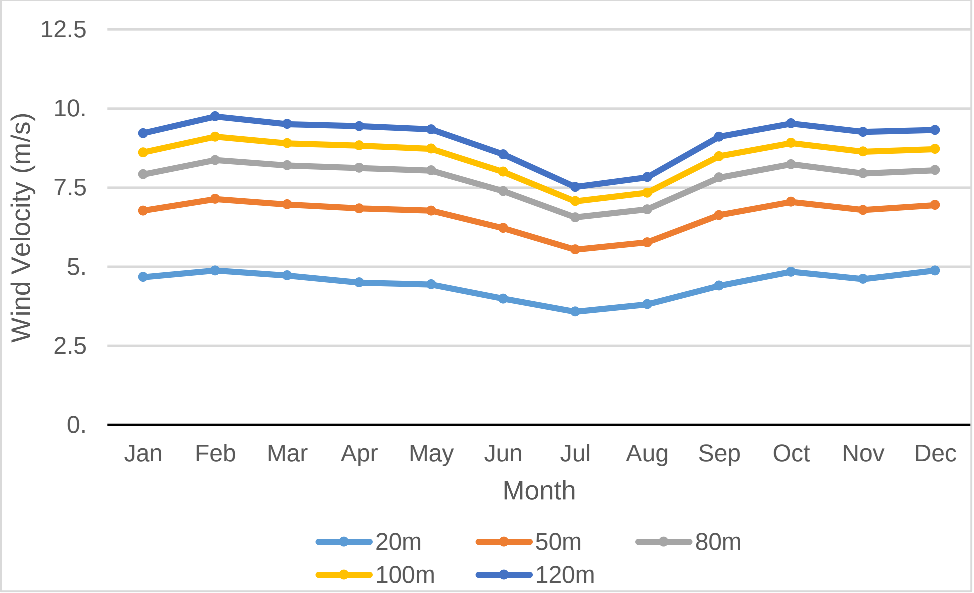


Figure B.2: Yearly wind speed of various hub heights

APPENDIX C

PV MODULE SPECIFICATIONS

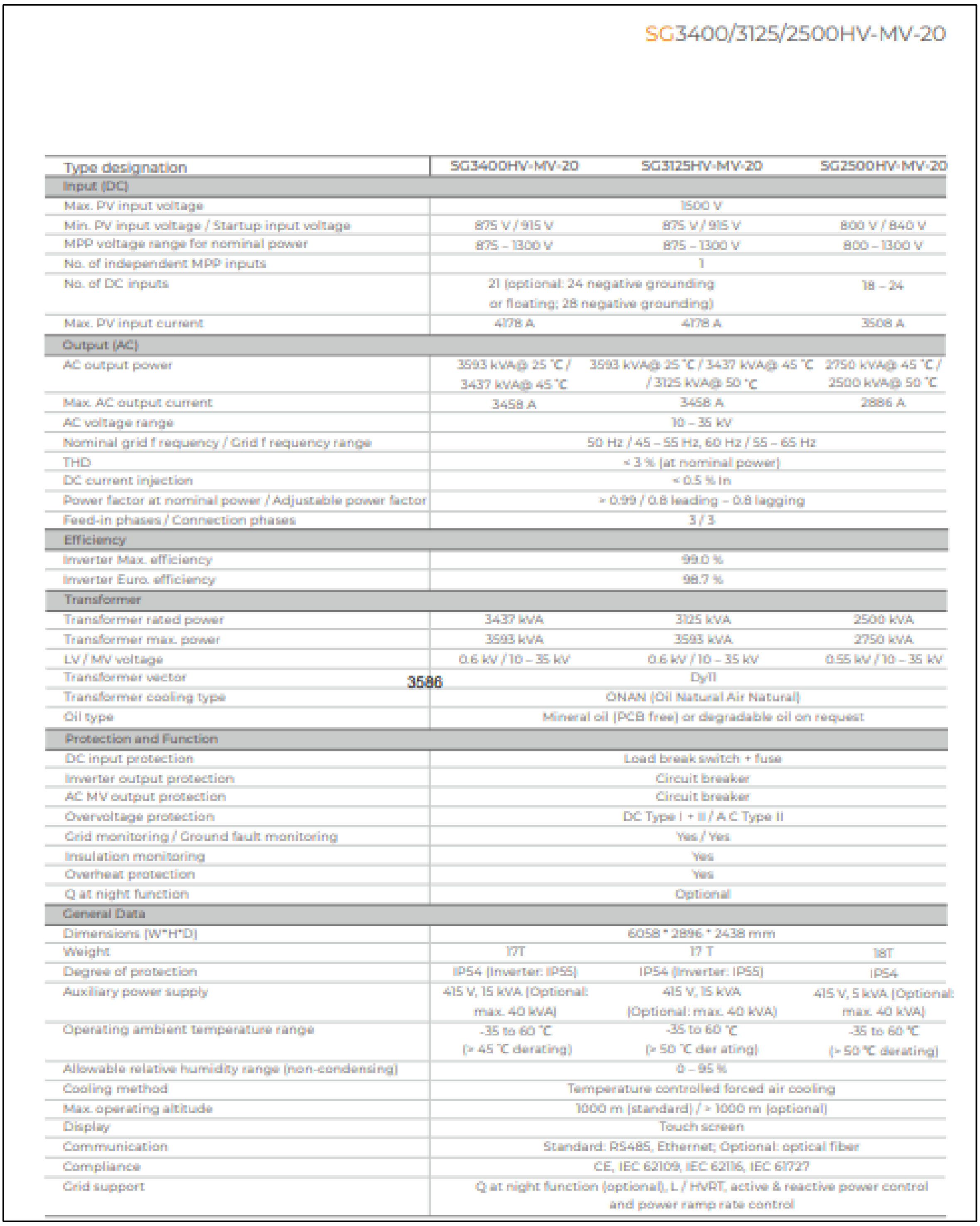
The PV module selected in this project is a poly-crystalline PV module type jinko solar jkm 340pp-72-v it has specifications listed in Table C.1.

Table C.1: PV module specifications

Item Description	Item specification
Maximum power (W)	340
Voltage @ maximum power point (V)	38.20
Current @ maximum power point (A)	8.900
Open circuit voltage (V)	47.50
Short circuit current (A)	9.220
Cells per module (Cell)	72
β (Voltage de-rating factor (Voc % / °C))	-0.162
α (Current de-rating factor (Isc % / °C))	0.060
γ (Power de-rating factor (Pmax % / °C))	-0.40
Frame size (m^2)	1.940
Thickness (mm)	40
Width (mm)	992
Length (mm)	1956
Weight (kg)	26.50

