A Project Report On

FUZZY BASED VOLTAGE SAG ENHANCEMENT OF GRID CONNECTED HYBRID PV-WIND POWER SYSTEM USING BATTERY AND SMES BASED DYNAMIC VOLTAGE RESTORER

Submitted to
the Department of Electrical and Electronics Engineering,
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CERTIFICATE

This is to certify that the project report entitled **FUZZY BASED VOLTAGE SAG ENHANCEMENT OF GRID CONNECTED HYBRID PV-WIND POWER SYSTEM USING BATTERY AND SMES BASED DYNAMIC VOLTAGE RESTORER** submitted by **Kontham Dilip Reddy (2451-19-734-002), Kanne Yashwanth (2451-19-734-046), Yelakonda Jashwanth Reddy (2451-19-734-058)** to the department of EEE, Maturi Venkata Subba Rao (MVSR) Engineering College, in the partial fulfillment of the requirement for the degree of Bachelor of Engineering in Electrical and Electronics Engineering is a bona fide record of project work carried out under my supervision. The contents of this report, in full or in parts, have not been submitted to any other Institution or University for the award of any degree or diploma.

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Declaration

We declare that this project report titled **FUZZY BASED VOLTAGE SAG ENHANCEMENT OF GRID CONNECTED HYBRID PV-WIND POWER SYSTEM USING BATTERY AND SMES BASED DYNAMIC VOLTAGE RESTORER** submitted in partial fulfillment of the degree of Bachelor of Engineering in Electrical and Electronics Engineering is a record of original work carried out by us under the supervision of **N.Ravi**, and has not formed the basis for the award of any other degree or diploma, in this or any other Institution or University. In keeping with the ethical practice in reporting scientific information, due acknowledgements have been made wherever the findings of others have been cited.

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Abstract

The microgrid (MG), if properly designed and with an efficient control system, is a platform for the development of distributed and renewable energy-based products. Because MG inertia is low due to its small structure and low resistance to change, it is very difficult to maintain frequency and voltage stability, especially in the island state. Unlike the power grid, inverter-based distributed generation is the main source of MGs. Due to the low response rate of primary energy sources in distributed generation, these productions, even if they have an efficient control system, alone cannot maintain MG stability, so by using electrical energy storage sources and D-STATCOM along with distributed generation, this project proposes an interactive and multilevel structure for voltage and MG frequency stability. This structure greatly speeds up the MG response to perturbations through an interactive control system. The proposed structure has been implemented and evaluated by MATLAB software on MGs that can be used in both connection and island modes in the presence of a renewable wind source.

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CHAPTER 1

INTRODUCTION

While the global demand for energy is increasing constantly, the use of classic sources of energy like oil and coal becomes problematic contributing among other things to climate change. One solution to address climate change is the use of clean renewable energy sources among other solar and wind. Most areas in South Africa average more than 2500 hours of sunshine per year with an annual 24-hour solar radiation of approx. 220 W/m2, compared with 150 W/m2 in the USA and averaging 100 W/m2 for Europe. This makes South Africa's solar radiation resource one of the highest in the world. The progress in power electronics [1], [2], [3], [4] facilitated integration of these renewable energy sources either grid or as stand-alone for small scale use. Historically, the integration was started with wind farms. When the price for photovoltaic panels became affordable, the penetration of PV became to be used more often but not necessarily at the same level of power as wind. For medium to high power the PVs are modularly used [5], [7], [8]. Many studies propose small power integration (few kW) for both wind and solar PV as hybrid stand-alone systems [6],[9], [11], [12]. Other studies added fuel cells and batteries creating the concept of the multi-port system [15]-[20].

1.1 Basic Introduction

While the global demand for energy is increasing constantly, the use of classic sources of energy like oil and coal becomes problematic contributing among other things to climate change. One solution to address climate change is the use of clean renewable energy sources among other solar and wind. Most areas in South Africa average more than 2500 hours of sunshine per year with an annual 24-hour solar radiation of approx. 220 W/m2, compared with 150 W/m2 in the USA and averaging 100 W/m2 for Europe. This makes South Africa's solar radiation resource one of the highest in the world. The progress in power electronics facilitated integration of these renewable energy sources either grid or as stand-alone for small scale use. Historically, the integration was started with wind farms. When the price for photovoltaic panels became affordable, the penetration of PV became to be used more often but not necessarily at the same level of power as wind. For medium to high power the PVs are modularly used. Many studies propose small power integration (few kW) for both wind and solar PV as hybrid stand-alone systems. Other studies added fuel cells and batteries creating the concept of a multi-port system.

Apart from methods of integration continuous attention was towards controlling the systems to maximize solar PV efficiency or wind. The stability of renewable systems was also under scrutiny. Double or multi-port integration systems for renewable have been previously proposed. The commonality of all these studies proposed a parallel connection of various renewable sources on a single dc bus.

In this study, a double-port integration system for renewable energy sources is proposed. Figure 1 shows a small-scale system ofa 1 kW PV array integrater with a 1.5 kW wind generator (WG).

1.2 Literature survey

Papathanassiou S.A. In this paper, a brief review is presented of common electrical generation schemes for wind turbines (WTs) and photovoltaics (PVs). Attention is mainly focused on the power converter interfaces used for the the grid-connectedd operation the renewable generators. The WT soft starting arrangements are described and the most common variable speed operation configurations are presented and discussed. The fundamental characteristics and requirements of the power conditioning equipment used in PVs are outlined and the power converters of certain PV generators are briefly presented

Blaabjerg, F. The global electrical energy consumption is rising and there is a steady increase in the demand for power capacity, efficient production, distribution, and utilization of energy. The traditional power systems are changing globally, many dispersed generation (DG) units, including both renewable and non-renewable energy sources such as wind turbines, photovoltaic (PV) generators, fuel cells, small hydro, wave generators, and gas/steam-powered combined heat and power stations, are being integrated into power systems at the distribution level. Power electronics, the technology of efficiently processing electric power, play an essential part in the integration of the dispersed generation units for good efficiency and high performance of the power systems. This paper reviews the applications of power electronics in the integration of DG units, in particular, wind power, fuel cells, and PV generators.

Carrasco, J.M. The use of distributed energy resources is increasingly being pursued as a supplement and an alternative to large conventional central power stations. The specification of a power-electronic interface is subject to requirements related not only to the renewable energy source itself but also to its effects on the power-system operation, especially where the intermittent energy source constitutes a significant part of the total system capacity. In this paper, new trends in power electronics for the integration of wind and photovoltaic (PV) power generators are presented. A review of the appropriate storage-system technology used for the integration of intermittent renewable energy sources is also introduced. Discussions about common and future trends in renewable energy systems based on the reliability and maturity of each technology are presented

Billinton, R. Renewable energy is being increasingly utilized in electric power systems due to environmental concerns and energy cost escalation associated with the use of conventional energy sources. Photovoltaics and wind energy sources can significantly offset costly fuel in small isolated systems and can also have a considerable impact on the system's reliability. The utilization of renewable energy in capacity planning requires realistic cost/reliability evaluation models that can recognize the highly erratic nature of these energy sources while maintaining the chronology and interdependence of the random variables inherent in them. This paper presents an evaluation model and applies it to analyze the optimum generation expansion of small isolated systems using PV and wind energy sources

J. Marques This paper presents a review of the main types of generators and static converters used to interface variable-speed wind turbines to the electric grid. Initially, the static and dynamic characteristics of wind turbines are presented. Then, different types of generators and static converters configurations are described and their main advantages and disadvantages are highlighted. Index terms-- Wind Turbine, Static Converters, Generators

1.3 Aim of thesis

This paper presents a micro-grid fed from wind and solar-based renewable energy generating sources (REGS). DFIG is used for wind power conversion while crystalline solar photovoltaic (PV) panels are used to convert solar energy. The control of the overall scheme, helps to provide quality power to its consumers for all conditions e.g. no-load, nonlinear load and unbalanced loads. The controls of both generating sources, are equipped with MPPT. Emmanouil et al. [12] have proposed a droop-based control system for micro-grid with the help of a standalone battery converter. In the presented scheme, the droop characteristic is embedded in the control of load side converter (LSC) of DFIG. This function varies the system frequency based on state of charge of the battery and slows down deep discharge and over-charge of the battery.

The DFIG in a proposed system, has also two voltage source converters (VSC). In addition to LSC, DFIG also has another VSC connected to rotor circuit termed as rotor side converter (RSC). The function of RSC is to achieve wind MPPT (W-MPPT). The solar PV system is connected to the DC bus through solar converter, which boosts the solar PV array voltage. With this configuration, the solar power can be evacuated in a cost-effective way. This converter too is equipped with solar MPPT(S-MPPT) control strategy to extract maximum solar energy. In case of unavailability of wind energy source and lower state of charge of the battery, the battery bank can be charged through the grid power or a diesel generator through the same RSC. With the help of the LSC, rated frequency and voltage at the load terminals, are maintained under following conditions.

1. Varying amount of solar and wind powers.

2. Unavailability of solar power or wind power.

3. Loss of load or breakdown of the distribution system.

4. Different types of loads as unbalanced and nonlinear loads.

It presents the design criteria of major components and control strategies for various converters. Finally it presents simulation results followed by experimental results obtained on a prototype developed in the laboratory.

CHAPTER 2

HYBRID POWER SYSTEMS

2.1 Introduction

Hybrid Power Systems incorporate several electricity generating components with usually one major control system which enables the system to supply electricity in the required quality. Components for electricity generation can utilize renewable energy sources like wind turbines, photovoltaic, solar thermal, hydro power, wave power or biomass power stations, etc. Furthermore, fossil power plant like diesel generators, gas turbines or fuel cells etc. can be added.

The term Hybrid Power System does not give any information about the size of the energy system. Generally, Hybrid Power Systems are considered to supply loads in the size of several watts up to several megawatts. They usually supply island networks that are not connected to an integrated grid covering countries or even continents – but represent small grids with a limited number of consumers. Due to the resulting fluctuating consumption pattern several specific features are required concerning the electricity supplying Hybrid Power System.

In integrated electricity grids the load equalizes due to the large number of consumers and its statistical application. This is how base, medium and peak load are defined which are covered by dedicated base, medium and peak load power plant to minimize the electricity cost price. Base load is needed continuously 24 hours per day, medium load is required in consecutive 3 to 6 hours and peak load is required in shorter sequences. Unfortunately, this cost effective procedure cannot be transferred to Hybrid Power Systems in most of the cases. On the contrary, Hybrid Power Systems have to cope with much more severe short term variations in power demand. Thus, different energy management structures have to be applied. These energy management structures vary with the size of the Hybrid Power System depending on the financially optimal system design.

In island networks it is essential to integrate one component that is responsible for frequency and voltage stabilization. In small systems up to 50 kW inverters and battery systems are applied for frequency and voltage stabilization; in lager systems continuously running synchronous generators with controllable engines are more cost effective. The further the technical progress of power electronics the more systems in the higher power class are controlled by inverter technology, too. Depending on the magnitude of the Hybrid Power System, different storages for equalization of load variations are applied. For Megawatt class systems pumped storage plants are most appropriate, for medium sizes of several hundred kilowatts the application of compressed air storage plant and for small scale systems the application of battery storages is advisable considering the economic point of view.

In larger systems, often geographical constraints prevent the application of appropriate storages. Thus, in these cases the storage component is replaced by a dynamically controlled generator driven by a fuel engine. The necessity for this operation results from the requirement to match demand and supply in electrical grids for each moment in time for stable grid operation. In order to avoid short term voltage drops and flickers power storages are applied. These storages provide high power for short periods. In contrast, the stored energy in such storages is rather small. Fly wheel storages, capacitors and special kinds of batteries belong to this group of storages.

In the range of up to 30 kW mainly classic DC-coupled systems are established; in larger systems AC-coupling is more common. However, even in small scale systems the little bit more complex but easily extendable AC-coupled systems are gaining market share. Even mixed AC and DC systems are being offered. The discussion about advantages and disadvantages of specific system types is being continued.

In general, Hybrid Power Systems have to meet different requirements depending on the appliances served, the consumer behaviour, the consumer’s demands on the power quality and the energy sources available locally. While mobile phone antennas need to be supplied with almost constant power of high quality, small villages have a fluctuating and usually growing energy demand while short term power outages are not critical. The integration of wind power at a gusty site requires different features of a Hybrid Power System than a continuously operating hydro power plant. To realize cost efficient power supply with the required power quality an individual system design considering all site specific aspects is essential.

For Hybrid Power Systems all areas without electricity supply from integrated networks but demand for electrification can be identified as potential markets. Large potential for rural electrification especially with renewable energy sources can be found in developing countries. Unfortunately, the market for such systems has not materialized to a substantial scale yet due to a lack of structures in financial and political aspects. Furthermore, in many countries the required infrastructure for assembly, operation and maintenance of complex technical systems is not available locally.

In 2005 the World Wind Energy Association Hybrid Systems Working Group was established. Its aim is to provide a platform for discussions about all problems concerning Hybrid Power Systems paving the way for increased Hybrid Power System utilization.

2.2 Sources of power generation

The conventional energy sources are limited and have pollution to the environment. For this reason more attention has been paid to the utilization of renewable energy sources such as wind energy, fuel cell and solar energy etc. Wind energy is the fastest growing and most promising renewable energy source. During last two decades, the high penetration of wind turbines in the power system has been closely related to the advancement of the wind turbine technology and the way of how to control. Doubly-fed induction machines are receiving increasing attention for wind energy conversion system during such situation.

Wind turbine is classified into two general types:

1. Horizontal axis
2. Vertical axis.

The limitations on the extraction of energy from the wind include the practical size of wind machines, their density, friction losses in the rotating machinery and efficiencies of conversion from rotational energy to electrical energy. A windmill works on the principle of converting kinetic energy of the wind to rotary mechanical energy. In more advanced model the rotational energy is converted into electricity.

Wind turbines convert the kinetic energy present in the wind into mechanical energy by means of producing torque. Since the energy contained by the wind is in the form of kinetic energy, its magnitude depends on the air density and the wind velocity. The wind power developed by the turbine is given by the equation:

$$\mathbf{P=1/2\ C_p\rho AV^3}$$

Where *Cp* is the Power Co-efficient, ρ is the air density in Kg/m3, A is the area of the turbine blades in m2, and V is the wind velocity in m/sec.

Hydro-electric power stations are generally located in hilly areas where dams can be built conveniently and large water reservoirs can be obtained. In a hydro-electric power station, water head is created by constructing a dam across a river or lake. From the dam, water is led to a water turbine. The water turbine captures the energy in the falling water and changes the hydraulic energy (i.e. product of head and flow of water) into mechanical energy at the turbine shaft. The turbine drives the alternator which converts mechanical energy into electrical energy. Hydro-electric power stations are becoming very popular because the reserves of fuels (i.e. coal and oil) are depleting day by day. They have the added importance for flood control, storage of water for irrigation and water for drinking purposes. The constituents of a hydro-electric plant are hydraulic structures, water turbines and electrical equipment.