APPENDIX D

INVERTER SPECIFICATIONS



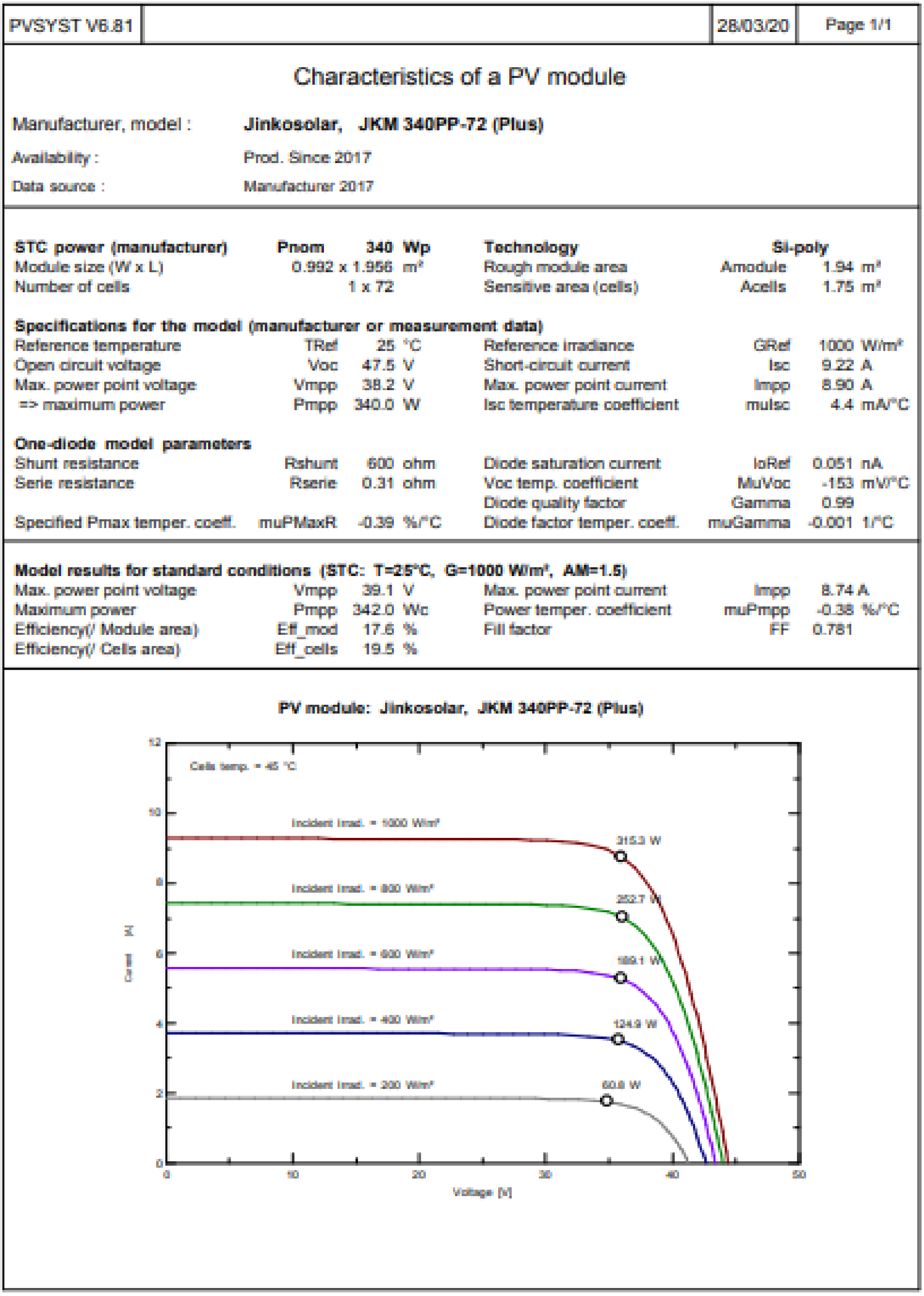
SG3400/3125/2500HV-MV-20

Type designation	SG3400HV-MV-20	SG3125HV-MV-20	SG2500HV-MV-20
Input (DC)			
Max. PV input voltage	1500 V		
Min. PV input voltage / Startup input voltage	875 V / 915 V	875 V / 915 V	800 V / 840 V
MPP voltage range for nominal power	875 – 1300 V	875 – 1300 V	800 – 1300 V
No. of independent MPP inputs	1		
No. of DC inputs	21 (optional: 24 negative grounding or floating; 28 negative grounding)		18 – 24
Max. PV input current	4178 A	4178 A	3508 A
Output (AC)			
AC output power	3593 kVA@ 25 ℃ / 3437 kVA@ 45 ℃	3593 kVA@ 25 ℃ / 3437 kVA@ 45 ℃ / 3125 kVA@ 50 ℃	2750 kVA@ 45 ℃ / 2500 kVA@ 50 ℃
Max. AC output current	3458 A	3458 A	2886 A
AC voltage range	10 – 35 kV		
Nominal grid f requency / Grid f requency range	50 Hz / 45 – 55 Hz, 60 Hz / 55 – 65 Hz		
THD	< 3 % (at nominal power)		
DC current injection	< 0.5 % In		
Power factor at nominal power / Adjustable power factor	> 0.99 / 0.8 leading – 0.8 lagging		
Feed-in phases / Connection phases	3 / 3		
Efficiency			
Inverter Max. efficiency	99.0 %		
Inverter Euro. efficiency	98.7 %		
Transformer			
Transformer rated power	3437 kVA	3125 kVA	2500 kVA
Transformer max. power	3593 kVA	3593 kVA	2750 kVA
LV / MV voltage	0.6 kV / 10 – 35 kV	0.6 kV / 10 – 35 kV	0.55 kV / 10 – 35 kV
Transformer vector 3586	Dy11		
Transformer cooling type	ONAN (Oil Natural Air Natural)		
Oil type	Mineral oil (PCB free) or degradable oil on request		
Protection and Function			
DC input protection	Load break switch + fuse		
Inverter output protection	Circuit breaker		
AC MV output protection	Circuit breaker		
Overvoltage protection	DC Type I + II / A C Type II		
Grid monitoring / Ground fault monitoring	Yes / Yes		
Insulation monitoring	Yes		
Overheat protection	Yes		
Q at night function	Optional		
General Data			
Dimensions (W*H*D)	6058 * 2896 * 2438 mm		
Weight	17T	17 T	18T
Degree of protection	IP54 (Inverter: IP55)	IP54 (Inverter: IP55)	IP54
Auxiliary power supply	415 V, 15 kVA (Optional: max. 40 kVA)	415 V, 15 kVA (Optional: max. 40 kVA)	415 V, 5 kVA (Optional: max. 40 kVA)
Operating ambient temperature range	-35 to 60 ℃ (> 45 ℃ derating)	-35 to 60 ℃ (> 50 ℃ der ating)	-35 to 60 ℃ (> 50 ℃ derating)
Allowable relative humidity range (non-condensing)	0 – 95 %		
Cooling method	Temperature controlled forced air cooling		
Max. operating altitude	1000 m (standard) / > 1000 m (optional)		
Display	Touch screen		
Communication	Standard: RS485, Ethernet; Optional: optical fiber		
Compliance	CE, IEC 62109, IEC 62116, IEC 61727		
Grid support	Q at night function (optional), L / HVRT, active & reactive power control and power ramp rate control		

Figure D.1: Inverter data sheet

APPENDIX E

PVSYST REPORT



PVSYST V6.81		28/03/20	Page 1/1

Characteristics of a PV module

Manufacturer, model :	**Jinkosolar, JKM 340PP-72 (Plus)**
Availability :	Prod. Since 2017
Data source :	Manufacturer 2017

STC power (manufacturer)	**Pnom**	**340**	**Wp**	**Technology**		**Si-poly**	
Module size (W x L)		0.992 x 1.956	m²	Rough module area	Amodule	1.94	m²
Number of cells		1 x 72		Sensitive area (cells)	Acells	1.75	m²

Specifications for the model (manufacturer or measurement data)

Reference temperature	TRef	25	°C	Reference irradiance	GRef	1000	W/m²
Open circuit voltage	Voc	47.5	V	Short-circuit current	Isc	9.22	A
Max. power point voltage	Vmpp	38.2	V	Max. power point current	Impp	8.90	A
=> maximum power	Pmpp	340.0	W	Isc temperature coefficient	muIsc	4.4	mA/°C

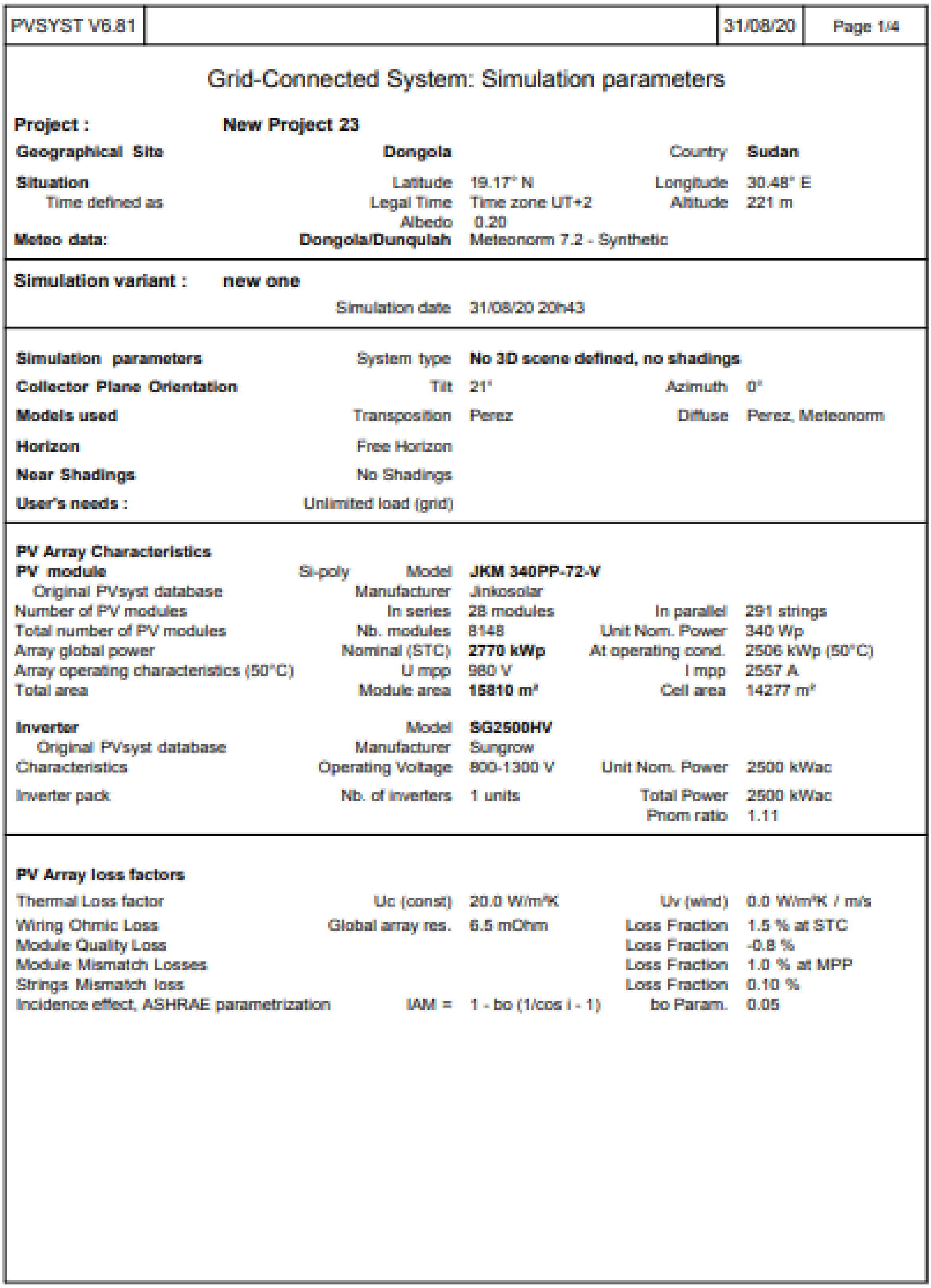
One-diode model parameters

Shunt resistance	Rshunt	600	ohm	Diode saturation current	IoRef	0.051	nA
Serie resistance	Rserie	0.31	ohm	Voc temp. coefficient	MuVoc	-153	mV/°C
				Diode quality factor	Gamma	0.99	
Specified Pmax temper. coeff.	muPMaxR	-0.39	%/°C	Diode factor temper. coeff.	muGamma	-0.001	1/°C

Model results for standard conditions (STC: T=25°C, G=1000 W/m², AM=1.5)

Max. power point voltage	Vmpp	39.1	V	Max. power point current	Impp	8.74	A
Maximum power	Pmpp	342.0	Wc	Power temper. coefficient	muPmpp	-0.38	%/°C
Efficiency(/ Module area)	Eff_mod	17.6	%	Fill factor	FF	0.781	
Efficiency(/ Cells area)	Eff_cells	19.5	%				

PV module: Jinkosolar, JKM 340PP-72 (Plus)



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Grid-Connected System: Simulation parameters

Project :	**New Project 23**			
Geographical Site		**Dongola**	Country	**Sudan**
Situation	Latitude	19.17° N	Longitude	30.48° E
Time defined as	Legal Time	Time zone UT+2	Altitude	221 m
	Albedo	0.20		
Meteo data:	**Dongola/Dunqulah**	Meteonorm 7.2 - Synthetic		

Simulation variant :	**new one**			
	Simulation date	31/08/20 20h43		

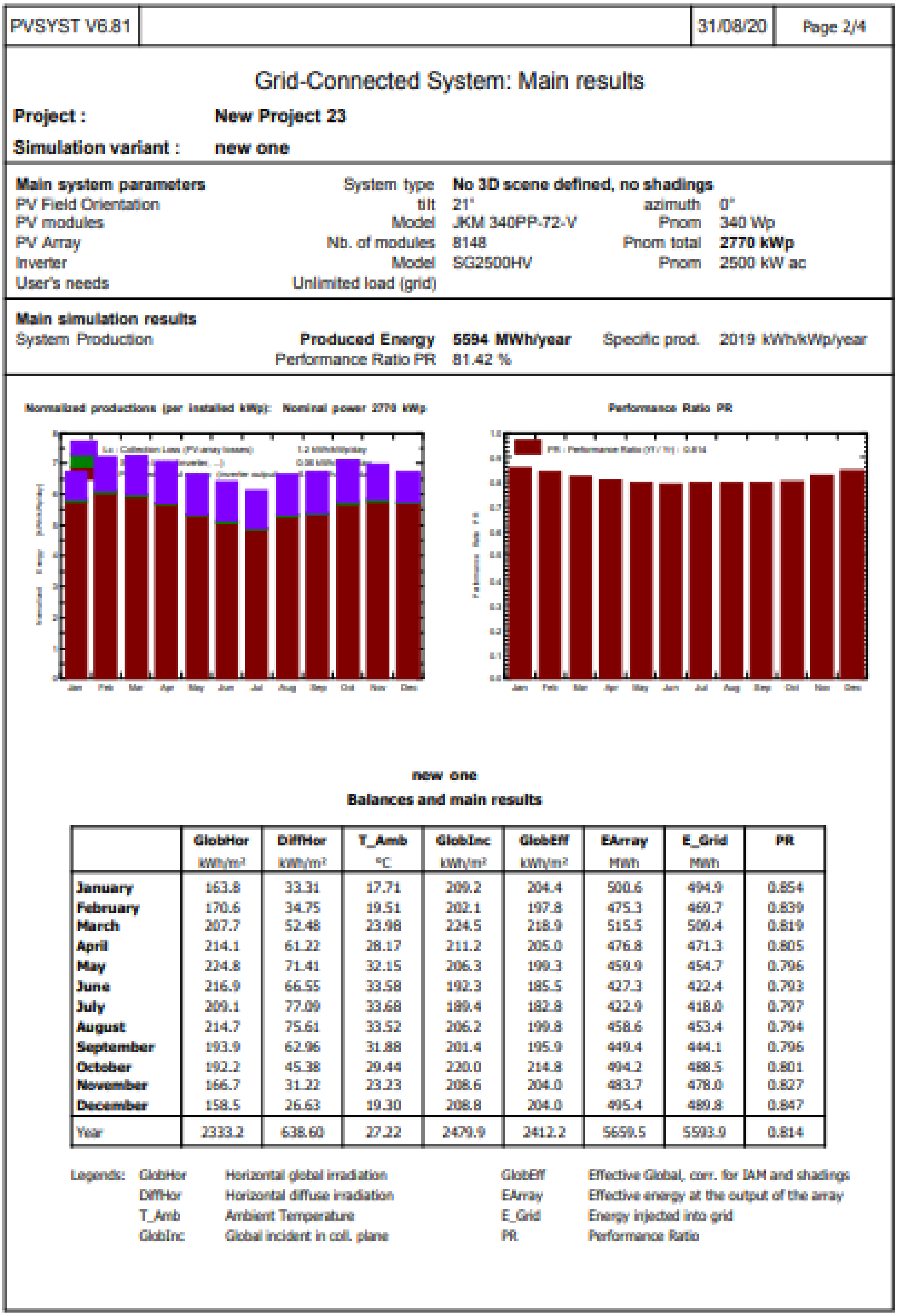
Simulation parameters	System type	**No 3D scene defined, no shadings**		
Collector Plane Orientation	Tilt	21°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			
User's needs :	Unlimited load (grid)			

PV Array Characteristics

PV module	Si-poly	Model	**JKM 340PP-72-V**		
Original PVsyst database		Manufacturer	Jinkosolar		
Number of PV modules		In series	28 modules	In parallel	291 strings
Total number of PV modules		Nb. modules	8148	Unit Nom. Power	340 Wp
Array global power		Nominal (STC)	**2770 kWp**	At operating cond.	2506 kWp (50°C)
Array operating characteristics (50°C)		U mpp	980 V	I mpp	2557 A
Total area		Module area	**15810 m^2**	Cell area	14277 m^2
Inverter		Model	**SG2500HV**		
Original PVsyst database		Manufacturer	Sungrow		
Characteristics		Operating Voltage	800-1300 V	Unit Nom. Power	2500 kWac
Inverter pack		Nb. of inverters	1 units	Total Power	2500 kWac
				Pnom ratio	1.11

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m^2K	Uv (wind)	0.0 W/m^2K / m/s
Wiring Ohmic Loss	Global array res.	6.5 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05



PVSYST V6.81		31/08/20	Page 2/4

Grid-Connected System: Main results

Project : **New Project 23**

Simulation variant : **new one**

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	21°	azimuth	0°
PV modules	Model	JKM 340PP-72-V	Pnom	340 Wp
PV Array	Nb. of modules	8148	Pnom total	**2770 kWp**
Inverter	Model	SG2500HV	Pnom	2500 kW ac
User's needs	Unlimited load (grid)			

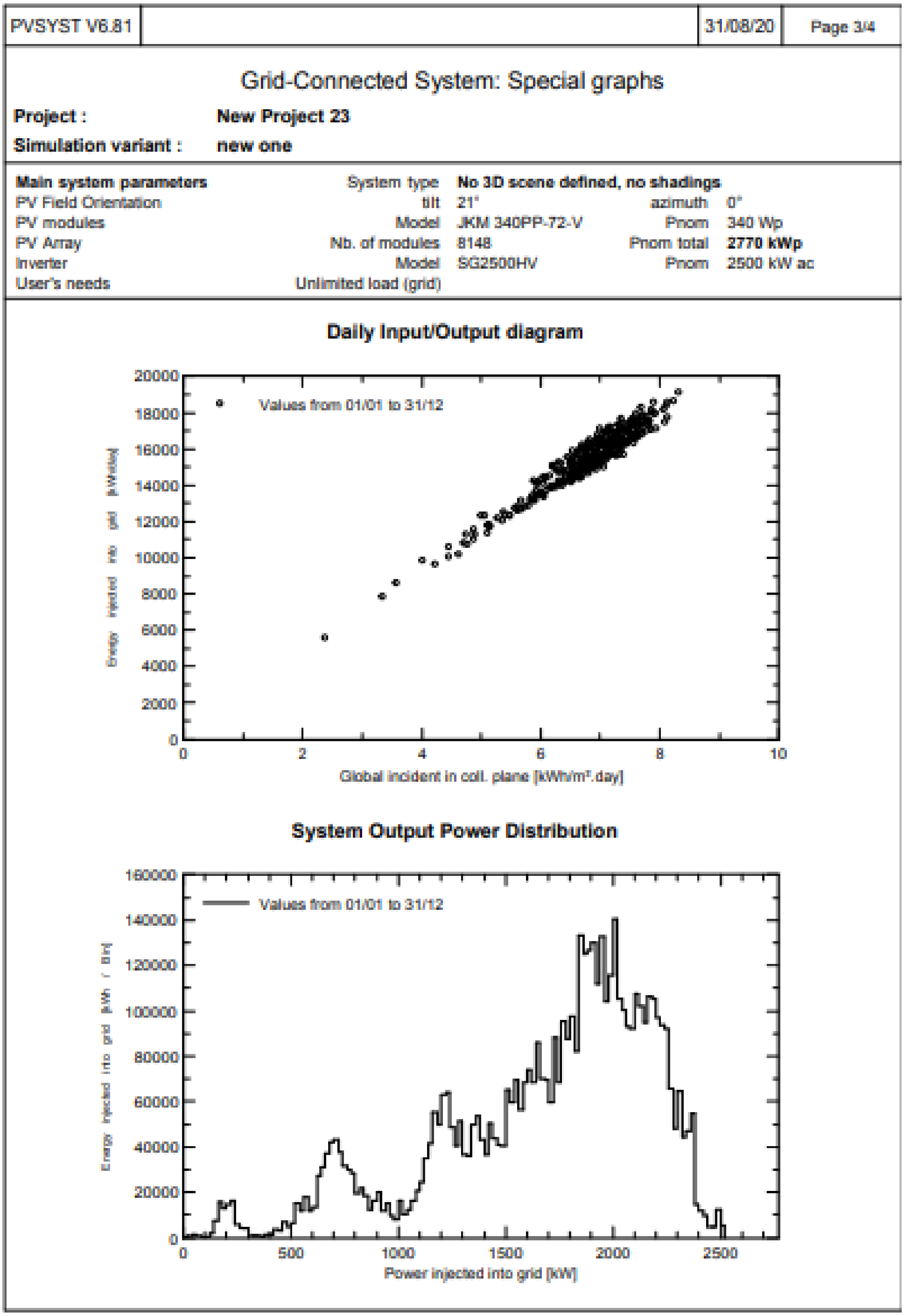
Main simulation results				
System Production	**Produced Energy**	**5594 MWh/year**	Specific prod.	2019 kWh/kWp/year
	Performance Ratio PR	81.42 %		