2.3 Renewable Energy sources

Renewable energy refers to energy from a source that is continuously replenished by natural processes. State law (Wis. Stat. §196.378(1)) defines the following as renewable resources when used to create electricity:

- Wind energy
- Solar thermal energy: Using heat from the sun to create electric power
- Photovoltaic energy: A system that directly converts sunlight intoelectric power
- Biomass: Defined as wood or plant material or residue, biological waste, crops grown for use as a resource or landfill gases. Biomass does not include garbage or non-vegetation-based industrial, commercial or household waste.
- Geothermal technology
- Hydroelectric with a capacity of less than 60 megawatts
- Tidal or Wave Action
- Fuel Cell: using a renewable fuel as determined by the Commission

2.4 Advantages and Disadvantages of Renewable Resources

The advantages of electric production from renewable resources include:

- The potential for low or no fuel cost (except for some biomass)
- The possibility of shorter lead-times for planning and construction as compared to conventional power plants
- The potential to utilize relatively small, modular plant sizes
- Significantly reduced environmental effects compared to fossil fuels

- For many renewable resources, a non-depletable resource base
- Public support for use of renewable resources
- The potential for use in distributed generation applications

The disadvantages of electric production from renewable resources include:

- Public concern for land use, biodiversity, birds and aesthetics in sitting a facility
- Relatively high capital cost to construct a renewable facility
- Uneven geographic distribution of renewable resources
- Intermittent availability of some renewable resources for electric production
- Lack of maturity or commercial availability of some technologies
- For some biomass resources, the need to consider environmental implications of the fuel supply

Utilities and independent power producers are researching ways to expand the use of renewable resources. One of the most important benefits of renewable resources is their long-term availability. Another important benefit is their minimal impact to the atmosphere. These technologies have not been associated with mercury emissions or the causes of acid rain and have little or no negative impact on climate change.

As of 1994, Wisconsin state law (Wis. Stat. § 1.12(3)(b)) mandates that, "It is the goal of the state that, to the extent that is cost-effective and technically feasible, all new installed capacity for electric generation in the state be based on renewable energy resources, including hydroelectric, wood, wind, solar, refuse, agricultural and biomass energy resources."

As part of 2005 Wisconsin Act 141, the Wisconsin Legislature established the current renewable portfolio standard (RPS), requiring each investor-owned electric utility, municipal electric utility and rural electric cooperative (electric providers) to meet a gradually increasing percentage of their retail sales with qualified renewable resources. The current RPS establishes the goal that by the end of 2015, 10 percent of all electric energy consumed in the state will be renewable energy.

2.5 Wind turbine

A wind turbine is a device that converts kinetic energy from the wind into electrical power. A wind turbine used for charging batteries may be referred to as a windcharger.

The result of over a millennium of windmill development and modern engineering, today's wind turbines are manufactured in a wide range of vertical and horizontal axis types. The smallest turbines are used for applications such as battery charging for auxiliary power for boats or caravans or to power traffic warning signs. Slightly larger turbines can be used for making contributions to a domestic power supply while selling unused power back to the utility supplier via the electrical grid. Arrays of large turbines, known as wind farms, are becoming an increasingly important source of renewable energy and are used by many countries as part of a strategy to reduce their reliance on fossil.

2.6 Types of wind turbine

Wind turbines can rotate about either a horizontal or a vertical axis, the former being both older and more common.

2.6.1 Horizontal axis

Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator.[19]

Since a tower produces turbulence behind it, the turbine is usually positioned upwind of its supporting tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted forward into the wind a small amount.

Downwind machines have been built, despite the problem of turbulence (mast wake), because they don't need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclical (that is repetitive) turbulence may lead to fatigue failures, most HAWTs are of upwind design.

Turbines used in wind farms for commercial production of electric power are usually three-bladed and pointed into the wind by computer-controlled motors. These have high tip speeds of over 320 km/h (200 mph), high efficiency, and low torque ripple, which contribute to good reliability. The blades are usually coloured white for daytime visibility by aircraft and range in length from 20 to 40 meters (66 to 131 ft.) or more. The tubular steel towers range from 60 to

90 meters (200 to 300 ft) tall. The blades rotate at 10 to 22 revolutions per minute. At 22 rotations per minute the tip speed exceeds 90 meters per second (300 ft/s).[20][21] A gear box is commonly used for stepping up the speed of the generator, although designs may also use direct drive of an annular generator. Some models operate at constant speed, but more energy can be collected by variable-speed turbines which use a solid-state power converter to interface to the transmission system. All turbines are equipped with protective features to avoid damage at high wind speeds, by feathering the blades into the wind which ceases their rotation, supplemented by brakes.

2.6.2 Vertical axis design

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. One advantage of this arrangement is that the turbine does not need to be pointed into the wind to be effective, which is an advantage on a site where the wind direction is highly variable. It is also an advantage when the turbine is integrated into a building because it is inherently less steerable. Also, the generator and gearbox can be placed near the ground, using a direct drive from the rotor assembly to the ground-based gearbox, improving accessibility for maintenance.

The key disadvantages include the relatively low rotational speed with the consequential higher torque and hence higher cost of the drive train, the inherently lower power coefficient, the 360 degree rotation of the aerofoil within the wind flow during each cycle and hence the highly dynamic loading on the blade, the pulsating torque generated by some rotor designs on the drive train, and the difficulty of modelling the wind flow accurately and hence the challenges of analysing and designing the rotor prior to fabricating a prototype.

When a turbine is mounted on a rooftop the building generally redirects wind over the roof and this can double the wind speed at the turbine. If the height of a rooftop mounted turbine tower is approximately 50% of the building height it is near the optimum for maximum wind energy and minimum wind turbulence. Wind speeds within the built environment are generally much lower than at exposed rural sites,[23][24] noise may be a concern and an existing structure may not adequately resist the additional stress.

2.7 Advantages and disadvantages of wind power

Advantages of wind power

1. The wind is free and with modern technology it can be captured efficiently.
2. Once the wind turbine is built the energy it produces does not cause greenhouse gases or other pollutants.

3. Although wind turbines can be very tall each takes up only a small plot of land. This means that the land below can still be used. This is especially the case in agricultural areas as farming can still continue.

4. Many people find wind farms an interesting feature of the landscape.

5. Remoteareas that are not connected to the electricity power grid can use wind turbines to produce their own supply.

6. Wind turbines have a role to play in both the developed and third world.

Disadvantages of wind power

1. The strength of the wind is not constant and it varies from zero to storm force. This means that wind turbines do not produce the same amount of electricity all the time. There will be times when they produce no electricity at all.

2. Many people feel that the countryside should be left untouched, without these large structures being built. The landscape should left in its natural form for everyone to enjoy.

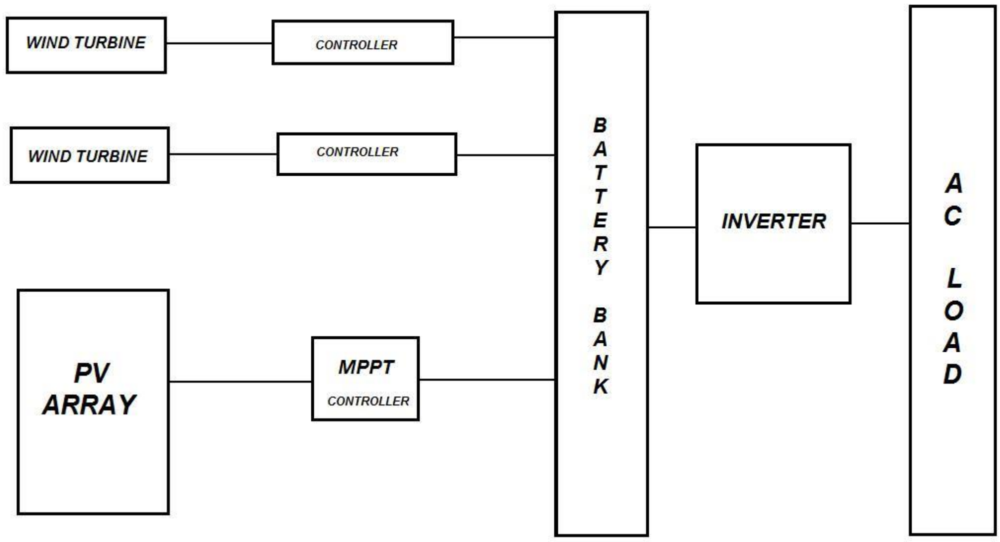
3. Wind turbines are noisy. Each one can generate the same level of noise as a family car travelling at 70 mph.

4. Many people see large wind turbines as unsightly structures and not pleasant or interesting to look at. They disfigure the countryside and are generally ugly.

5. When wind turbines are being manufactured some pollution is produced. Therefore wind power does produce some pollution.

2.8 Biomass-wind-fuel cell

For example, let us consider a load of 100% power supply and there is no renewable system to fulfil this need, so two or more renewable energy system can be combined. For example, 60% from a biomass system, 20% from a wind energy system and the remainder from fuel cells. Thus combining all these renewable energy systems may provide 100% of the power and energy requirements for the load, such as a home or business.



2.8 Block diagram of a PV/wind hybrid energy system

Another example of a hybrid energy system is a photovoltaic array coupled with a wind turbine. This would create more output from the wind turbine during the winter, whereas during the summer, the solar panels would produce their peak output. Hybrid energy systems often yield greater economic and environmental returns than wind, solar,geothermal or tri-generation stand-alone systems by themselves.

2.9 Drawback

Most of us already know how a solar/wind/biomass power generating system works, all these generating systems have some or the other drawbacks, like Solar panels are too costly and the production cost of power by using them is generally higher than the conventional process, it is not available in the night or cloudy days. Similarly Wind turbines can't operate in high or low wind speeds and Biomass plant collapses at low temperatures.

2.10 How to over come

So if all the three are combined into one hybrid power generating system the drawbacks can be avoided partially/completely, depending on the control units. As the one or more drawbacks can be overcome by the other, as in northern hemisphere it is generally seen that in windy days the solar power is limited and vice versa and in summer and rainy season the biomass plant can operate in a full flagged so the power generation can be maintained in the above stated condition. The cost of solar panel can be subsided by using glass lenses, mirrors to heat up a fluid that can rotate the common turbine used by wind and other sources. Now the question arises what about the winter nights or cloudy winter days with very low wind speeds. Here comes the activity of the Hydrogen. As we know the process of electrolysis can produce hydrogen by breaking water into hydrogen and oxygen, it can be stored; hydrogen is also a good fuel and burns with oxygen to give water. Hydrogen can be used to maintain the temperature of the biomass reservoir in winter so that it can produce biogas in optimum amount for the power generation. As stated above biogas is a good source in summer; in this period the solar energy available is also at its peak, so if the demand and supply is properly checked and calculated the excess energy can be used in the production of hydrogen and can be stored. In sunny, windy &hot day, the turbine operates with full speed as the supply is maximum, and this excess power can be consumed for the process of manufacturing hydrogen. In winter, the power consumption is also low so the supply limit is low, and obtained with lesser consumption.

2.10.1 Area of research

- Amount of Hydrogen produce by amount of power utilized and reusing the hydrogen for maintaining the temperature. Is it cost efficient?
- Limited to areas near equatorial regions (23deg N-23deg S) at low altitudes.
- Infrastructure cost may be high.
- Hybrid renewable energy system is a way to use less energy then what people use today.This energy is not just regular energy it’s almost just like wind energy but they have something the same about each other that is they are both renewable energy sources.

2.10.2 Regulation

To get constant power supply, the output of the renewable may be connected to the rechargeable battery bank and then to the load. If the load is alternating current (AC), then an inverter is used to convert the direct current (DC) supply from the battery to the AC load. Consideration about voltage transition among modules starting from Wind Generator,Battery

Charger Controller and Inverter should be subject to voltage standard which mainly focus about voltage compatibility.

2.10.3 Need for research

The key to cost reductions of this order is, of course, the right sort of support for innovation and development - something that has been lacking for the past and, arguably, is still only patchy at present. Research and development efforts in solar, wind, and other renewable energy technologies are required to continue for:

- Improving their performance,
- Establishing techniques for accurately predicting their output
- Reliably integrating them with other conventional generating sources
- Economic aspects of these technologies are sufficiently promising to include them in developing power generation capacity for developing countries.

CHAPTER 3

PHOTOVOLTAIC SYSTEM

3.1 Introduction

A photovoltaic system, also photovoltaic power system, solar PV system, PV system or casually solar array, is a power system designed to supply usable solar power by means of photovoltaic . It consists of an arrangement of several components, including solar panels to absorb and directly convert sunlight into electricity, a solar inverter to change the electrical current from DC to AC, as well as mounting, cabling and other electrical accessories to set-up a working system. It may also use a solar tracking system to improve the system's overall performance or include an integrated battery solution, as prices for storage devices are expected to decline. Strictly speaking, a solar array only encompasses the ensemble of solar panels, the visible part of the PV system, and does not include all the other hardware, often summarized as balance of system (BOS). Moreover, PV systems convert light directly into electricity and shouldn't be confused with other solar technologies, such as concentrated solar power (CSP) and solar thermal, used for both, heating and cooling.

PV systems range from small, roof-top mounted or building-integrated systems with capacities from a few to several tens of kilowatts, to large utility-scale power stations of hundreds of megawatts. Nowadays, most PV systems are connected to the electrical grid, while stand-alone or off-grid systems only account for a small portion of the market.

Operating silently and without any moving parts or environmental emissions, PV systems have developed into a mature technology that has been used for fifty years in specialized applications, and grid-connected systems have been operating for over twenty years. A roof-top system recoups the invested energy for its manufacturing and installation within 0.7 to 2 years and produces about 95 percent of net clean renewable energy over a 30-year service lifetime.[1]:30[2][3]

As new installations are growing exponentially, prices for PV systems have rapidly declined in recent years. However, they vary by market and the size of the system. In 2013 overall prices for installed rooftop systems were just below $5.00 per watt in the United States and Japan, while prices in the highly penetrated German market reached $2.00.[4][5] Nowadays, solar panels account for less than half of the system's overall cost, leaving the rest to installation labour and to the PV system's remaining components.

3.2 Solar array

3.2 Solar array system

Conventional c-Si solar cells, normally wired in series, are encapsulated in a solar module to protect them from the weather. The module consists of a tempered glass as cover, a soft and flexible encapsulate, a rear back sheet made of a weathering and fire-resistant material and an aluminium frame around the outer edge. Electrically connected and mounted on a supporting structure, solar modules build a string of modules, often called solar panel. A solar array consists of one or many such panels.

A photovoltaic array (or solar array) is a linked collection of solar panels. The power that one module can produce is seldom enough to meet requirements of a home or a business, so the modules are linked together to form an *array*.

Most PV arrays use an inverter to convert the DC power produced by the modules into alternating current that can power lights, motors, and other loads. The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current. Solar panels are typically measured under STC (standard test conditions) or PTC (PVUSA test conditions), in watts. Typical panel ratings range from less than 100 watts to over 400 watts.[28] The array rating consists of a summation of the panel ratings, in watts, kilowatts, or megawatts.

3.3 Solar trackers

A solar tracking system tilts a solar panel throughout the day. Depending on the type of tracking system, the panel is either aimed directly at the sun or the brightest area of a partly clouded sky.