new one

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	163.8	33.31	17.71	209.2	204.4	500.6	494.9	0.854
February	170.6	34.75	19.51	202.1	197.8	475.3	469.7	0.839
March	207.7	52.48	23.98	224.5	218.9	515.5	509.4	0.819
April	214.1	61.22	28.17	211.2	205.0	476.8	471.3	0.805
May	224.8	71.41	32.15	206.3	199.3	459.9	454.7	0.796
June	216.9	66.55	33.58	192.3	185.5	427.3	422.4	0.793
July	209.1	77.09	33.68	189.4	182.8	422.9	418.0	0.797
August	214.7	75.61	33.52	206.2	199.8	458.6	453.4	0.794
September	193.9	62.96	31.88	201.4	195.9	449.4	444.1	0.796
October	192.2	45.38	29.44	220.0	214.8	494.2	488.5	0.801
November	166.7	31.22	23.23	208.6	204.0	483.7	478.0	0.827
December	158.5	26.63	19.30	208.8	204.0	495.4	489.8	0.847
Year	2333.2	638.60	27.22	2479.9	2412.2	5659.5	5593.9	0.814

Legends:				
	GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
	DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
	T_Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	PR	Performance Ratio



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Grid-Connected System: Special graphs

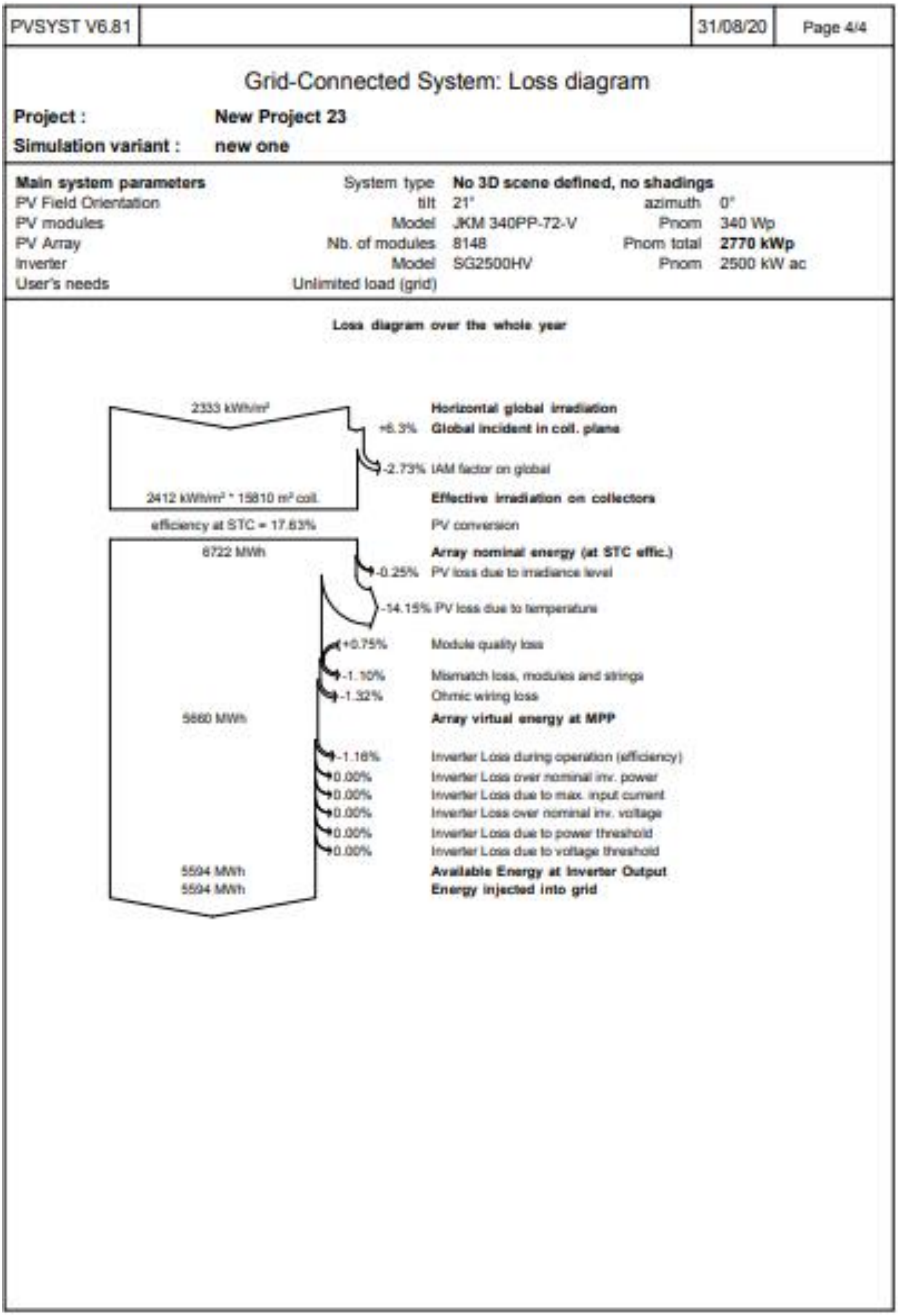
Project : **New Project 23**

Simulation variant : **new one**

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	21°	azimuth	0°
PV modules	Model	JKM 340PP-72-V	Pnom	340 Wp
PV Array	Nb. of modules	8148	Pnom total	**2770 kWp**
Inverter	Model	SG2500HV	Pnom	2500 kW ac
User's needs	Unlimited load (grid)			

Daily Input/Output diagram

System Output Power Distribution



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Grid-Connected System: Loss diagram

Project : **New Project 23**
Simulation variant : **new one**

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	21°	azimuth	0°
PV modules	Model	JKM 340PP-72-V	Pnom	340 Wp
PV Array	Nb. of modules	8148	Pnom total	**2770 kWp**
Inverter	Model	SG2500HV	Pnom	2500 kW ac
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

2333 kWh/m² **Horizontal global irradiation**
+6.3% **Global incident in coll. plane**
-2.73% IAM factor on global
2412 kWh/m² * 15810 m² coll. **Effective irradiation on collectors**
efficiency at STC = 17.63% PV conversion
6722 MWh **Array nominal energy (at STC effic.)**
-0.25% PV loss due to irradiance level
-14.15% PV loss due to temperature
+0.75% Module quality loss
-1.10% Mismatch loss, modules and strings
-1.32% Ohmic wiring loss
5660 MWh **Array virtual energy at MPP**
-1.16% Inverter Loss during operation (efficiency)
0.00% Inverter Loss over nominal inv. power
0.00% Inverter Loss due to max. input current
0.00% Inverter Loss over nominal inv. voltage
0.00% Inverter Loss due to power threshold
0.00% Inverter Loss due to voltage threshold
5594 MWh **Available Energy at Inverter Output**
5594 MWh **Energy injected into grid**

APPENDIX F

WIND TURBINE SPECIFICATIONS

www.thewindpower.net
November 4, 2020

SE12120 (Sany)

Main data

Rated power: 2000 kW
Rotor diameter: 121 m
Old model
Class: IEC IIIC
Offshore model: no
Commissioning: 2017