Trackers greatly enhance early morning and late afternoon performance, increasing the total amount of power produced by a system by about 20–25% for a single axis tracker and about 30% or more for a dual axis tracker, depending on latitude. Trackers are effective in regions that receive a large portion of sunlight directly. In diffuse light (i.e. under cloud or fog),tracking has little or no value. Because most concentrated Photovoltaic systems are very sensitive to the sunlight's angle, tracking systems allow them to produce useful power for more than a brief period each day.Tracking systems improve performance for two main reasons. First, when a solar panel is perpendicular to the sunlight, it receives more light on its surface than if it were angled. Second, direct light is used more efficiently than angled light. Special Anti-reflective coatings can improve solar panel efficiency for direct and angled light, somewhat reducing the benefit of tracking.

Trackers and sensors to optimise the performance are often seen as optional, but tracking systems can increase viable output by up to 45%.PV arrays that approach or exceed one megawatt often use solar trackers. Accounting for clouds, and the fact that most of the world is not on the equator, and that the sun sets in the evening, the correct measure of solar power is insulation – the average number of kilowatt-hours per square meter per day. For the weather and latitudes of the United States and Europe, typical insulation ranges from 2.26 kWh/m²/day in northern climes to 5.61 kWh/m²/day in the sunniest regions.

For large systems, the energy gained by using tracking systems can outweigh the added complexity (trackers can increase efficiency by 30% or more). For very large systems, the added maintenance of tracking is a substantial detriment. Tracking is not required for flat panel and low-concentration photovoltaic systems. For high-concentration photovoltaic systems, dual axis tracking is a necessity.

Pricing trends affect the balance between adding more stationary solar panels versus having fewer panels that track. When solar panel prices drop, trackers become a less attractive option.

3.4 Solar inverters

Systems designed to deliver alternating current (AC), such as grid-connected applications need an inverter to convert the direct current(DC) from the solar modules to AC. Grid connected inverters must supply AC electricity in sinusoidal form, synchronized to the grid frequency, limit feed in voltage to no higher than the grid voltage and disconnect from the grid if the grid voltage is turned off. Islanding inverters need only produce regulated voltages and frequencies in a sinusoidal waveshape as no synchronisation or co-ordination with grid supplies is required.

A solar inverter may connect to a string of solar panels. In some installations a inverters connected at each solar panel.[62] For safety reasons a circuit breaker is provided both on the AC and DC side to enable maintenance. AC output may be connected through an electricity meterinto the public grid.[63] The number of modules in the system determines the total DC watts capable of being generated by the solar array; however, the inverter ultimately governs the amount of AC watts that can be distributed for consumption. For example: A PV system comprising 11 kilowatts DC (kWDC) worth of PV modules, paired with one 10-kilowatt AC (kWAC) inverter, will be limited by the maximum output of the inverter: 10 kW AC.

As of 2014, conversion efficiency for state-of-the-art converters reached more than 98 percent. While string inverters are used in residential to medium-sized commercial PV systems, central inverters cover the large commercial and utility-scale market. Market-share for central and string inverters are about 50 percent and 48 percent, respectively, leaving less than 2 percent to micro-inverters.

3.5 Battery

Although still expensive, PV systems increasingly use rechargeable batteries to store a surplus to be later used at night. Batteries used for grid-storage also stabilize the electrical grid by levelling out peak loads, and play an important role in a smart grid, as they can charge during periods of low demand and feed their stored energy into the grid when demand is high.

Common battery technologies used in today's PV systems include, the valve regulated lead-acid battery - a modified version of the conventional lead–acid battery, nickel–cadmium and lithium-ion batteries. Compared to the other types, lead-acid batteries have a shorter lifetime and lower energy density. However, due to their high reliability, low self-discharge as well as low investment and maintenance costs, they are currently the predominant technology used in small-scale, residential PV systems, as lithium-ion batteries are still being developed and about 3.5 times as expensive as lead-acid batteries. Furthermore, as storage devices for PV systems are used stationary, the lower energy and power density and therefore higher weight of lead-acid batteries are not as critical as, for example, in electric transportation

Other rechargeable batteries that are considered for distributed PV systems include, sodium–sulphur and vanadium red-ox batteries, two prominent types of a molten salt and a flow battery , respectively.

3.6 Standalone system

A stand-alone, or off-grid system is not connected to the electrical grid. Standalone systems vary widely in size and application from wristwatches or calculators to remote buildings or spacecraft.

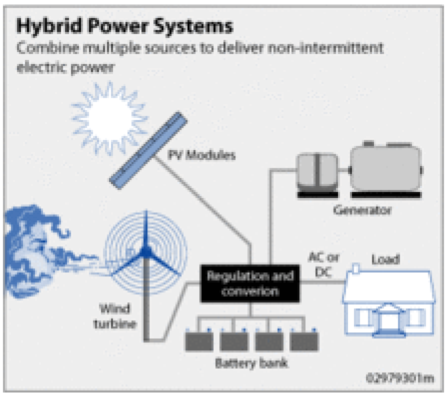
If the load is to be supplied independently of solar insulation, the generated power is stored and buffered with a battery. In non-portable applications where weight is not an issue, such as in buildings, lead acid batteries are most commonly used for their low cost and tolerance for abuse.

A charge controller may be incorporated in the system to: a) avoid battery damage by excessive charging or discharging and, b) optimizing the production of the cells or modules by maximum power point tracking (MPPT). However, in simple PV systems where the PV module voltage is matched to the battery voltage, the use of MPPT electronics is generally considered unnecessary, since the battery voltage is stable enough to provide near-maximum power collection from the PV module. In small devices (e.g. calculators, parking meters) only direct current (DC) is consumed. In larger systems (e.g. buildings, remote water pumps) AC is usually required. To convert the DC from the modules or batteries into AC, an inverter is used.

In agricultural settings, the array may be used to directly power DC pumps, without the need for an inverter. In remote settings such as mountainous areas, islands, or other places where a power grid is unavailable, solar arrays can be used as the sole source of electricity, usually by charging a storage battery.

3.7 Hybrid system

A hybrid system combines PV with other forms of generation, usually a diesel generator. Biogas is also used. The other form of generation may be a type able to modulate power output as a function of demand.



However more than one renewable form of energy may be used e.g. wind. The photovoltaic power generation serves to reduce the consumption of non-renewable fuel. Hybrid systems are most often found on islands. Pellworm island in Germany and Kythnos island in Greece are notable examples (both are combined with wind).The Kythnos plant has reduced diesel consumption by 11.2%.

There has also been recent work showing that the PV penetration limit can be increased by deploying a distributed network of PV+CHP hybrid systems in the U.S. The temporal distribution of solar flux, electrical and heating requirements for representative U.S. single family residences were analysed and the results clearly show that hybridizing CHP with PV can enable additional PV deployment above what is possible with a conventional centralized electric generation system. This theory was reconfirmed with numerical simulations using per second solar flux data to determine that the necessary battery backup to provide for such a hybrid system is possible with relatively small and inexpensive battery systems.In addition, large PV+CHP systems are possible for institutional buildings, which again provide back up for intermittent PV and reduce CHP runtime.

CHAPTER 4

SYSTEMCOMPONENTS DESCRIPTION

4.1 Introduction

A single line diagram of the proposed renewable energy generation system (REGS) fed micro-grid is shown in Fig. 1. The same has been designed for location having maximum power demand and average power demand of 15 kW and 5 kW, respectively. The rated capacity of both wind and solar energy block in REGS, is taken as 15 kW. The capacity utilisation factor of 20% is considered for both energy blocks, which is enough to provide full day energy requirement of the hamlet.

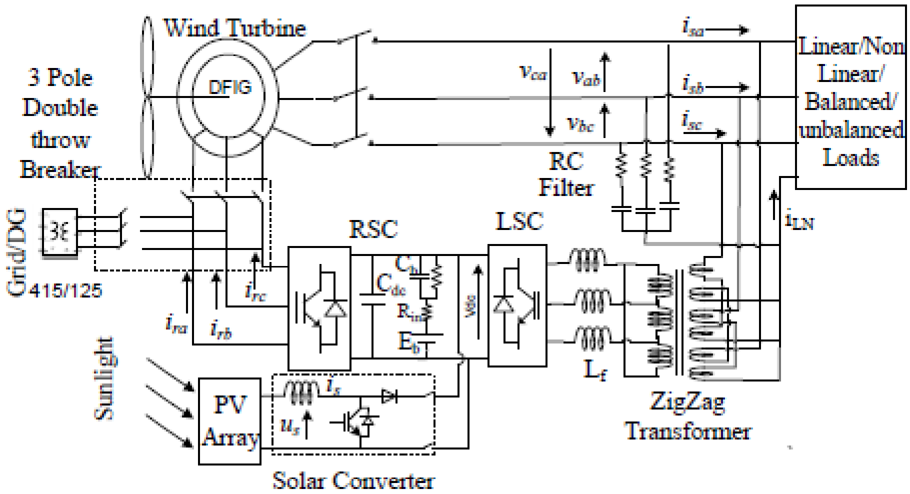


Figure 4.1: Schematic of isolated micro-grid network fed by renewable energy source using battery storage

As shown in a schematic diagram, the wind energy source is isolated using a 3-pole breaker from the network in case of insufficient wind speed. The DC side of both RSC and LSC along with HV side of solar converter, is connected at the battery bank. RSC helps the wind energy system to run at the optimum rotation speed as required by W-MPPT algorithm. The LSC controls the network voltage and frequency. The energy flow diagram of the system is shown in Figure 4.1.

The design methodology of major components of REGS, is shown in following sub-sections.

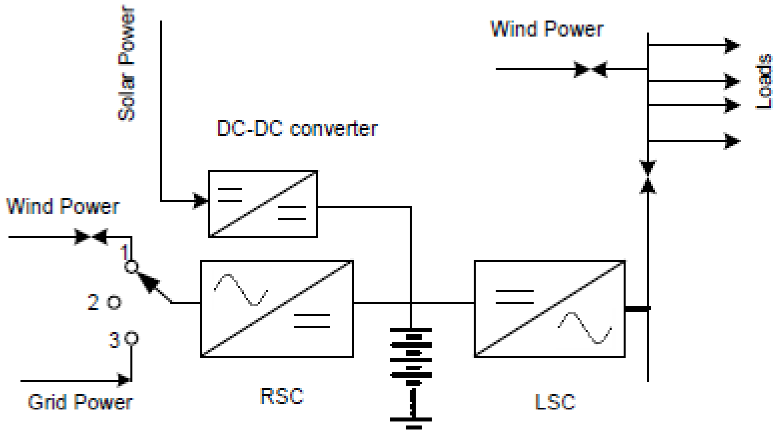


Figure 4.2: Energy flow diagram of isolated micro-grid network fed by renewable energy source using battery storage

4.2 Power Electronic For Wind Power Generation Systems

4.2.1. Characteristics of Wind Power Conversion

The aerodynamic power of a wind turbine is given by

$$\mathbf{P=1/2\rho\Pi R^2\upsilon^3C_p} \qquad \mathbf{(1)}$$

Where R is the air density, is the turbine radius, is the wind speed, and Cpis the turbine power coefficient which represents the power conversion efficiency of a wind turbine. Cp is a function of the tip speed ratio, λ as well as the blade pitch angle β in a pitch controlled wind turbine. λ is defined as the ratio of the tip speed of the turbine blades to wind speed, and given by

$$\boldsymbol{\lambda= \frac{R.\ \Omega}{\upsilon}} \mathbf{(2)}$$

WhereΩ is the rotational speed of the wind turbine. A typical C_p - λ curve for a fixed pitch angle β is shown in Fig. 1. It can be seen that there is a maximum power coefficient, $C_{p,\ max}$.

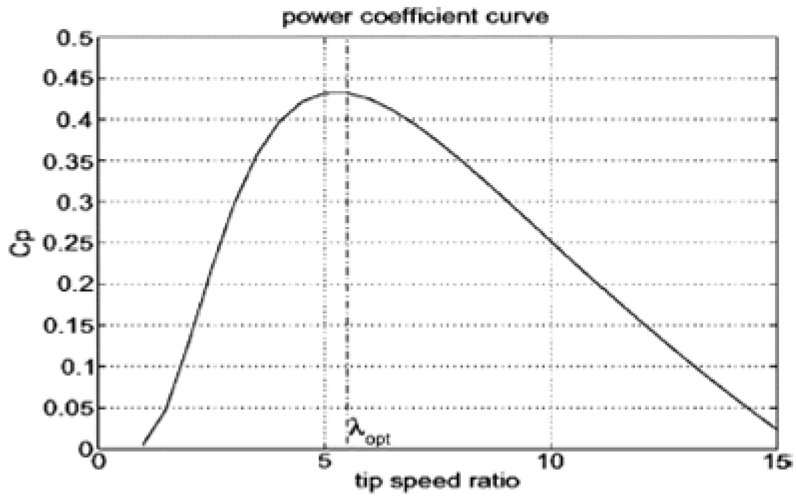


Figure 4.3: Typical C_P-λ curve for a wind turbine

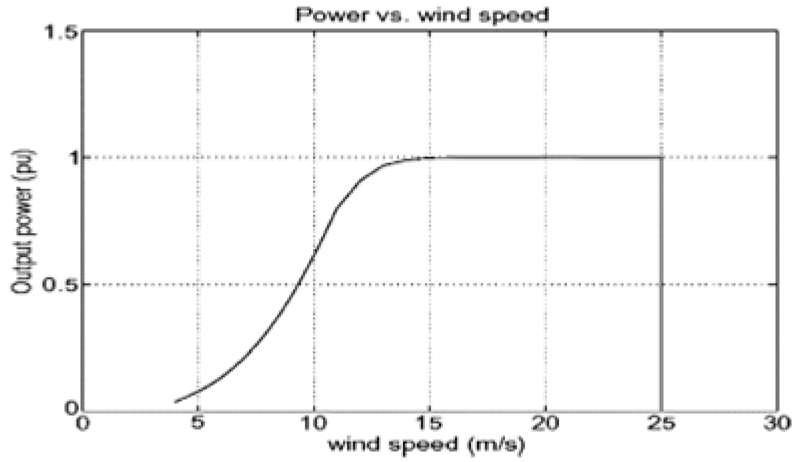


Figure 4.4: Power-wind speed characteristics for a wind turbine.

Normally, a variable speed wind turbine follows the $C_{p,max}$ to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at λ. Then it operates at the rated power with power regulation during the periods of high wind by the active control of the blade pitch angle or the passive regulation based on aerodynamic stall. A typical power-wind speed curve with a cut-off wind speed of 25 m/s is shown in Fig.2, however, the cut-off wind speed may vary depending on the type of wind turbines.

4.2.2 Variable Speed Wind Turbines

The development in wind turbine systems has been steady for the last 25 years and four to five generations of wind turbines exist. The wind turbine technology can basically be divided into three categories: the systems without power electronics, the systems with partially rated power electronics and the systems with full-scale power electronic interfacing wind turbines. The wind turbine systems in Fig. 3 using induction generators, which independent of torque variation, keep an almost fixed speed (variation of 1–2%). The power is limited aerodynamically either by stall, active stall or by pitch control. A soft-starter is normally used in order to reduce the inrush current during start-up. Also a reactive power compensator is needed to reduce (almost eliminate) the reactive power demand from the turbine generators. It is usually done by activating continuously the capacitor banks following load variation (5–25 steps). Those solutions are attractive due to low cost and high reliability.

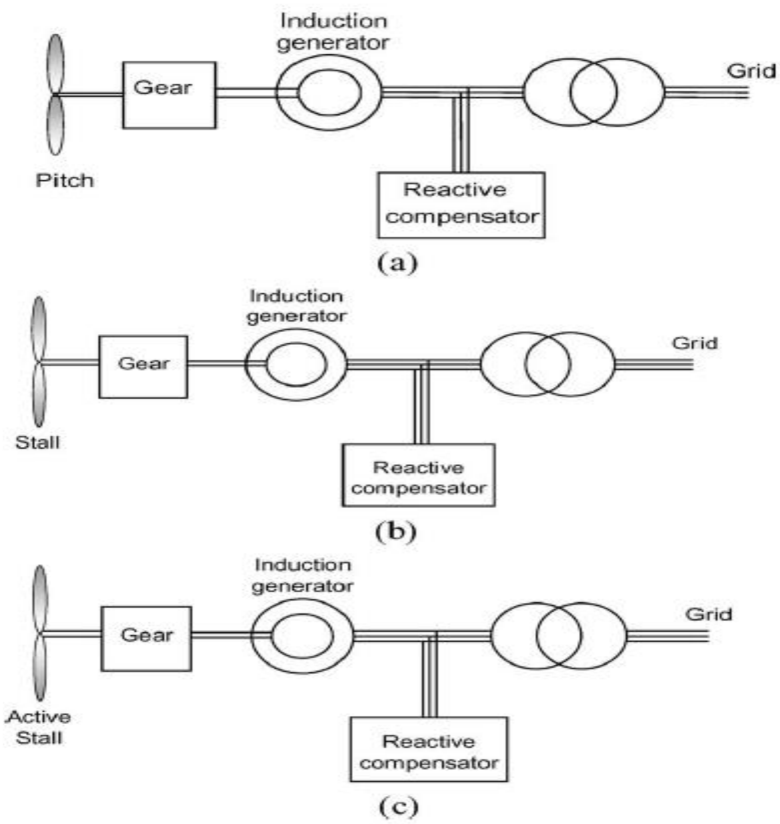


Figure 4.5: Wind turbine systems without power converter but with aerodynamic power control: (a) pitch controlled, (b) stall controlled, and (c) active stall controlled.

The next category is wind turbines with partially rated power converters and much more improved control performance can be obtained. Fig. 4 shows two such solutions. Fig. 4(a) shows a wind turbine system where the generator is an induction generator with a wounded rotor. An extra resistance controlled by power electronics is added in the rotor, which gives a speed range of 2 to 4%. The power converter for the rotor resistance control is for low voltage but high currents.

At the same time an extra control freedom is obtained at higher wind speeds in order to keep the output power fixed. This solution also needs a soft starter and a reactive power compensator.

Another solution of using a medium scale power converter with a wounded rotor induction generator is shown in Figure 4.5(b). A power converter connected to the rotor through slip rings controls the rotor currents. If the generator is running super-synchronously, the electrical power is delivered through both the rotor and the stator. If the generator is running sub-synchronously the electrical power is only delivered into the rotor from the grid. A speed variation of 60% around synchronous speed may be obtained by the use of a power converter of 30% of nominal power. Furthermore, the required rating of the power converter can be higher, depending on the designed fault handing capability as well as the ability of controlling reactive power,

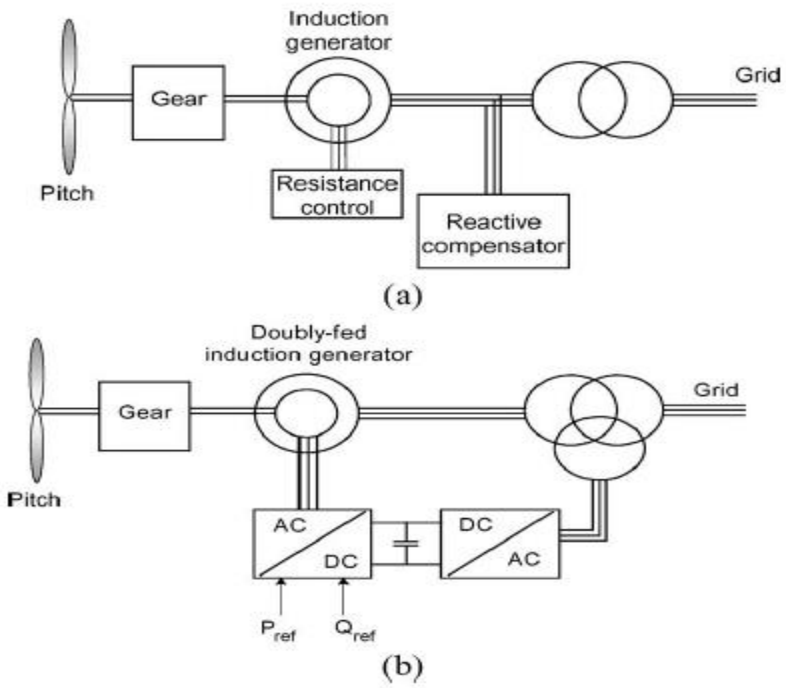


Figure 4.6: Wind turbine topologies with partially rated power electronics: (a) rotor-resistance converter and (b) doubly fed induction generator.

Which give a better grid performance. The solution is naturally a little bit more expensive compared to the classical solutions, however it is possible to save on the safety margin of gear, having reactive power compensation/production and more energy captured from the wind.

The third category is wind turbines with a full-scale power converter between the generator and grid, which gives extra losses in the power conversion but it will gain the added technical performance. Figure 4.6 shows four possible solutions with full-scale power converters.

The solutions shown in Fig. 4.6(a) and (b) are characterized by having a gear. A synchronous generator solution shown in Figure 4.6(b) needs a small power converter for field excitation. Multipole generator systems with the synchronous generator without a gear are shown in Figure 4.7(c) and (d). Permanent magnets are used for the system shown in Fig. 5(d), which are still becoming cheaper. Various power electronic interfaces may be used with permanent magnet wind power generators [6]–[8]. Simulation tools are developed to investigate the design and operation of the wind turbines [9]. All four solutions have the same controllable characteristics since the generator is decoupled from the grid by a voltage-sourced dc-link. The power converter to the grid enables a fast control of active and reactive power. However, the negative side is a more complex system with a more sensitive power electronic part. Comparing the different wind turbine systems in respect to performance shows a contradiction between the cost and the performance. By introducing power electronics many of the wind turbine systems behave like a power plant [10]. In respect to control performance they are faster, but the produced real power depends on the available wind. On the other hand they may always be able to deliver reactive power, which can be used for power system control.

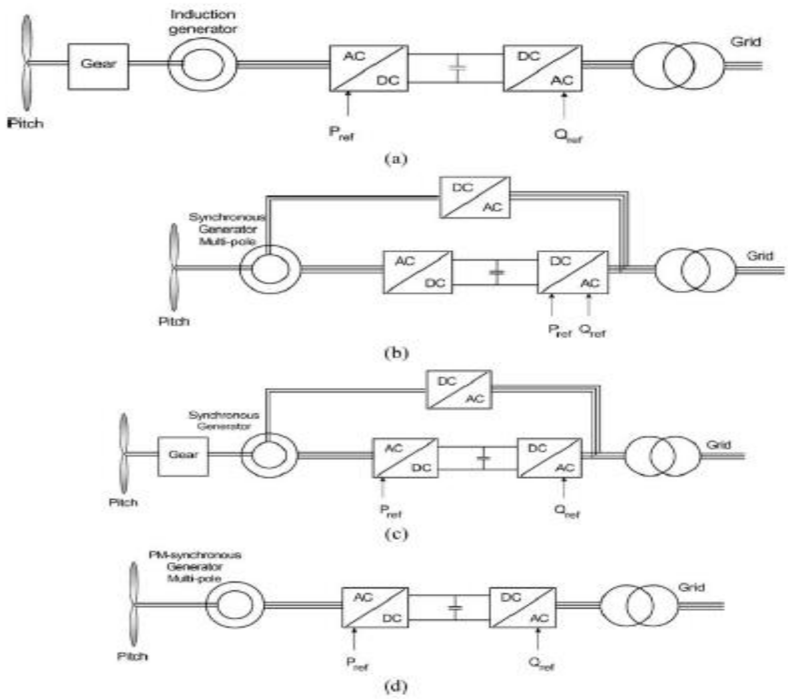


Figure 4.7: Wind turbine systems with full-scale power converters with active and reactive power control: (a) induction generator with gear (b) synchronous generator with gear, (c) multipole synchronous generator (d) multipole permanent magnet synchronous generator.

4.2.3 Power Electronics for Offshore Wind Farms

Wind energy systems are developing toward higher capacity and offshore locations. For example, ambitious energy planning in Denmark has scheduled a level of 50% wind energy penetration in the year 2030—mainly covered by large offshore wind farms. These wind farms present a significant power contribution on the grid, and therefore, play a very important role on the power quality and the control of power systems. Consequently high technical demands are expected to be met by these renewable generation units, such as to perform frequency and voltage control, regulation of active and reactive power, quick responses under power system transient and dynamic situations. The power electronic technology is again an important part in both system configurations and the control of the offshore wind farms in order to fulfil the future demands [11]. The wind farms may be connected into different types of configurations with various control and compensation arrangements. For example, ac local network with centralized compensation or with a dc transmission system, and dc local network, decentralized control with a dc transmission system. In Rejsby Hede, Denmark, a test installation with ac local network and centralized compensation, an 8-MVAr GTO based advanced static VAr compensation unit (ASVC), as sketched in Fig. 6(a), is a 24 MW wind farm with 40 stall regulated wind turbines. The power electronic based ASVC controls the reactive power of the wind farm and therefore the system voltage. It is noted that for the wind turbines directly connected to the ac grid without

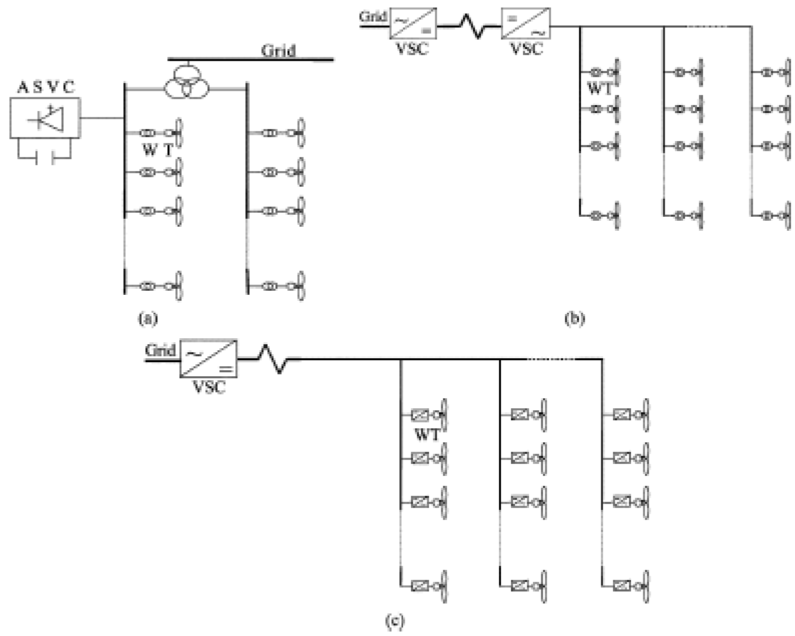


Figure 4.8: Wind farm arrangements: (a) a wind farm (40 turbines) with an ASVC unit (b) a wind farm with a VSC based HVDC transmission and common ac-grid (c) a wind farm with an internal dc network and individual power control.

Power electronic interface, the real power cannot easily be controlled without a pitch control mechanism or dumping devices. However, if the rotor is connected to the grid via power electronic converters as shown in Fig. 4.8(b), the offshore wind farm equipped with doubly fed induction generators can perform both real and reactive power control while operate the wind turbines in variable speed to maximize the energy capture and to reduce the mechanical stress and noise. The power electronic converters are normally only rated as a small part of the system capacity, say 20–30%. Since the controllability is related to the rating of the power electronic converters, other compensation methods/devices may still be required dependent on system demands. For long distance transmission of power from offshore wind farm, HVDC may be a viable option. In a HVDC transmission, the low or medium ac voltage at the wind farm is converted into a high dc voltage on the transmission side and the dc power is transferred to the on-shore system where the dc voltage is converted back into ac voltage as shown in Fig. 6(b). For certain power level, a voltage source converter (VSC) based HVDC transmission system may be used instead of the conventional thyristor based HVDC technology. A configuration of using dc local network, decentralized control with a dc transmission is shown in Fig. 6(c), where each wind turbine has its own power electronic converter, so that it is possible to operate each wind turbine at an individual optimal speed. Each system configuration has its own feature and suitability; the most suitable system configuration for a particular wind farm has to be determined by taking the details of the concerned wind farm into consideration.

4.3 FUZZY LOGIC CONTROLLER

4.3.1 INTRODUCTION

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection. To understand why use of fuzzy logic has grown, we must first understand what is meant by fuzzy logic.

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalve logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with un sharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of fl. Even in its more narrow definition, fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

4.3.2 FUZZY LOGIC CONTROLLER

In fuzzy Logic Toolbox software, fuzzy logic should be interpreted as FL, that is, fuzzy logic in its wide sense. The basic ideas underlying FL are explained very clearly and insightfully in Foundations of Fuzzy Logic. What might be added is that the basic concept underlying FL is that of a linguistic variable, that is, a variable whose values are words rather than numbers. In effect, much of FL may be viewed as a methodology for computing with words rather than numbers. Although words are inherently less precise than numbers, their use is closer to human intuition. Furthermore, computing with words exploits the tolerance for imprecision and thereby lowers the cost of solution.

Another basic concept in FL, which plays a central role in most of its applications, is that of a fuzzy if-then rule or, simply, fuzzy rule. Although rule-based systems have a long history of use in Artificial Intelligence (AI), what is missing in such systems is a mechanism for dealing with fuzzy consequents and fuzzy antecedents. In fuzzy logic, this mechanism is provided by the calculus of fuzzy rules. The calculus of fuzzy rules serves as a basis for what might be called the Fuzzy Dependency and Command Language (FDCL).

Although FDCL is not used explicitly in the toolbox, it is effectively one of its principal constituents. In most of the applications of fuzzy logic, a fuzzy logic solution is, in reality, a translation of a human solution into FDCL.

A trend that is growing in visibility relates to the use of fuzzy logic in combination with neuro computing and genetic algorithms. More generally, fuzzy logic, neuro computing, and genetic algorithms may be viewed as the principal constituents of what might be called soft computing. Unlike the traditional, hard computing, soft computing accommodates the imprecision of the real world.

The guiding principle of soft computing is: Exploit the tolerance for imprecision, uncertainty, and partial truth to achieve tractability, robustness, and low solution cost. In the future, soft computing could play an increasingly important role in the conception and design of systems whose MIQ (Machine IQ) is much higher than that of systems designed by conventional methods.

Among various combinations of methodologies in soft computing, the one that has highest visibility at this juncture is that of fuzzy logic and neuro computing, leading to neuro-fuzzy systems. Within fuzzy logic, such systems play a particularly important role in the induction of rules from observations. An effective method developed by Dr. Roger Jang for this purpose is called ANFIS (Adaptive Neuro-Fuzzy Inference System). This method is an important component of the toolbox.

The fuzzy logic toolbox is highly impressive in all respects. It makes fuzzy logic an effective tool for the conception and design of intelligent systems. The fuzzy logic toolbox is easy to master and convenient to use. And last, but not least important, it provides a reader friendly and up-to-date introduction to methodology of fuzzy logic and its wide ranging applications.