Rotor

Number of blades: 3
Type: Pitch
Swept area: 11499 m2
Power density: 5.75 m2/kW

Tower

Minimum hub height: 80 m
Maximum hub height: 90 m

Weights

Nacelle: 70 t
Rotor + hub: 62,5 t

Gearbox

Gearbox: yes

Wind speeds

Cut-in wind speed: 3 m/s
Cut-off wind speed: 22 m/s

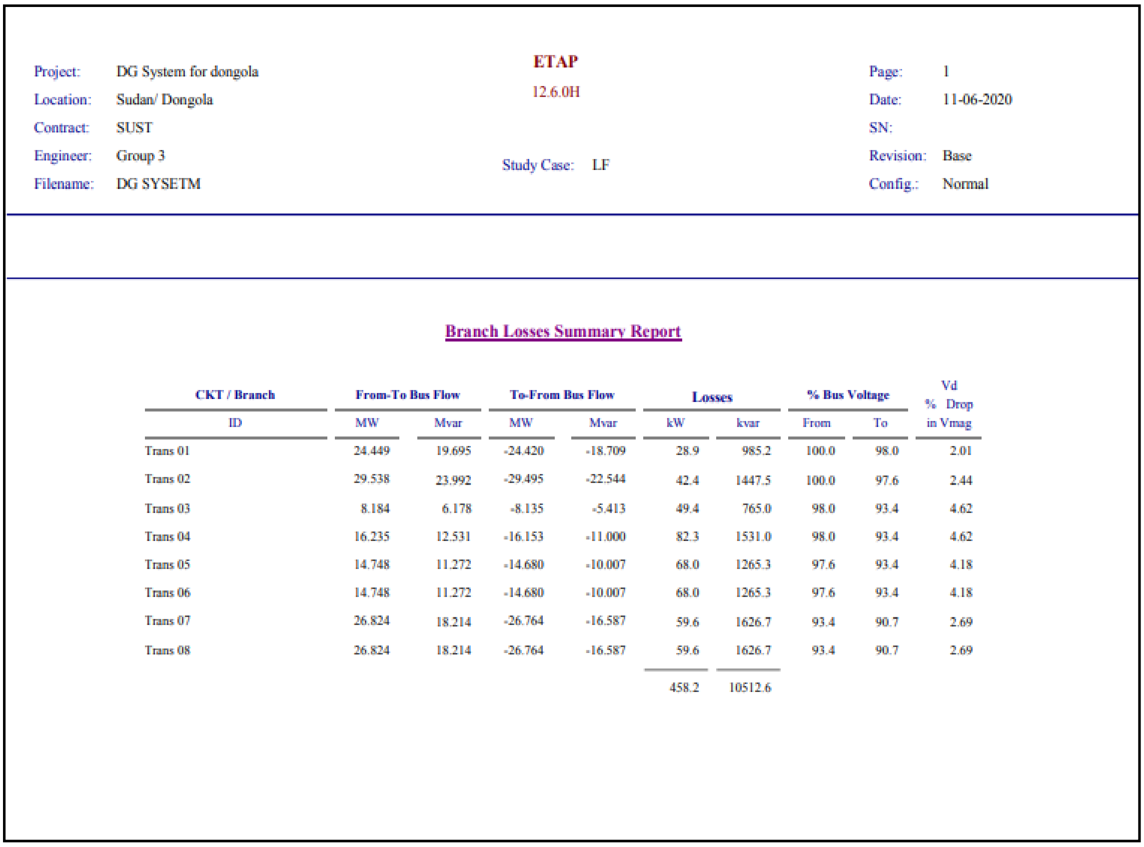
Generator

Type: DFIG
Number: 1
Maximum speed: 1800 rd/min

Figure F.1: Wind turbine data sheet

APPENDIX G

POWER SYSTEM STUDIES WITHOUT PV/WIND SYSTEMS



Project: DG System for dongola
Location: Sudan/ Dongola
Contract: SUST
Engineer: Group 3
Filename: DG SYSETM

ETAP
12.6.0H

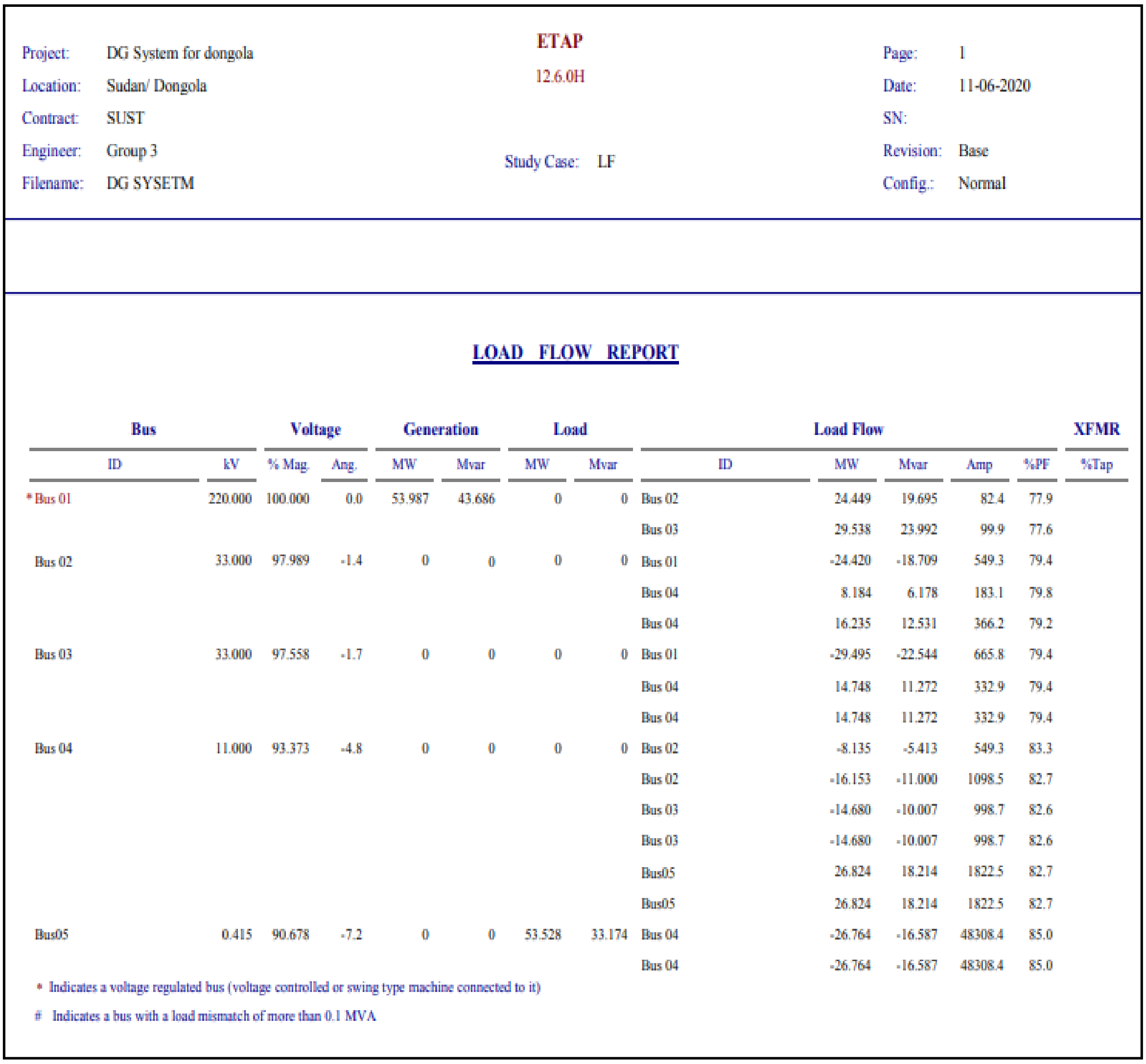
Study Case: LF

Page: 1
Date: 11-06-2020
SN:
Revision: Base
Config.: Normal

Branch Losses Summary Report

CKT / Branch	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd
ID	MW	Mvar	MW	Mvar	kW	kvar	From	To	% Drop in Vmag
Trans 01	24.449	19.695	-24.420	-18.709	28.9	985.2	100.0	98.0	2.01
Trans 02	29.538	23.992	-29.495	-22.544	42.4	1447.5	100.0	97.6	2.44
Trans 03	8.184	6.178	-8.135	-5.413	49.4	765.0	98.0	93.4	4.62
Trans 04	16.235	12.531	-16.153	-11.000	82.3	1531.0	98.0	93.4	4.62
Trans 05	14.748	11.272	-14.680	-10.007	68.0	1265.3	97.6	93.4	4.18
Trans 06	14.748	11.272	-14.680	-10.007	68.0	1265.3	97.6	93.4	4.18
Trans 07	26.824	18.214	-26.764	-16.587	59.6	1626.7	93.4	90.7	2.69
Trans 08	26.824	18.214	-26.764	-16.587	59.6	1626.7	93.4	90.7	2.69
					458.2	10512.6			

Figure G.1: Total power loss before the integration



Project: DG System for dongola
Location: Sudan/ Dongola
Contract: SUST
Engineer: Group 3
Filename: DG SYSETM

ETAP
12.6.0H

Study Case: LF

Page: 1
Date: 11-06-2020
SN:
Revision: Base
Config.: Normal

LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
* Bus 01	220.000	100.000	0.0	53.987	43.686	0	0	Bus 02	24.449	19.695	82.4	77.9	
								Bus 03	29.538	23.992	99.9	77.6	
Bus 02	33.000	97.989	-1.4	0	0	0	0	Bus 01	-24.420	-18.709	549.3	79.4	
								Bus 04	8.184	6.178	183.1	79.8	
								Bus 04	16.235	12.531	366.2	79.2	
Bus 03	33.000	97.558	-1.7	0	0	0	0	Bus 01	-29.495	-22.544	665.8	79.4	
								Bus 04	14.748	11.272	332.9	79.4	
								Bus 04	14.748	11.272	332.9	79.4	
Bus 04	11.000	93.373	-4.8	0	0	0	0	Bus 02	-8.135	-5.413	549.3	83.3	
								Bus 02	-16.153	-11.000	1098.5	82.7	
								Bus 03	-14.680	-10.007	998.7	82.6	
								Bus 03	-14.680	-10.007	998.7	82.6	
								Bus05	26.824	18.214	1822.5	82.7	
								Bus05	26.824	18.214	1822.5	82.7	
Bus05	0.415	90.678	-7.2	0	0	53.528	33.174	Bus 04	-26.764	-16.587	48308.4	85.0	
								Bus 04	-26.764	-16.587	48308.4	85.0	