4.3.3 FUZZY LOGIC BACKGROUND

Fuzzy logic is a logic having many values. Unlike the binary logic system, here the reasoning is not crisp, rather it is approximate and having a vague boundary. The variables in fuzzy logic system may have any value in between 0 and 1 and hence this

type of logic system is able to address the values of the variables those lay between completely true and completely false. The variables are called linguistic variables and each linguistic variable is described by a membership function which has a certain degree of membership at a particular instance.

System based on fuzzy logic carries out the process of decision making by incorporation of human knowledge into the system. Fuzzy inference system is the major unit of a fuzzy logic system. The decision making is an important part of the entire system. The fuzzy inference system formulates suitable rules and based on these rules the decisions are made. This whole process of decision making is mainly the combination of concepts of fuzzy set theory, fuzzy IFTHEN rules and fuzzy reasoning. The fuzzy inference system makes use of the IF-THEN statements and with the help of connectors present (such as OR and AND), necessary decision rules are constructed.

The basic Fuzzy inference system may take fuzzy inputs or crisp inputs depending upon the process and its outputs, in most of the cases, are fuzzy sets.

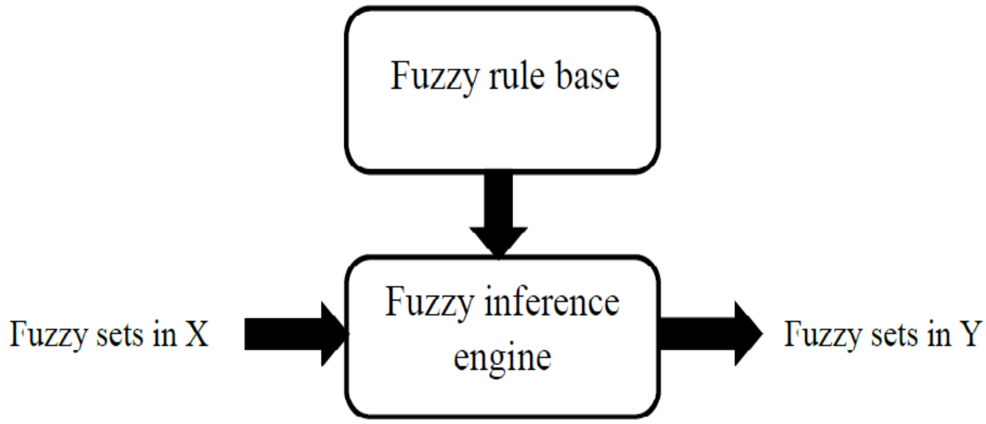


Fig 4.9 A Pure Fuzzy System

The fuzzy inference system in Fig. 4.1 can be called as a pure fuzzy system due to the fact that it takes fuzzy sets as input and produces output that are fuzzy sets. The fuzzy rule base is the part responsible for storing all the rules of the system and hence it can also be called as the knowledge base of the fuzzy system. Fuzzy inference system is responsible for necessary decision making for producing a required output.

In most of the practical applications where the system is used as a controller, it is desired to have crisp values of the output rather than fuzzy set values. Therefore a method of defuzzification is required in such case which converts the fuzzy values into corresponding crisp values. In general there are three main types of fuzzy inference systems such as Mamdani model, Sugeno model and Tsukamoto model. Out of these three, Mamdani model is the most popular one. There are also various defuzzification techniques such as Mean of maximum method, Centroid of area method, Bisector of area method etc.

In this work Mamdani fuzzification technique is used. There are two types of Mamdani fuzzy inference system such as, “min and max” and “product and max”. In our example, the “min and max” Mamdani system is used. For this type of system, min and max operators are used for AND and OR methods respectively The defuzzification technique used is „center of mass‟ defuzzification method for transforming the implied output fuzzy set into a crisp output.

4.4 FUZZY LOGIC TOOLBOX SOFTWARE

We can create and edit fuzzy inference systems with Fuzzy Logic Toolbox software. We can create these systems using graphical tools or command-line functions, or generate them automatically using either clustering or adaptive neuro-fuzzy techniques.

If we have access to Simulink software, we can easily test your fuzzy system in a block diagram simulation environment.The toolbox also lets to run our own stand-alone C programs directly. This is made possible by a stand-alone Fuzzy Inference Engine that reads the fuzzy systems saved from a mat lab session. We can customize the stand-alone engine to build fuzzy inference into our own code.

Because of the integrated nature of the mat lab environment, we can create our own tools to customize the toolbox or harness it with another toolbox, such as the Control System Toolbox, Neural Network Toolbox, or Optimization Toolbox software.

4.5 FUZZY LOGIC TOOL BOX

The Fuzzy Logic Toolbox extends the MATLAB technical computing environment with tools for designing systems based on fuzzy logic. Graphical user interfaces (GUIs) guide us through the steps of fuzzy inference system design. Functions are provided for many common fuzzy logic methods, including fuzzy clustering and adaptive neuro fuzzy learning. The toolbox helps to model complex system behaviors using simple logic rules and then implements these rules in a fuzzy inference system. We can use the toolbox as a standalone fuzzy inference engine. Alternatively, we can use fuzzy inference blocks in Simulink and simulate the fuzzy systems within a comprehensive model of the entire dynamic system

4.6 WORKING WITH THE FUZZY LOGIC TOOLBOX

The Fuzzy Logic Toolbox provides GUIs to perform classical fuzzy system development and pattern recognition. Using the toolbox, we can develop and analyze fuzzy inference systems, develop adaptive neuro fuzzy inference systems, and perform fuzzy clustering. In addition, the toolbox provides a fuzzy controller block that you can use in Simulink to model and simulate a fuzzy logic control system. From Simulink, we can generate C code for use in embedded applications that include fuzzy logic.

4.7 BUILDING A FUZZY INFERENCE SYSTEM

Fuzzy inference is a method that interprets the values in the input vector and, based on user defined rules, assigns values to the output vector. Using the GUI editors and viewers in the Fuzzy Logic Toolbox, we can build the rules set, define the membership functions, and analyze the behavior of a fuzzy inference system (FIS).

KEY FEATURES

- Specialized GUIs for building fuzzy inference systems and viewing and analyzing results
- Membership functions for creating fuzzy inference systems
- Support for AND, OR, and NOT logic in user-defined rules
- Standard Mamdani and Sugeno-type fuzzy inference systems
- Automated membership function shaping through neuro adaptive and fuzzy clustering learning techniques
- Ability to embed a fuzzy inference system in a Simulink model
- Ability to generate embeddable C code or stand-alone executable fuzzy inference engines.

In this section we'll be building a simple tipping example using the graphical user interface (GUI) tools provided by the Fuzzy Logic Toolbox. Although it's possible to use the Fuzzy Logic Toolbox by working strictly from the command line, in general it's much easier to build a system graphically. There are five primary GUI tools for building, editing, and observing fuzzy inference systems in the Fuzzy Logic Toolbox. The Fuzzy Inference System or FIS Editor, the Membership Function Editor, the Rule Editor, the Rule Viewer, and the Surface Viewer. These GUIs are dynamically linked, in that changes we make to the FIS using one of them, can affect what we see on any of the other open GUIs. We can have any or all of them open for any given system. These are shown in Fig. 4.10

The FIS Editor handles the high level issues for the system: How many input and output variables? What are their names? The Fuzzy Logic Toolbox doesn't limit the number of inputs. However, the number of inputs may be limited by the available memory of our machine. If the number of inputs is too large, or the number of membership functions is too big, then it may also be difficult to analyze the FIS using the other GUI tools.

The Membership Function Editor is used to define the shapes of all the membership functions associated with each variable. The Rule Editor is for editing the list of rules that defines the behavior of the system.

The Rule Viewer and the Surface Viewer are used for looking at, as opposed to editing, the FIS. They are strictly read-only tools. The Rule Viewer is a mat lab-based display of the fuzzy inference diagram shown at the end of the last section. Used as a diagnostic, it can show (for example) which rules are active, or how individual membership function shapes are influencing the results. The Surface Viewer is used to display the dependency of one of the outputs on any one or two of the inputs that is, it generates and plots an output surface map for the system.The five primary GUIs can all interact and exchange information. Any one of them can read and write both to the workspace and to the disk (the read-only viewers can still exchange plots with the workspace and/or the disk). For any fuzzy inference system, any or all of these five GUIs may be open. If more than one of these editors is open for a single system, the various GUI windows are aware of the existence of the others, and will, if necessary, update related windows. Thus if the names of the membership functions are changed using the Membership Function Editor, those changes are reflected in the rules shown in the Rule Editor. The editors for any number of different FIS systems may be open simultaneously. The FIS Editor, the Membership Function Editor, and the Rule Editor can all read and modify the FIS data, but the Rule Viewer and the Surface Viewer do not modify the FIS data in any way.

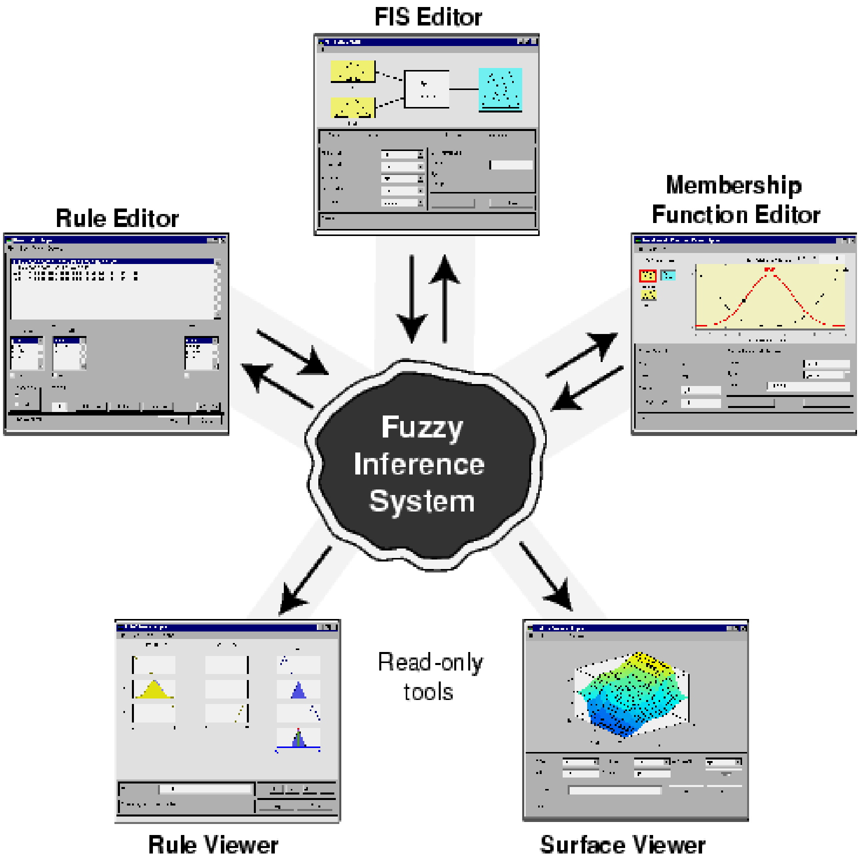


Fig.4.10 The Primary GUI Tools of the Fuzzy Logic Toolbox

4.7.1 THE FIS EDITOR

The following discussion walks you through building a new fuzzy inference system from scratch. If we want to save time and follow along quickly, we can load the already built system by typing fuzzy in Command window. This will launch the FIS Editor.

The FIS Editor displays general information about a fuzzy inference system. There's a simple diagram as shown in Fig4.11 that shows the names of each input variable on the left, and those of each output variable on the right. The sample membership functions shown in the boxes are just icons and do not depict the actual shapes of the membership functions.

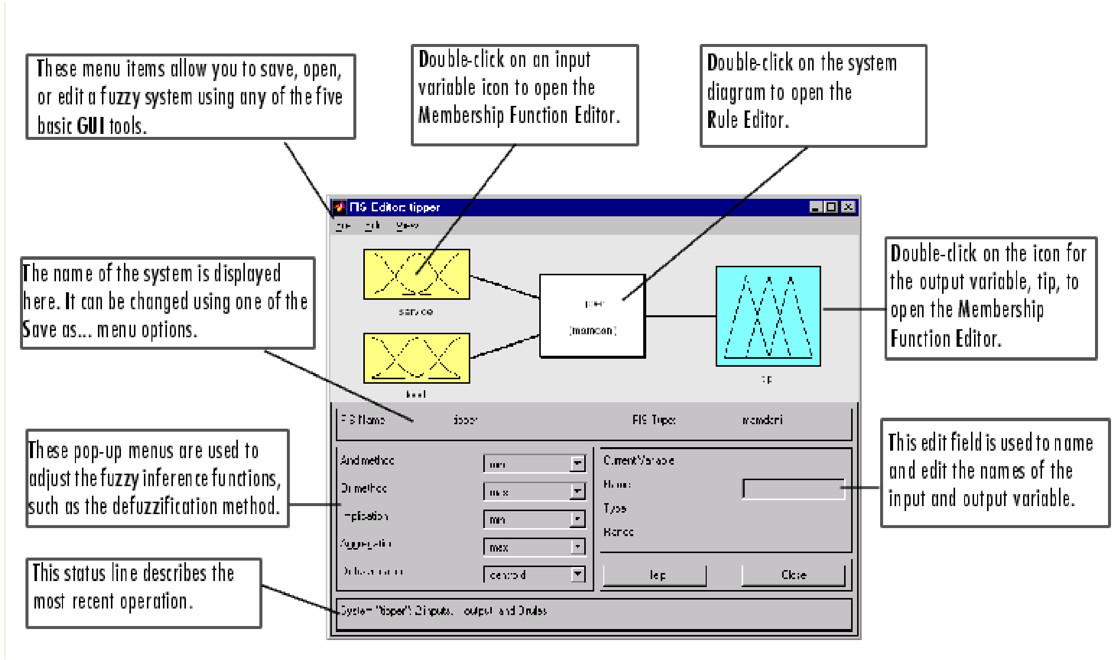


Fig 4.11 The FIS Editor

Below the diagram is the name of the system and the type of inference used. The default, Madman-type inference, is what we'll continue to use for this example. Another slightly different type of inference, called Surgeon-type inference, is also available. Below the name of the fuzzy inference system, on the left side of the figure, are the pop-up menus that allow you to modify the various pieces of the inference process. On the right side at the bottom of the figure is the area that displays the name of an input or output variable, its associated membership function type, and its range. The latter two fields are specified only after the membership functions have been. Below that region are the Help and Close buttons that call up online help and close the window, respectively. At the bottom is a status line that relays information about the system.

To start this system from scratch, type fuzzy at the mat lab prompt. The generic untitled FIS Editor opens, with one input, labeled input1, and one output, labeled output1. For this example, we will construct a two-input, one output system, so in the Edit menu select Add input. A second yellow box labeled input2 will appear.

We'd like to change the variable names to reflect that, though:

- By Clicking once on the left-hand (yellow) box marked input1 (the box will be highlighted in red).

- In the white edit field on the right, changed the input1 to ip1 and Returned.

- Clicking once on the left-hand (yellow) box marked **i**nput2 (the box will be highlighted in red).