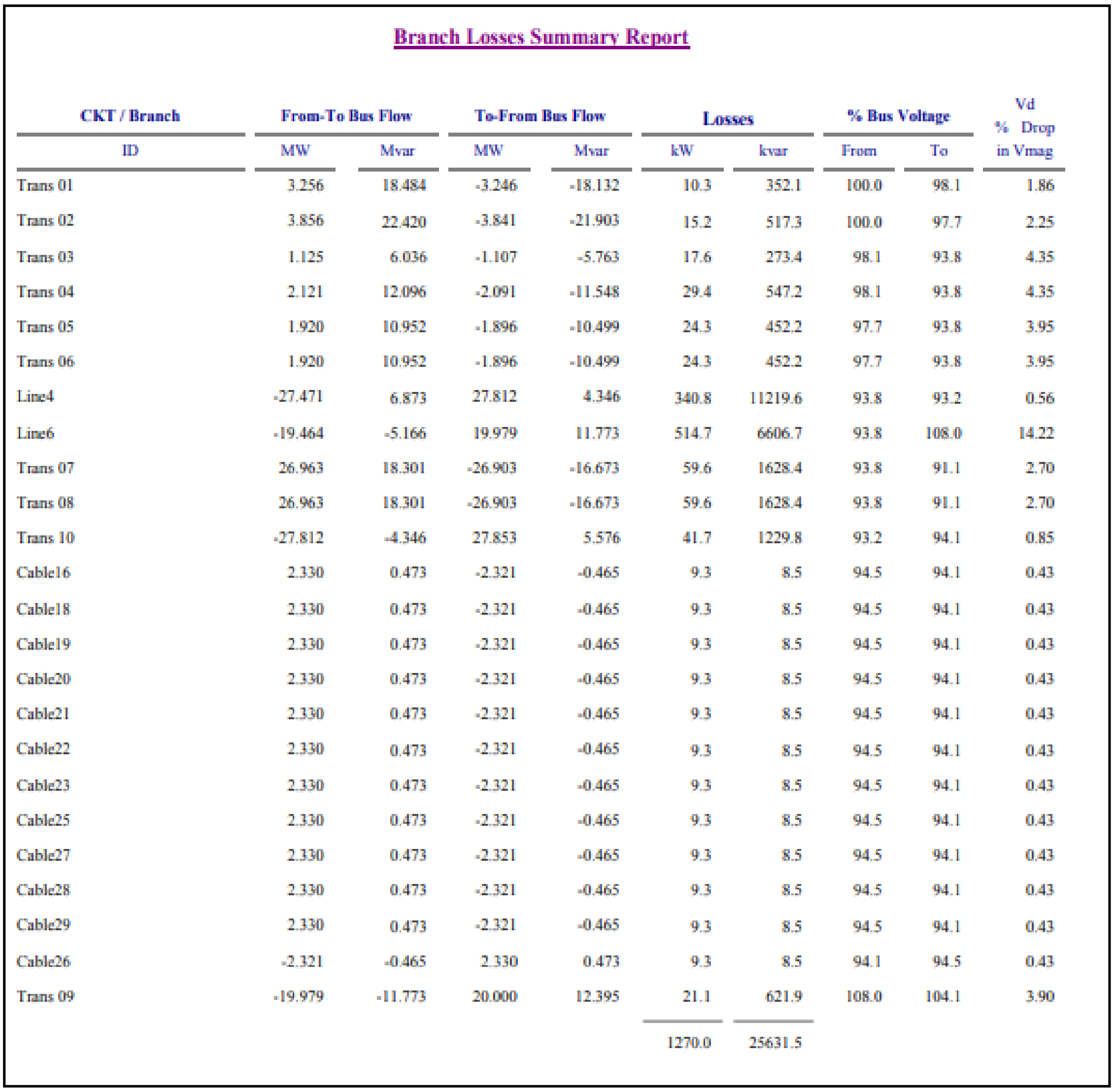
* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)