- In the white edit field on the right, changed the input2 to ip2 and pressed Returned.

- Clicking once on the right-hand (blue) box marked output1.

- In the white edit field on the right, changed the output1 to op.

- From the File menu selected Save to workspace as and a window appears as shown in fig.4.4.

- Entered the variable name as our choice and clicked on ok.

We will see the diagram updated to reflect the new names of the input and output variables. There is now a new variable in the workspace called tipper that contains all the information about this system. By saving to the workspace with a new name, we will also rename the entire system. The window will look like as shown in Fig 4.4.

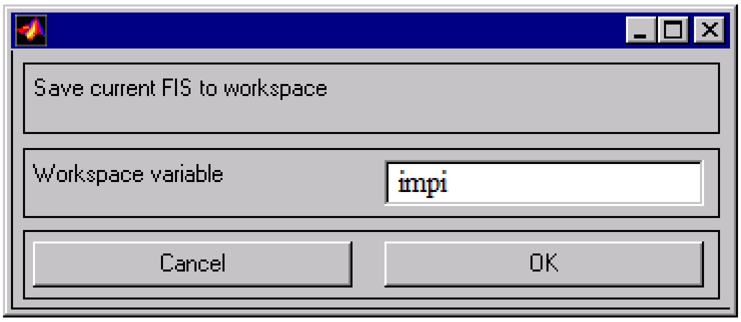


Figure 4.12 „Save to workspace as..." Window

Leave the inference options in the lower left in their default positions for now. We've entered all the information as we need for this particular GUI. Next defined the membership functions associated with each of the variables. To do this, open the Membership Function Editor. we can open the Membership Function Editor in one of three ways:

- Pull down the View menu item and select Edit Membership Functions....

- Double-click on the icon for the output variable, tip.
- Type mfedit at the command line.

4.7.2 THE MEMBERSHIP FUNCTION EDITOR

The Membership Function Editor shares some features with the FIS Editor. In fact, all of the five basic GUI tools have similar menu options, status lines, and Help and Close buttons. The Membership Function Editor is the tool that lets you display and edits all of the membership functions associated with all of the input and output variables for the entire fuzzy inference system. Fig.4.6 shows the Membership Function Editor.

When we open the Membership Function Editor to work on a fuzzy inference system that does not already exist in the workspace, there is not yet any membership functions associated with the variables that you have just defined with the FIS Editor.

On the upper left side of the graph area in the Membership Function Editor is a "Variable Palette" that lets us set the membership functions for a given variable. To set up our membership functions associated with an input or an output variable for the FIS, selected an FIS variable in this region by clicking on it.

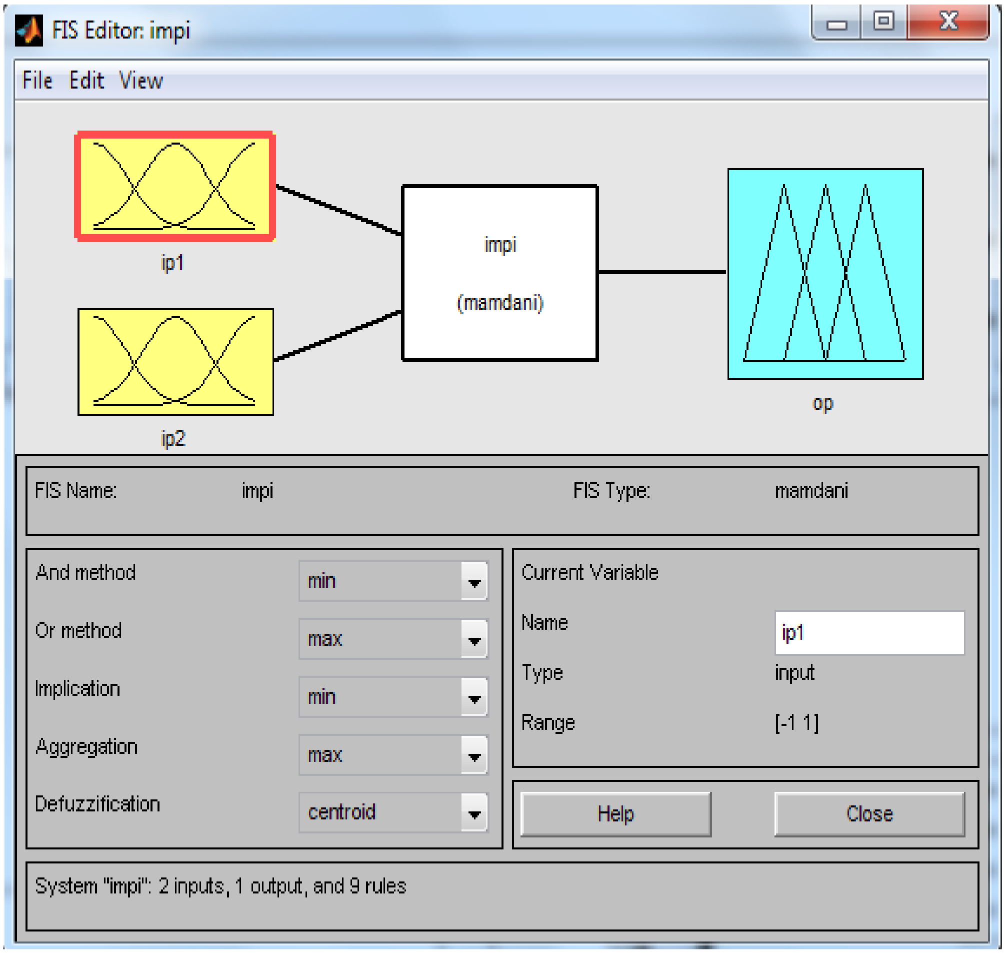


Figure 4.13 The updated FIS Editor

Next selected the Edit pull-down menu, and choose Add MFs.... A new window will appear which allows us to select both the membership function type and the number of membership functions associated with the selected variable. In the lower right corner of the window are the controls that let to change the name, type, and parameters (shape), of the membership function, once it has been selected.

The membership functions from the current variable are displayed in the main graph. These membership functions can be manipulated in two ways. We can first use the mouse to select a particular membership function associated with a given variable quality, (such as poor, for the variable, service), and then drag the membership function from side to side. This will affect the mathematical description of the quality associated with that membership function for a given variable. The selected membership function can also be tagged for dilation or contraction by clicking on the small square drag points on the membership function, and then dragging the function with the mouse toward the outside, for dilation, or toward the inside, for contraction. This will change the parameters associated with that membership function.

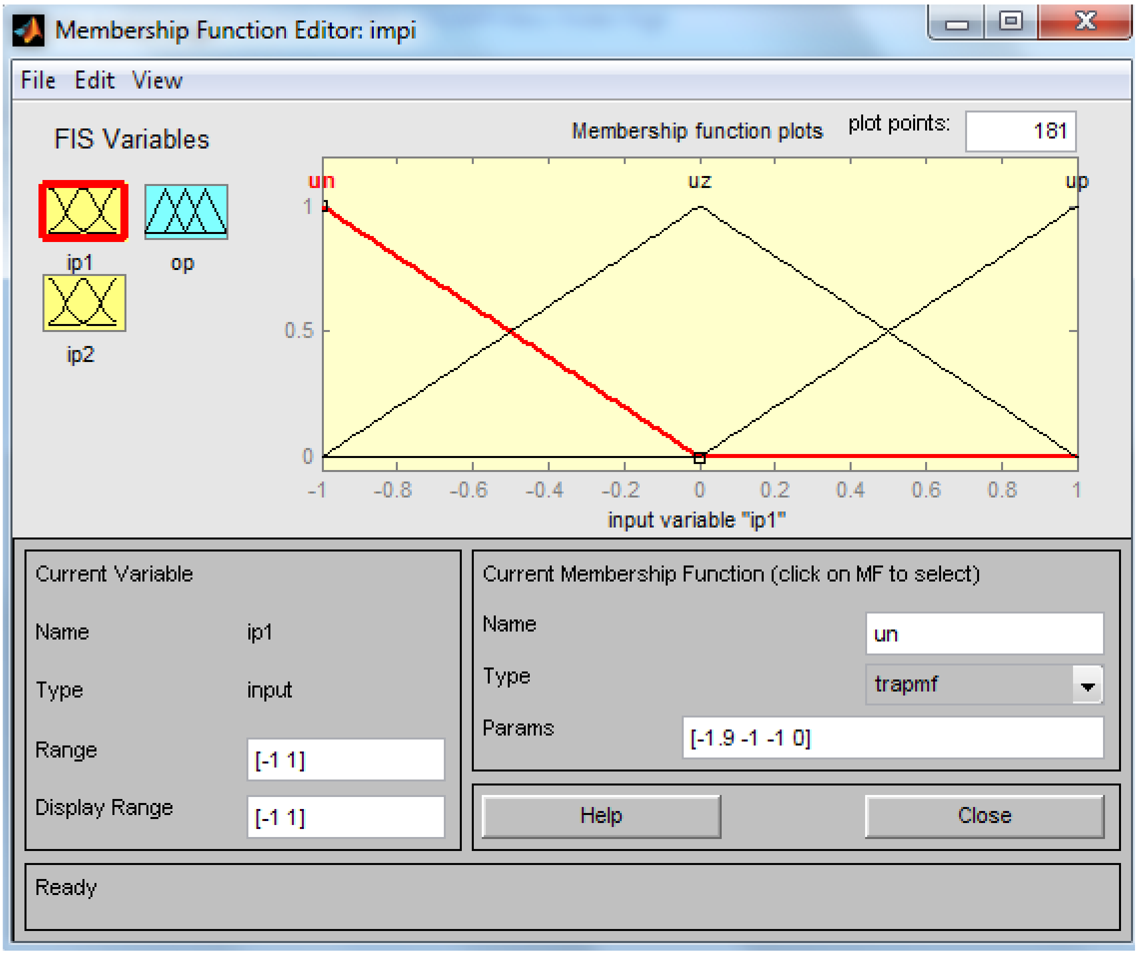


Figure 4.14 The updated Membership Function Editor

Now that the variables have been named, and the membership functions have appropriate shapes and names, we're ready to write down the rules. To call up the Rule Editor, go to the View menu and select Edit rules..., or type ruleedit at the command line. The Rule Editor window pops open as shown in Fig 4.14.

4.7.3 THE RULE EDITOR

Constructing rules using the graphical Rule Editor interface is fairly self-evident. Based on the descriptions of the input and output variables defined with the FIS Editor, the Rule Editor allows to construct the rule statements automatically, by clicking on and selecting one item in each input variable box, one item in each output box, and one connection item. Choosing none as one of the variable qualities will exclude that variable from a given rule.

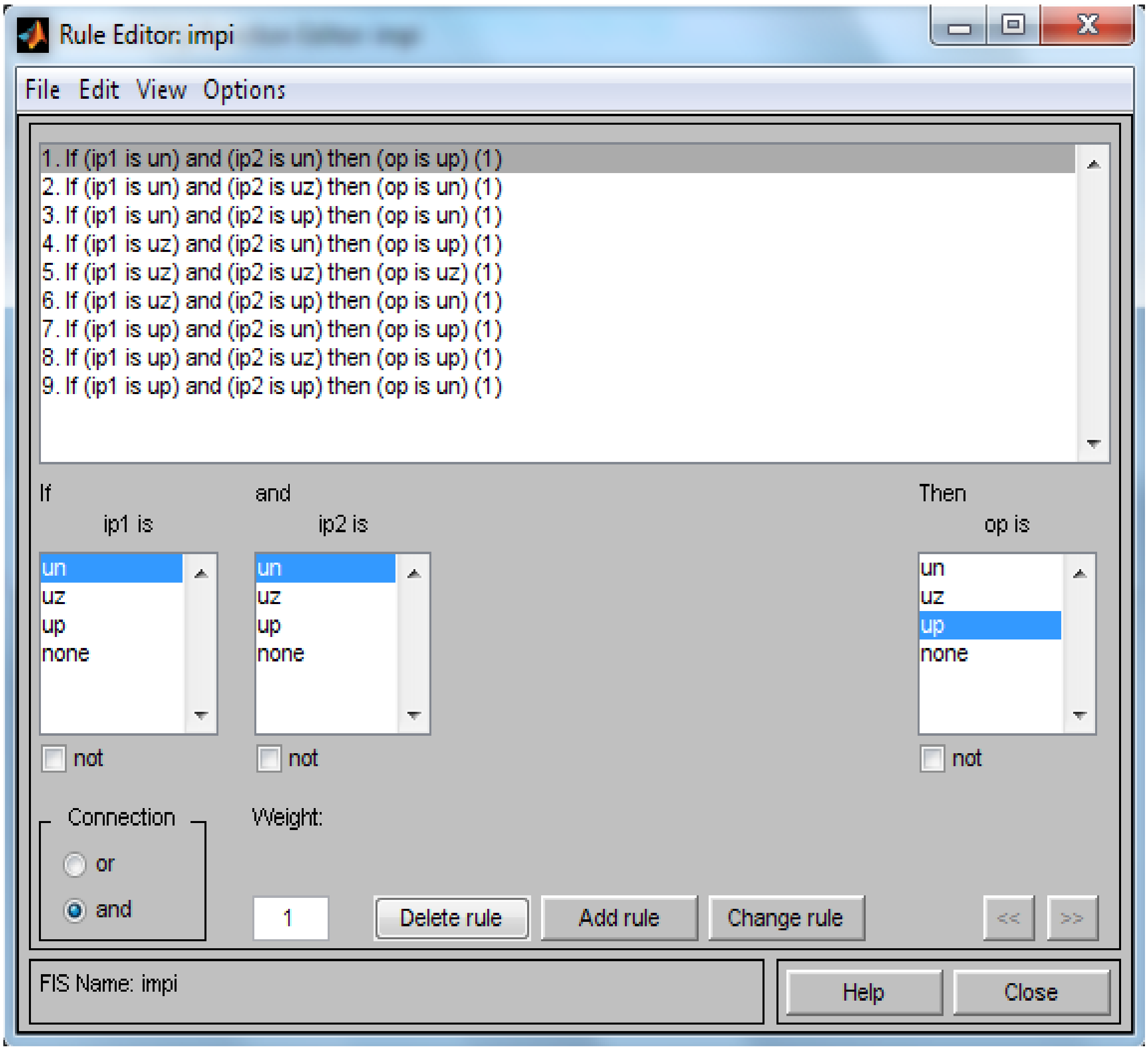


Figure 4.15 The Rule Editor

Choosing not under any variable name will negate the associated quality. Rules may be changed, deleted, or added, by clicking on the appropriate button.

The Rule Editor also has some familiar landmarks, similar to those in the FIS Editor and the Membership Function Editor, including the menu bar and the status line. The Format pop-up menu is available from the Options pull-down menu from the top menu bar -- this is used to set the format for the display. Similarly, Language can be set from under Options as well. The Help button will bring up a MATLAB Help window.