# Indicates a bus with a load mismatch of more than 0.1 MVA

Figure G.2: Load flow analysis before the integration

APPENDIX H

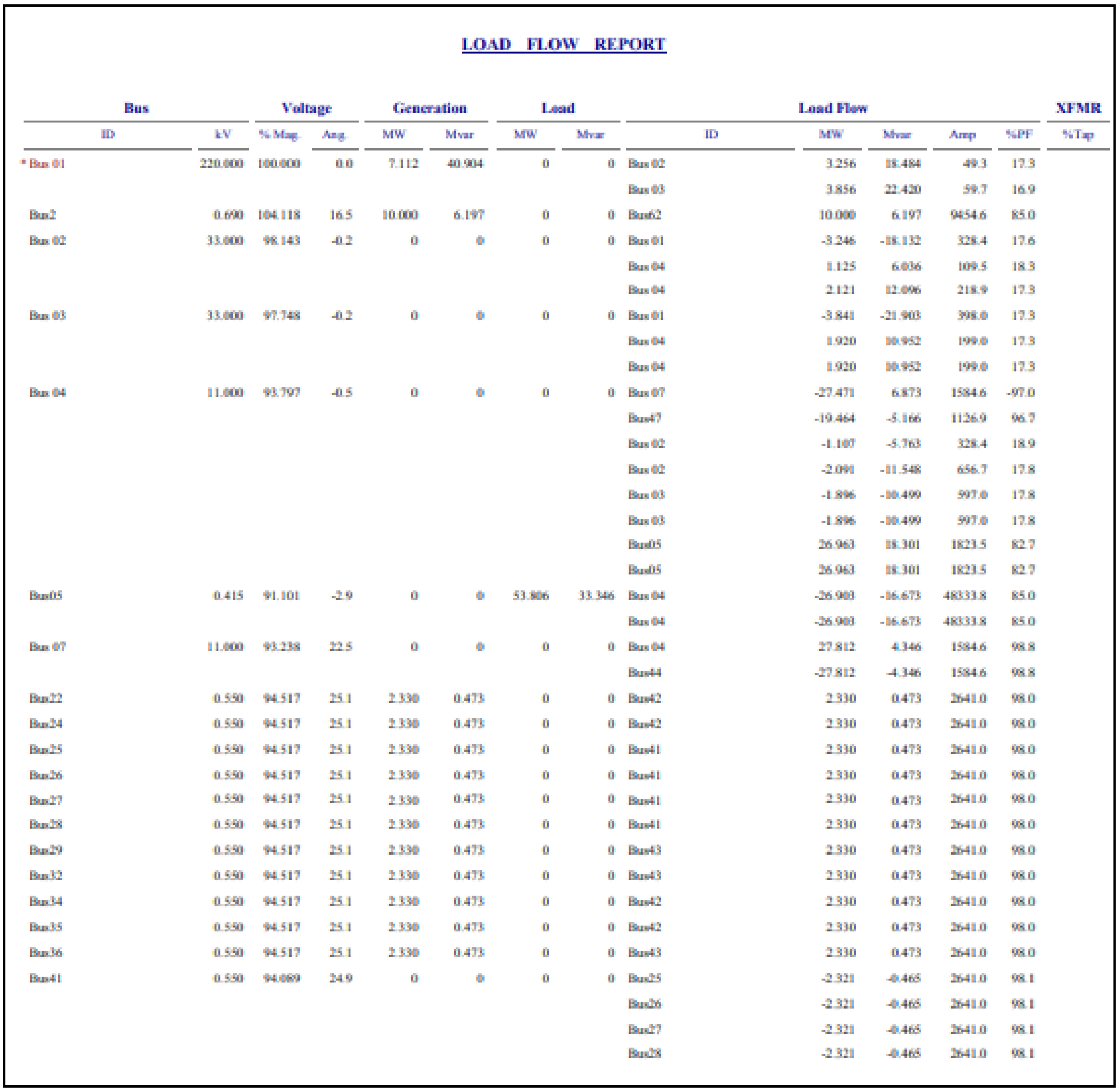
LOAD FLOW REPORT SCENARIO I



Branch Losses Summary Report

CKT / Branch	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop in Vmag
ID	MW	Mvar	MW	Mvar	kW	kvar	From	To	
Trans 01	3.256	18.484	-3.246	-18.132	10.3	352.1	100.0	98.1	1.86
Trans 02	3.856	22.420	-3.841	-21.903	15.2	517.3	100.0	97.7	2.25
Trans 03	1.125	6.036	-1.107	-5.763	17.6	273.4	98.1	93.8	4.35
Trans 04	2.121	12.096	-2.091	-11.548	29.4	547.2	98.1	93.8	4.35
Trans 05	1.920	10.952	-1.896	-10.499	24.3	452.2	97.7	93.8	3.95
Trans 06	1.920	10.952	-1.896	-10.499	24.3	452.2	97.7	93.8	3.95
Line4	-27.471	6.873	27.812	4.346	340.8	11219.6	93.8	93.2	0.56
Line6	-19.464	-5.166	19.979	11.773	514.7	6606.7	93.8	108.0	14.22
Trans 07	26.963	18.301	-26.903	-16.673	59.6	1628.4	93.8	91.1	2.70
Trans 08	26.963	18.301	-26.903	-16.673	59.6	1628.4	93.8	91.1	2.70
Trans 10	-27.812	-4.346	27.853	5.576	41.7	1229.8	93.2	94.1	0.85
Cable16	2.330	0.473	-2.321	-0.465	9.3	8.5	94.5	94.1	0.43
Cable18	2.330	0.473	-2.321	-0.465	9.3	8.5	94.5	94.1	0.43
Cable19	2.330	0.473	-2.321	-0.465	9.3	8.5	94.5	94.1	0.43
Cable20	2.330	0.473	-2.321	-0.465	9.3	8.5	94.5	94.1	0.43
Cable21	2.330	0.473	-2.321	-0.465	9.3	8.5	94.5	94.1	0.43
Cable22	2.330	0.473	-2.321	-0.465	9.3	8.5	94.5	94.1	0.43
Cable23	2.330	0.473	-2.321	-0.465	9.3	8.5	94.5	94.1	0.43
Cable25	2.330	0.473	-2.321	-0.465	9.3	8.5	94.5	94.1	0.43
Cable27	2.330	0.473	-2.321	-0.465	9.3	8.5	94.5	94.1	0.43
Cable28	2.330	0.473	-2.321	-0.465	9.3	8.5	94.5	94.1	0.43
Cable29	2.330	0.473	-2.321	-0.465	9.3	8.5	94.5	94.1	0.43
Cable26	-2.321	-0.465	2.330	0.473	9.3	8.5	94.1	94.5	0.43
Trans 09	-19.979	-11.773	20.000	12.395	21.1	621.9	108.0	104.1	3.90
					1270.0	25631.5			

Figure H.1: System power loss with 30 MW PV/20 MW wind



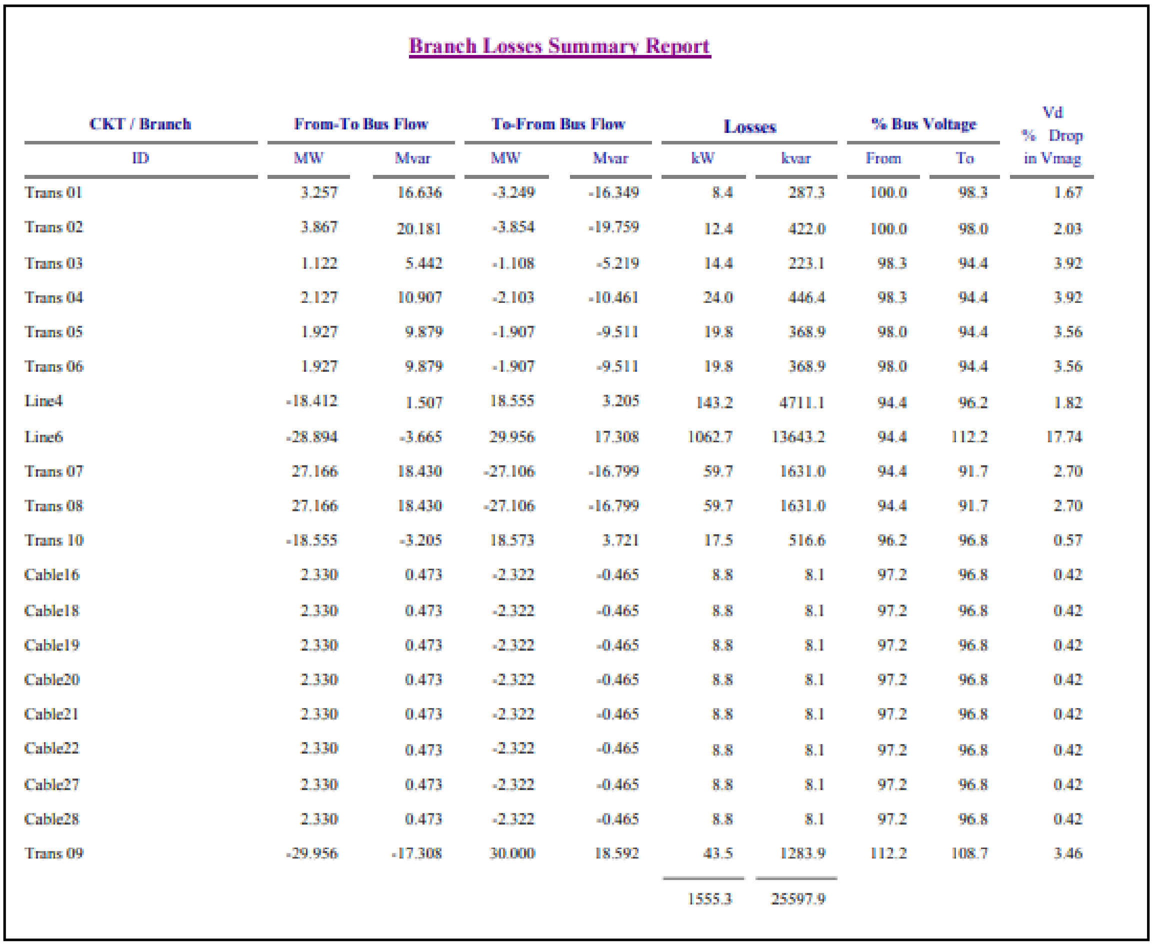
LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
* Bus 01	220.000	100.000	0.0	7.112	40.904	0	0	Bus 02	3.256	18.484	49.3	17.3	
								Bus 03	3.856	22.420	59.7	16.9	
Bus2	0.690	104.118	16.5	10.000	6.197	0	0	Bus62	10.000	6.197	9454.6	85.0	
Bus 02	33.000	98.143	-0.2	0	0	0	0	Bus 01	-3.246	-18.132	328.4	17.6	
								Bus 04	1.125	6.036	109.5	18.3	
								Bus 04	2.121	12.096	218.9	17.3	
Bus 03	33.000	97.748	-0.2	0	0	0	0	Bus 01	-3.841	-21.903	398.0	17.3	
								Bus 04	1.920	10.952	199.0	17.3	
								Bus 04	1.920	10.952	199.0	17.3	
Bus 04	11.000	93.797	-0.5	0	0	0	0	Bus 07	-27.471	6.873	1584.6	-97.0	
								Bus47	-19.464	-5.166	1126.9	96.7	
								Bus 02	-1.107	-5.763	328.4	18.9	
								Bus 02	-2.091	-11.548	656.7	17.8	
								Bus 03	-1.896	-10.499	597.0	17.8	
								Bus 03	-1.896	-10.499	597.0	17.8	
								Bus05	26.963	18.301	1823.5	82.7	
								Bus05	26.963	18.301	1823.5	82.7	
Bus05	0.415	91.101	-2.9	0	0	53.806	33.346	Bus 04	-26.900	-16.673	48333.8	85.0	
								Bus 04	-26.900	-16.673	48333.8	85.0	
Bus 07	11.000	93.238	22.5	0	0	0	0	Bus 04	27.812	4.346	1584.6	98.8	
								Bus44	-27.812	-4.346	1584.6	98.8	
Bus22	0.550	94.517	25.1	2.330	0.473	0	0	Bus42	2.330	0.473	2641.0	98.0	
Bus24	0.550	94.517	25.1	2.330	0.473	0	0	Bus42	2.330	0.473	2641.0	98.0	
Bus25	0.550	94.517	25.1	2.330	0.473	0	0	Bus41	2.330	0.473	2641.0	98.0	
Bus26	0.550	94.517	25.1	2.330	0.473	0	0	Bus41	2.330	0.473	2641.0	98.0	
Bus27	0.550	94.517	25.1	2.330	0.473	0	0	Bus41	2.330	0.473	2641.0	98.0	
Bus28	0.550	94.517	25.1	2.330	0.473	0	0	Bus41	2.330	0.473	2641.0	98.0	
Bus29	0.550	94.517	25.1	2.330	0.473	0	0	Bus43	2.330	0.473	2641.0	98.0	
Bus32	0.550	94.517	25.1	2.330	0.473	0	0	Bus43	2.330	0.473	2641.0	98.0	
Bus34	0.550	94.517	25.1	2.330	0.473	0	0	Bus42	2.330	0.473	2641.0	98.0	
Bus35	0.550	94.517	25.1	2.330	0.473	0	0	Bus42	2.330	0.473	2641.0	98.0	
Bus36	0.550	94.517	25.1	2.330	0.473	0	0	Bus43	2.330	0.473	2641.0	98.0	
Bus41	0.550	94.089	24.9	0	0	0	0	Bus25	-2.321	-0.465	2641.0	98.1	
								Bus26	-2.321	-0.465	2641.0	98.1	
								Bus27	-2.321	-0.465	2641.0	98.1	
								Bus28	-2.321	-0.465	2641.0	98.1	