4.7.4 THE RULE VIEWER

The Rule Viewer displays a roadmap of the whole fuzzy inference process. It's based on the fuzzy inference diagram described in the previous section. The single figure window as shown in fig.4.16. The three small plots across the top of the figure represent the antecedent and consequent of the first rule. Each rule is a row of plots, and each column is a variable. The first two columns of plots show the membership functions referenced by the antecedent, or the if-part of each rule. The third column of plots shows the membership functions referenced by the consequent, or the then-part of each rule. If we click once on a rule number, the corresponding rule will be displayed at the bottom of the figure. This decision will depend on the input values for the system.There are also familiar items like the status line and the menu bar. In the lower right there is a text field into which we can enter specific input values. For the two-input system,

We will enter an input vector. We can also adjust these input values by clicking anywhere on any of the three plots for each input. This will move the red index line horizontally, to the point where we have clicked. This can also do by just click and drag this line in order to change the input values. When we release the line, (or after manually specifying the input), a new calculation is performed, and we can see the whole fuzzy inference process take place.

The Rule Viewer allows interpreting the entire fuzzy inference process at once. The Rule Viewer also shows how the shape of certain membership functions influences the overall result. Since it plots every part of every rule, it can become unwieldy for particularly large systems, but, for a relatively small number of inputs and outputs, it performs well (depending on how much screen space we devote to it) with up to 30 rules and as many as 6 or 7 variables.

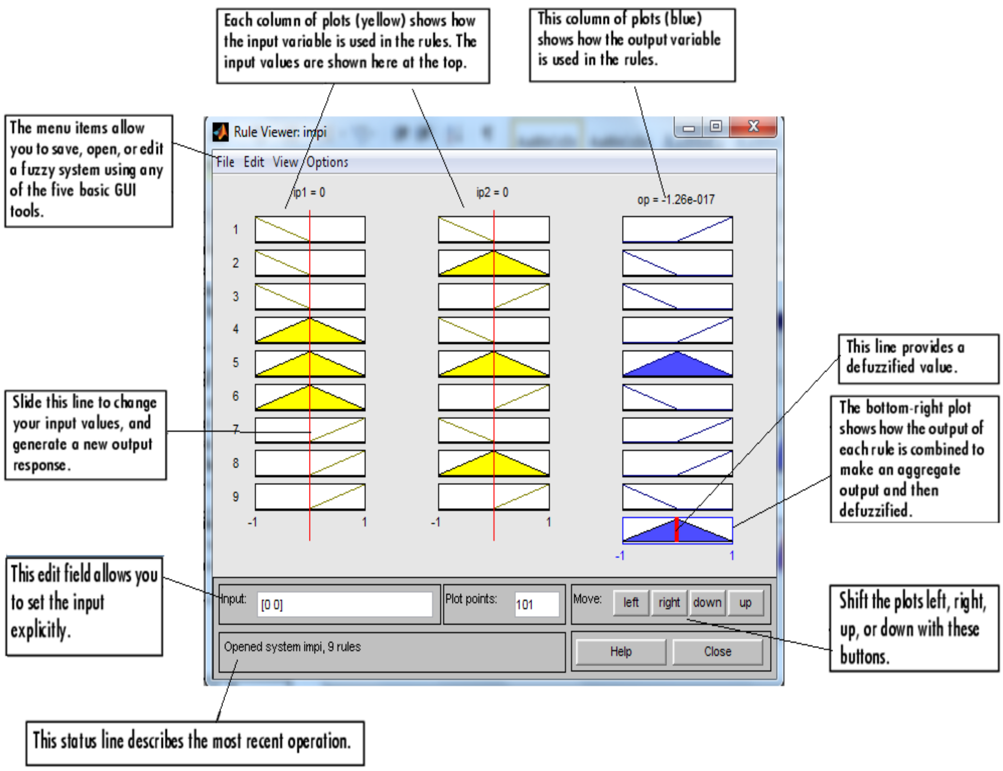


Figure 4.16 The Rule Viewer

The Rule Viewer shows one calculation at a time and in great detail. In this sense, it presents a sort of micro view of the fuzzy inference system. If we want to see the entire output surface of our system, that is, the entire span of the output set based on the entire span of the input set, we need to open up the Surface Viewer.

This is the last of our five basic GUI tools in the Fuzzy Logic Toolbox, and we can open it by selecting View surface... from the View menu. The Surface Viewer window pops open as shown in fig.4.17.

4.7.5 THE SURFACE VIEWER

Upon opening the Surface Viewer, we are presented with a two-dimensional curve that represents the mapping. In case of one-input one-output, we can see the entire mapping in one plot. Two-input one-output systems also work well, as they generate three-dimensional plots that mat lab can adeptly manage. When we move beyond three dimensions overall, we start to encounter trouble displaying the results. Accordingly, the Surface Viewer is equipped with pop-up menus that let to select any two inputs and any one output for plotting. Just below the pop-up menus are two text input fields that let we determine how many x-axis and y-axis grid lines we want to include. This allows keeping the calculation time reasonable for complex problems. Pushing the Evaluate button initiates the calculation, and the plot comes up soon after the calculation is complete. To change the x-axis or y-axis grid after the surface is in view, simply change the appropriate text field, and click on either X-grids or Y-grids, according to which text field has to change, to redraw the plot.

The Surface Viewer has a special capability that is very helpful in cases with two (or more) inputs and one output: we can actually grab the axes and reposition them to get a different three-dimensional view on the data. The Ref. Input field is used in situations when there are more inputs required by the system than the surface is mapping. Suppose if we have a four-input one-output system and would like to see the output surface. The Surface Viewer can generate a three-dimensional output surface where any two of the inputs vary, but two of the inputs must be held constant since computer monitors cannot display a five-dimensional shape

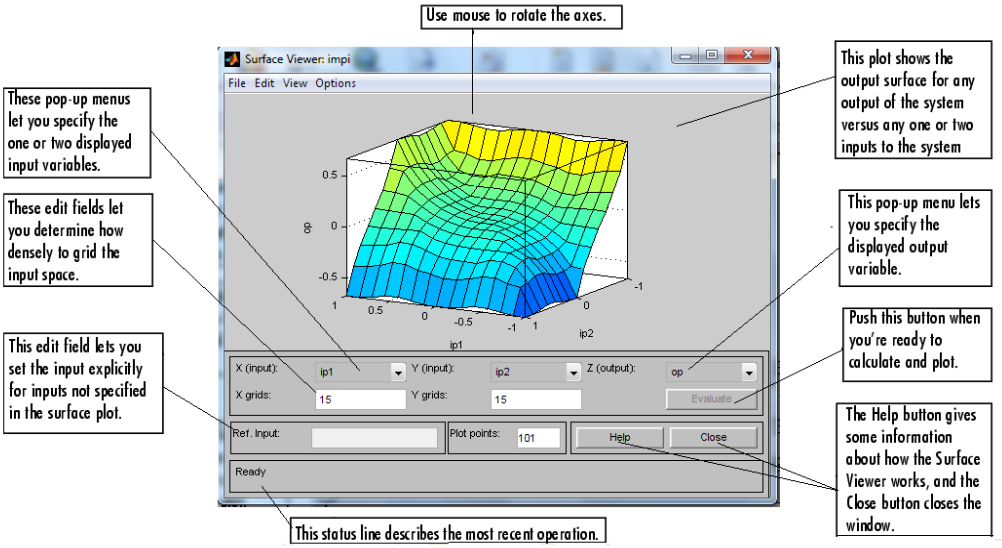


Figure 4.17. The Surface Viewer

CHAPTER 5

MICROGRID

5.1 Introduction

Our electric power system was designed to move central station alternating current (AC) power, via high-voltage transmission lines and lower voltage distribution lines, to households and businesses that used the power in incandescent lights, AC motors, and other AC equipment. Today's consumer equipment and tomorrow's distributed renewable generation requires us to rethink this model. Electronic devices (such as computers, florescent lights, variable speed drives, and many other household and business appliances and equipment) need direct current (DC) input. However, all of these DC devices require conversion of the building's AC power into DC for use, and that conversion typically uses inefficient rectifiers. Moreover, distributed renewable generation (such as rooftop solar) produces DC power but must be converted to AC to tie into the building's electric system, only later to be re-converted to DC for many end uses. These AC-DC conversions (or DC-AC-DC in the case of rooftop solar) result in substantial energy losses.

One possible solution is a DC microgrid, which is a DC grid within a building (or serving several buildings) that minimizes or eliminates entirely these conversion losses. In the DC microgrid system, AC power converts to DC when entering the DC grid using a high-efficiency rectifier, which then distributes the power directly to DC equipment served by the DC grid. On average, this system reduces AC to DC conversion losses from an average loss of about 32% down to 10%.2 In addition, roof top photovoltaic (PV) and other distributed DC generation can be fed directly to DC equipment, via the DC microgrid, without the double conversion loss (DC to AC to DC), which would be required if the DC generation output was fed into an AC system.

This paper describes the operation of DC micro grids, potential national benefits, barriers to deployment, and policy measures that could accelerate this deployment.

5.2 DC microgrid technology

The Energy Independence and Security Act of 2007, Title XIII, identifies the elements that characterize the "Smart Grid" policy goals. In summary, these are:

_ reliability; security; storage; distributed generation _ energy efficiency sustainability; renewable inputs IT/communications leverage/full cyber-security _ load awareness; demand side management; plug-in vehicles lowering unnecessary barriers to achieving the above Each of these goals can be advanced through the use of DC micro grids, and often at lower cost with greater effectiveness than measures applied to the greater AC grid.

The national power grid system in the U.S. and around the world was not designed to handle the energy demands of the modern economy. To meet the contemporary needs of the grid's customers today, we should consider the tools available through DC micro grids, which can optimize the use of electronic devices, electrical storage, and distributed generation.

The national Smart Grid discussion should thus focus on ensuring that the grid optimally balances what we refer to as the "Power Equation" (power generated, less line and conversion losses, equals power used). The interest in DC micro grids over the past 10 years has been growing. The U.S. Department of Energy (DOE), the California Energy Commission (CEC), the Electric Power Research Institute (EPRI), several utilities and many entrepreneurs and investors have sought through Smart Grid initiatives to upgrade the interface between the utility grids. The vast majority of these efforts have been designed to operate in the AC currency of the national grid.

The present discussion focuses on DC micro grids as a way to improve the efficiency, reliability and security of the implementation of the Smart Grid

A.What is a DC microgrid?

Defining "microgrid" is important for our discussion, but not necessarily simple. The DOE and the CEC jointly commissioned a report from Navigant Consulting in 2005 that wrestled with this very definition. The final report identified two "Points of Universal Agreement" of what constitutes a microgrid, which remain valid today: A microgrid consists of interconnected distributed energy resources capable of providing sufficient and continuous energy to a significant portion of internal load demand.

A microgrid possesses independent controls, and intentional islanding takes place with minimal service interruption (seamless transition from grid-parallel to islanded operation).

These two definitions work easily in both the AC and DC domain, so we will borrow them both.DC micro grids can be deployed in a portion of a building, building-wide or covering several buildings. We will refer to these systems (whatever their scale) as "DC micro grids" in the balance of this paper.

This defined physical area that the DC microgrid serves is an important element when considering the deployment– more so than power level – because an important design consideration of DC networks at these voltages has to do with scale.

DC power is highly susceptible to impedance (or resistance) losses, which are those imposed by the transmission medium itself, usually wire. The nature of DC is such that resistance can quickly sap power, but the efficiencies of DC systems—as we shall see—are dramatic and must be considered in deciding the scale of a DC system. All of these grids have the common need to adopt standards to guarantee interoperability. These standards are essential to the efficient development of the grid and the successful achievement of the key goals of the Smart Grid at a lower cost than possible in the AC domain, as discussed above.

B.What can DC microgrids do?

How would the grid look if its architecture optimized solar PV inputs, and maximized the efficiency of all of our electronic devices? What benefits would be gained by further accelerating these two fast growing elements of the Power Equation? Let us start with DC-powered electronic devices—which represent 50% of the electric load in many buildings today. In the 50 years following the advent of semiconductors in consumer products, electronic devices have become ubiquitous.

Computing and Internet connectivity is showing up in many appliances, incandescent lights are giving way to electronic ones (either fluorescent or LED) and portable electronic devices continue to proliferate. Another element of the growing DC load is the Variable Speed Drives (VFD) for electric motors.

These electronic devices have been deployed in the millions to improve the efficiency of the nearly ubiquitous AC induction motor. By installing VFDs in front of their AC motors, building owners and operators are able to control the speed of the motor, which delivers an outsized benefit: for every one-eighth the motor slows in speed, one-third of the energy is saved. Therefore, when a pump, fan or blower motor can opportunistically be throttled back, a great deal of electricity is saved for the customer. The grid benefits too, by not suffering the demand spikes that are caused when regular AC motors are turned off and on because they cannot modulate their speed.

A VFD is not just an AC device that has AC going into it from the grid, and AC leaving it to the motor; instead the electricity must pass through a DC state, meaning that the AC motor connected to a VFD can become a DC consuming device, just like your cell phone, laptop, LCD or plasma TV and overhead lights. Let us imagine these loads distributed throughout a building as they are now and imagine how we should power them, again borrowing the Smart Grid's guiding principles for our better-optimized Power Equation. Because we are looking for reliability and redundancy, we will want to create a DC environment to deliver power to these loads as the telecommunications has done historically in switching stations, and more recently to support servers in data centre applications. But better redundancy is only the beginning benefit a DC network brings because a DC Network does not need the ubiquitous AC to DC converting power supply (like the brick that plugs into your laptop) for every electronic device. Assumed to be a necessity, power supplies currently on the market impose losses on the power going to the device, typically 15% to 40%.9 This range of losses in a DC micro-grid can be readily lowered to 10% to 15% by using a higher efficiency conversion for multiple loads. This topology will persistently win out due to the superior economics of bulk conversion versus converter at every point-of-use.

Another benefit of the decision to incorporate DC micro-grids is the superior compatibility of the DC power with electricity storage. During every major grid blackout (or brown-out, as periods of insufficient power production are called) experts note that further development of grid-scale power storage would vastly improve the stability of the grid. This concept, while technically possible, appears implausible because it evokes an image of some giant C-Cell Battery in the desert that would sustain the grid in case of emergency. This would simply be too expensive tomake much sense. On the other hand, using distributed batteries connected to a DC network maximizes the battery's power by avoiding the conversion of its output, but also equals the sum of its parts precisely, such that 1000 small battery banks each having 10 hours of capacity to run a laptop needing 100 watts equals 1 megawatt hour just as if it came from a giant battery owned by the utility. But this analogy is too generous to the latter: power from the distant battery would suffer other losses the local battery would not. These include inversion losses (going from the DC in the battery to the AC of the grid), transmission and distribution losses (estimated to be 7to 11% by the U.S. Department of Energy) and finally rectification losses when it gets to your electronic load. Collectively, these losses could add up to as much as 41% of the energy ultimately delivered to a DC device.10 These conversion losses and line losses can largely be avoided by use of distributed batteries in a DC micro-grid. Thus, although the DC network improves the economics of batteries (which are themselves DC devices) by marrying them closely to the DC devices they back-up in a highly distributed fashion, storage can be added to our developing DC micro-grid in preference to large centralized battery storage schemes.

Fortunately, adding DC storage to a DC micro-grid is a comparatively simple piece of engineering compared to the complications of integrating DC storage in the AC domain where additional hardware is required. The oldest continuously operating electrical systems in the world, stretching back to the origins of Bell Telephone, use DC storage. Those early exchanges formed the model of reliability, if not universal connectivity — it took over 30 years to resolve barriers between exchanges so that callers could reach customers of other exchanges.