Figure H.2: System load flow with 30 MW PV/20 MW wind

APPENDIX I

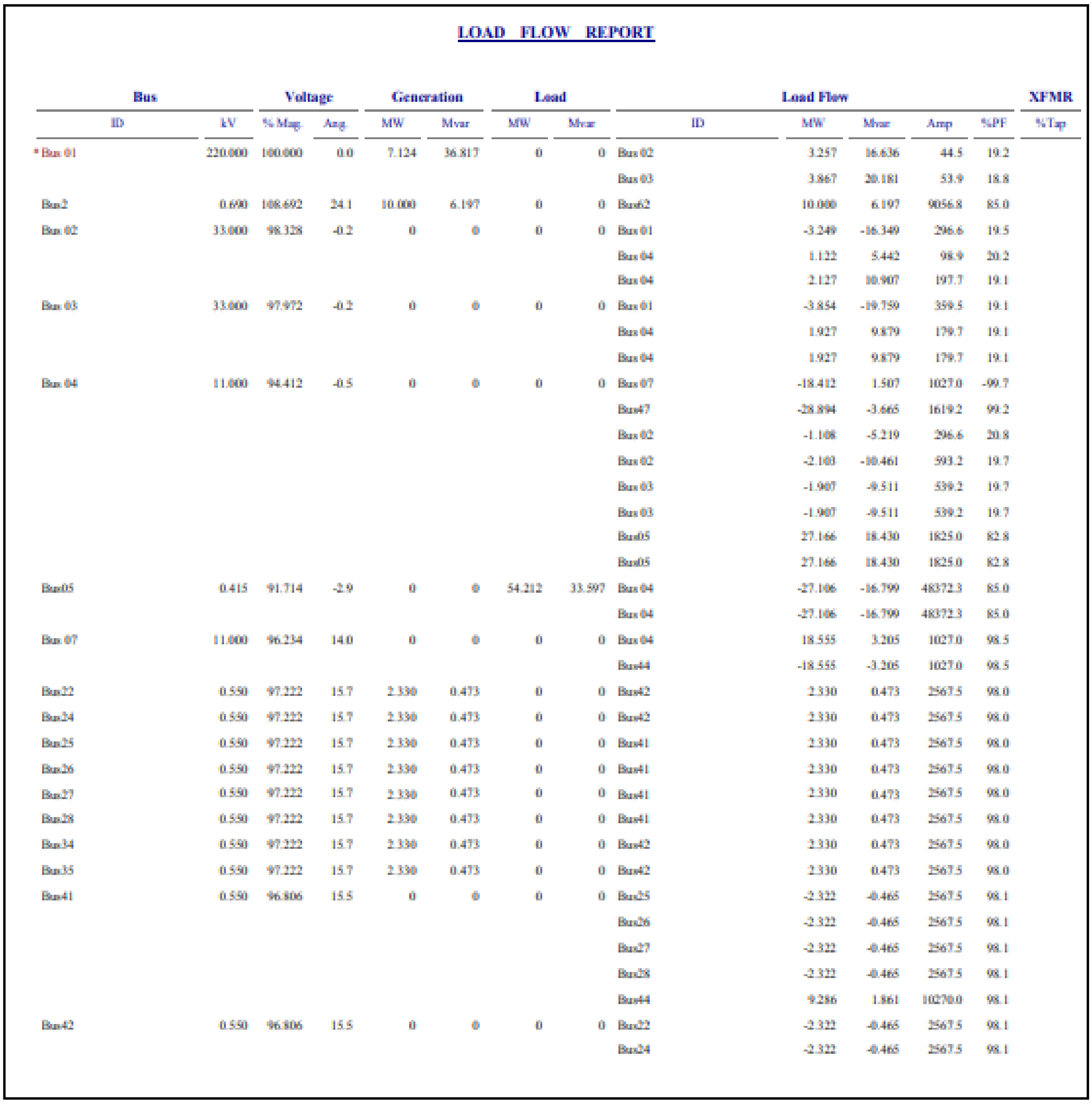
LOAD FLOW REPORT SCENARIO II



Branch Losses Summary Report

CKT / Branch	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop in Vmag
ID	MW	Mvar	MW	Mvar	kW	kvar	From	To	
Trans 01	3.257	16.636	-3.249	-16.349	8.4	287.3	100.0	98.3	1.67
Trans 02	3.867	20.181	-3.854	-19.759	12.4	422.0	100.0	98.0	2.03
Trans 03	1.122	5.442	-1.108	-5.219	14.4	223.1	98.3	94.4	3.92
Trans 04	2.127	10.907	-2.103	-10.461	24.0	446.4	98.3	94.4	3.92
Trans 05	1.927	9.879	-1.907	-9.511	19.8	368.9	98.0	94.4	3.56
Trans 06	1.927	9.879	-1.907	-9.511	19.8	368.9	98.0	94.4	3.56
Line4	-18.412	1.507	18.555	3.205	143.2	4711.1	94.4	96.2	1.82
Line6	-28.894	-3.665	29.956	17.308	1062.7	13643.2	94.4	112.2	17.74
Trans 07	27.166	18.430	-27.106	-16.799	59.7	1631.0	94.4	91.7	2.70
Trans 08	27.166	18.430	-27.106	-16.799	59.7	1631.0	94.4	91.7	2.70
Trans 10	-18.555	-3.205	18.573	3.721	17.5	516.6	96.2	96.8	0.57
Cable16	2.330	0.473	-2.322	-0.465	8.8	8.1	97.2	96.8	0.42
Cable18	2.330	0.473	-2.322	-0.465	8.8	8.1	97.2	96.8	0.42
Cable19	2.330	0.473	-2.322	-0.465	8.8	8.1	97.2	96.8	0.42
Cable20	2.330	0.473	-2.322	-0.465	8.8	8.1	97.2	96.8	0.42
Cable21	2.330	0.473	-2.322	-0.465	8.8	8.1	97.2	96.8	0.42
Cable22	2.330	0.473	-2.322	-0.465	8.8	8.1	97.2	96.8	0.42
Cable27	2.330	0.473	-2.322	-0.465	8.8	8.1	97.2	96.8	0.42
Cable28	2.330	0.473	-2.322	-0.465	8.8	8.1	97.2	96.8	0.42
Trans 09	-29.956	-17.308	30.000	18.592	43.5	1283.9	112.2	108.7	3.46
					1555.3	25597.9			

Figure I.1: System power loss with 20 MW PV/30 MW wind



LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
* Bus 01	220.000	100.000	0.0	7.124	36.817	0	0	Bus 02	3.257	16.636	44.5	19.2	
								Bus 03	3.867	20.181	53.9	18.8	
Bus2	0.690	108.692	24.1	10.000	6.197	0	0	Bus62	10.000	6.197	9056.8	85.0	
Bus 02	33.000	98.328	-0.2	0	0	0	0	Bus 01	-3.249	-16.349	296.6	19.5	
								Bus 04	1.122	5.442	98.9	20.2	
								Bus 04	2.127	10.907	197.7	19.1	
Bus 03	33.000	97.972	-0.2	0	0	0	0	Bus 01	-3.854	-19.759	359.5	19.1	
								Bus 04	1.927	9.879	179.7	19.1	
								Bus 04	1.927	9.879	179.7	19.1	
Bus 04	11.000	94.412	-0.5	0	0	0	0	Bus 07	-18.412	1.507	1027.0	-99.7	
								Bus47	-28.894	-3.665	1619.2	99.2	
								Bus 02	-1.108	-5.219	296.6	20.8	
								Bus 02	-2.103	-10.461	593.2	19.7	
								Bus 03	-1.907	-9.511	539.2	19.7	
								Bus 03	-1.907	-9.511	539.2	19.7	
								Bus05	27.166	18.430	1825.0	82.8	
								Bus05	27.166	18.430	1825.0	82.8	
Bus05	0.415	91.714	-2.9	0	0	54.212	33.597	Bus 04	-27.106	-16.799	48372.3	85.0	
								Bus 04	-27.106	-16.799	48372.3	85.0	
Bus 07	11.000	96.234	14.0	0	0	0	0	Bus 04	18.555	3.205	1027.0	98.5	
								Bus44	-18.555	-3.205	1027.0	98.5	
Bus22	0.550	97.222	15.7	2.330	0.473	0	0	Bus42	2.330	0.473	2567.5	98.0	
Bus24	0.550	97.222	15.7	2.330	0.473	0	0	Bus42	2.330	0.473	2567.5	98.0	
Bus25	0.550	97.222	15.7	2.330	0.473	0	0	Bus41	2.330	0.473	2567.5	98.0	
Bus26	0.550	97.222	15.7	2.330	0.473	0	0	Bus41	2.330	0.473	2567.5	98.0	
Bus27	0.550	97.222	15.7	2.330	0.473	0	0	Bus41	2.330	0.473	2567.5	98.0	
Bus28	0.550	97.222	15.7	2.330	0.473	0	0	Bus41	2.330	0.473	2567.5	98.0	
Bus34	0.550	97.222	15.7	2.330	0.473	0	0	Bus42	2.330	0.473	2567.5	98.0	
Bus35	0.550	97.222	15.7	2.330	0.473	0	0	Bus42	2.330	0.473	2567.5	98.0	
Bus41	0.550	96.806	15.5	0	0	0	0	Bus25	-2.322	-0.465	2567.5	98.1	
								Bus26	-2.322	-0.465	2567.5	98.1	
								Bus27	-2.322	-0.465	2567.5	98.1	
								Bus28	-2.322	-0.465	2567.5	98.1	
								Bus44	9.286	1.861	10270.0	98.1	
Bus42	0.550	96.806	15.5	0	0	0	0	Bus22	-2.322	-0.465	2567.5	98.1	
								Bus24	-2.322	-0.465	2567.5	98.1	

Figure I.2: System load flow with 20 MW PV/30 MW wind