Moreover, we have in this set of DC building loads the opportunity to integrate at higher efficiency – other renewable energy generators that are intrinsically DC sources such as solar PV, small wind turbines, or fuel cells. Unlike an AC system, these various DC elements can work in concert without regard to matching phases. In a DC system, only the voltage needs to be considered, whereas AC systems require each element to have identical wave shapes—or be synchronized—to operate. This coordination is achieved through a complex device called an inverter, which provides the perennial weak link in distributed generation systems.

The DC microgrid thus can accommodate DC inputs because they enjoy a common currency. Therefore, given a suitably robust generator and ample storage, we now have quite an efficient local grid network that uses solar PV and integrates electrical storage at higher efficiencies than are possible in a conventional AC system. Existing plug-in devices pose a transitional challenge for DC microgrids because until these products are replaced by ones using a standard voltage, not all can be plugged in without a DC to DC converter.

The DC microgrid can also simplify and raise the efficiency of how plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV) connect to the grid. Rather than automatically requiring the grid to negotiate opportunistic givers or takers of electric power, which could have large adverse impacts on the grid's stability, a DC microgrid can act like a high-efficiency buffer, optimizing generation and storage and increasing grid reliability. Moreover, because DC power has no phase to match, the connection to the vehicle is simplified, providing a more efficient path to its DC battery. As a system, the DC microgrid also creates more possibilities for the vehicle's stored or generated power by enabling either high efficiency on site use, or the more marginal economics of sending the power to the grid. This option is valuable and will help create more efficient markets for all DG connected in this manner throughout the system.

By locally managing sources and loads, a DC microgrid can optimize its net surplus of power (output to the grid) or deficit (input from the grid). This greater local management of both supply and demand creates a buffer to the grid and relieves some of its burden. Conventional means of Demand Side Management (DSM) do not accomplish these ends as efficiently. This becomes possible because of better exploitation of DC's natural characteristics, which remains the lifeblood of all electronic devices and the de facto fuel of the digital economy.

5.3 Grid-connection

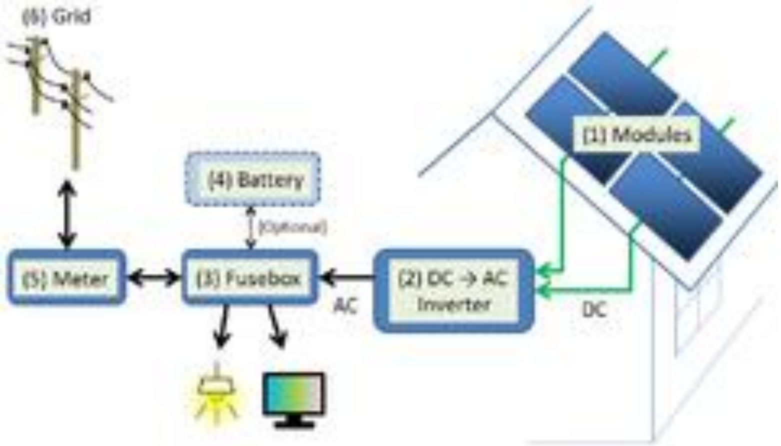


Figure 5.1: Grid connection

A grid connected system is connected to a larger independent grid (typically the public electricity grid) and feeds energy directly into the grid. This energy may be shared by a residential or commercial building before or after the revenue measurement point. The difference being whether the credited energy production is calculated independently of the customer's energy consumption (feed-in tariff) or only on the difference of energy (net metering). Grid connected systems vary in size from residential (2-10kWp) to solar power stations (up to 10s of MWp). This is a form of decentralized electricity generation. The feeding of electricity into the grid requires the transformation of DC into AC by a special, synchronising grid-tie inverter.[15] In kW sized installations the DC side system voltage is as high as permitted (typically 1000V except US residential 600V) to limit ohmic losses. Most modules (72 crystalline silicon cells) generate 160W to 300W at 36 volts. It is sometimes necessary or desirable to connect the modules partially in parallel rather than all in series. One set of modules connected in series is known as a 'string'.

CHAPTER 6
DC-DC CONVERTERS

6.1 Dc-dc converters

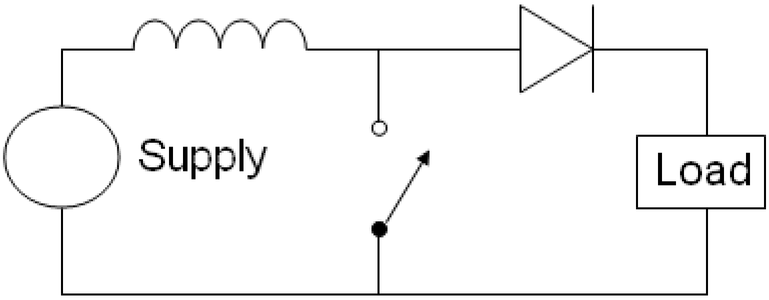
There are three basic types of dc-dc converter circuits, termed as buck, boost and buck-boost. In all of these circuits, a power device is used as a switch. This device earlier used was a thyristor, which is turned on by a pulse fed at its gate. In all these circuits, the thyristor is connected in series with load to a dc supply, or a positive (forward) voltage is applied between anode and cathode terminals.

The thyristor turns off, when the current decreases below the holding current, or a reverse (negative) voltage is applied between anode and cathode terminals. So, a thyristor is to be force-commutated, for which additional circuit is to be used, where another thyristor is often used. Later, GTO's came into the market, which can also be turned off by a negative current fed at its gate, unlike thyristors, requiring proper control circuit. The turn-on and turn-off times of GTOs are lower than those of thyristors. So, the frequency used in GTO-based choppers can be increased, thus reducing the size of filters. Earlier, dc-dc converters were called 'choppers', where thyristors or GTOs are used. It may be noted here that buck converter (dc-dc) is called as 'step-down chopper', whereas boost converter (dc-dc) is a 'step-up chopper'. In the case of chopper, no buck-boost type was used.

With the advent of bipolar junction transistor (BJT), which is termed as self-commutated device, it is used as a switch, instead of thyristor, in dc-dc converters. This device (NPN transistor) is switched on by a positive current through the base and emitter, and then switched off by withdrawing the above signal. The collector is connected to a positive voltage. Now-a-days, MOSFETs are used as a switching device in low voltage and high current applications. It may be noted that, as the turn-on and turn-off time of MOSFETs are lower as compared to other switching devices, the frequency used for the dc-dc converters using it (MOSFET) is high, thus, reducing the size of filters as stated earlier. These converters are now being used for applications, one of the most important being Switched Mode Power Supply (SMPS). Similarly, when application requires high voltage, Insulated Gate Bi-polar Transistors (IGBT) are preferred over BJTs, as the turn-on and turn-off times of IGBTs are lower than those of power transistors (BJT), thus the frequency can be increased in the converters using them. So, mostly self-commutated devices of transistor family as described are being increasingly used in dc-dc converters.

6.2 Boost Converters (dc-dc)

A boost converter (dc-dc) is shown in Fig.6.1. Only a switch is shown, for which a device belonging to transistor family is generally used. Also, a diode is used in series with the load. The load is of the same type as given earlier. The inductance of the load is small. An inductance, L is assumed in series with the input supply. The position of the switch and diode in this circuit may be noted, as compared to their position in the buck converter.



6.1 Boost converter (dc-dc)

6.3 Operating principleof boost converter

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current by creating and destroying a magnetic field. In a boost converter, the output voltage is always higher than the input voltage. A schematic of a boost power stage is shown in Figure 1.

- When the switch is closed, current flows through the inductor in clockwise direction and the inductor stores some energy by generating a magnetic field. Polarity of the left side of the inductor is positive.
- When the switch is opened, current will be reduced as the impedance is higher. The magnetic field previously created will be destroyed to maintain the current flow towards the load. Thus the polarity will be reversed (means left side of inductor will be negative now). As a result two sources will be in series causing a higher voltage to charge the capacitor through the diode D.

If the switch is cycled fast enough, the inductor will not discharge fully in between charging stages, and the load will always see a voltage greater than that of the input source alone when the switch is opened. Also while the switch is opened, the capacitor in parallel with the load is charged to this combined voltage. When the switch is then closed and the right hand side is shorted out from the left hand side, the capacitor is therefore able to provide the voltage and energy to the load. During this time, the blocking diode prevents the capacitor from discharging through the switch. The switch must of course be opened again fast enough to prevent the capacitor from discharging too much.

The basic principle of a Boost converter consists of 2 distinct states (see figure 2):

- In the On-state, the switch S (see figure 1) is closed, resulting in an increase in the inductor current;
- in the Off-state, the switch is open and the only path offered to inductor current is through the flyback diode D, the capacitor C and the load R. This results in transferring the energy accumulated during the On-state into the capacitor.
- The input current is the same as the inductor current as can be seen in figure 2. So it is not discontinuous as in the buck converterand the requirements on the input filter are relaxed compared to a buck converter.

6.4 Applications of boost converter

Battery power systems often stack cells in series to achieve higher voltage. However, sufficient stacking of cells is not possible in many high voltage applications due to lack of space. Boost converters can increase the voltage and reduce the number of cells. Two battery-powered applications that use boost converters are hybrid electric vehicles (HEV) and lighting systems.

The NHW20 model Toyota Prius HEV uses a 500 V motor. Without a boost converter, the Prius would need nearly 417 cells to power the motor. However, a Prius actually uses only 168 cells and boosts the battery voltage from 202 V to 500 V. Boost converters also power devices at smaller scale applications, such as portable lighting systems. A white LED typically requires 3.3 V to emit light, and a boost converter can step up the voltage from a single 1.5 V alkaline cell to power the lamp. Boost converters can also produce higher voltages to operate cold cathode fluorescent tubes (CCFL) in devices such as LCD backlights and some flashlights.

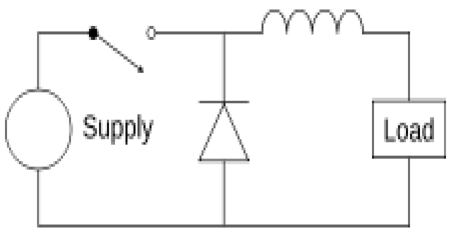
A boost converter is used as the voltage increase mechanism in the circuit known as the 'Joule thief'. This circuit topology is used with low power battery applications, and is aimed at the ability of a boost converter to 'steal' the remaining energy in a battery. This energy would otherwise be wasted since the low voltage of a nearly depleted battery makes it unusable for a normal load. This energy would otherwise remain untapped because many applications do not allow enough current to flow through a load when voltage decreases. This voltage decrease occurs as batteries become depleted, and is a characteristic of the ubiquitous alkaline battery. Since ($P=V^2/R$) as well, and R tends to be stable, power available to the load goes down significantly as voltage decreases.

6.5 Buck coverter

A buck converter is a voltage step down and current step up converter.

The simplest way to reduce the voltage of a DC supply is to use a linear regulator (such as a 7805), but linear regulators waste energy as they operate by dissipating excess power as heat. Buck converters, on the other hand, can be remarkably efficient (95% or higher for integrated circuits), making them useful for tasks such as converting the main voltage in a computer (12 V in a desktop, 12-24 V in a laptop) down to the 0.8-1.8 volts needed by the processor.

6.5.1 Theory of operation of buck converter



The basic operation of the buck converter has the current in an inductor controlled by two switches (usually a transistor and a diode). In the idealised converter, all the components are considered to be perfect. Specifically, the switch and the diode have zero voltage drop when on and zero current flow when off and the inductor has zero series resistance. Further, it is assumed that the input and output voltages do not change over the course of a cycle (this would imply the output capacitance as being infinite).

6.5.2 Concept of buck converter

The conceptual model of the buck converter is best understood in terms of the relation between current and voltage of the inductor. Beginning with the switch open (in the "off" position), the current in the circuit is 0. When the switch is first closed, the current will begin to increase, and the inductor will produce an opposing voltage across its terminals in response to the changing current. This voltage drop counteracts the voltage of the source and therefore reduces the net voltage across the load.

Over time, the rate of change of current decreases, and the voltage across the inductor also then decreases, increasing the voltage at the load. During this time, the inductor is storing energy in the form of a magnetic field. If the switch is opened while the current is still changing, then there will always be a voltage drop across the inductor, so the net voltage at the load will always be less than the input voltage source.

When the switch is opened again, the voltage source will be removed from the circuit, and the current will decrease. The changing current will produce a change in voltage across the inductor, now aiding the source voltage. The stored energy in the inductor's magnetic field supports current flow through the load. During this time, the inductor is discharging its stored energy into the rest of the circuit. If the switch is closed again before the inductor fully discharges, the voltage at the load will always be greater than zero.

6.6 Buck-boost converter

The buck–boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is equivalent to a flyback converter using a single inductor instead of a transformer.[1]

Two different topologies are called *buck–boost converter*. Both of them can produce a range of output voltages, from an output voltage much larger (in absolute magnitude) than the input voltage, down to almost zero.

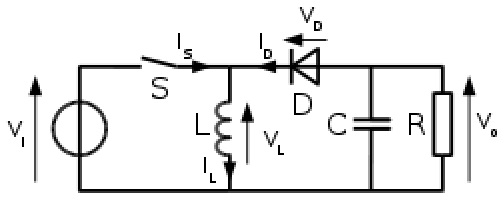
6.6.1 The inverting topology

The output voltage is of the opposite polarity than the input. This is a switched-mode power supply with a similar circuit topology to the boost converter and the buck converter. The output voltage is adjustable based on the duty cycle of the switching transistor. One possible drawback of this converter is that the switch does not have a terminal at ground; this complicates the driving circuitry. Neither drawback is of any consequence if the power supply is isolated from the load circuit (if, for example, the supply is a battery) because the supply and diode polarity can simply be reversed. The switch can be on either the ground side or the supply side.

6.6.2 A Buck (Step-Down) Converter Combined With A Boost (Step-Up) Converter

The output voltage is typically of the same polarity of the input, and can be lower or higher than the input. Such a non-inverting buck-boost converter may use a single inductor which is used for both the buck inductor and the boost inductor,[2][3][4] it may use multiple inductors but only a single switch as in the SEPIC and Ćuk topologies.

6.6.3 Principle Of Operation



- While in the On-state, the input voltage source is directly connected to the inductor (L). This results in accumulating energy in L. In this stage, the capacitor supplies energy to the output load.
- While in the Off-state, the inductor is connected to the output load and capacitor, so energy is transferred from L to C and R.
- Compared to the buck and boost converters, the characteristics of the buck–boost converter are mainly:
- Polarity of the output voltage is opposite to that of the input;
- The output voltage can vary continuously from 0 to $-\infty$ (for an ideal converter). The output voltage ranges for a buck and a boost converter are respectively 0 to V_i and V_i to ∞.

6.7 Conceptual overview

Like the buck and boost converters, the operation of the buck-boost is best understood in terms of the inductor's "reluctance" to allow rapid change in current. From the initial state in which nothing is charged and the switch is open, the current through the inductor is zero. When the switch is first closed, the blocking diode prevents current from flowing into the right hand side of the circuit, so it must all flow through the inductor. However, since the inductor doesn't like rapid current change, it will initially keep the current low by dropping most of the voltage provided by the source. Over time, the inductor will allow the current to slowly increase by decreasing its voltage drop. Also during this time, the inductor will store energy in the form of a magnetic field.

Cuk converter

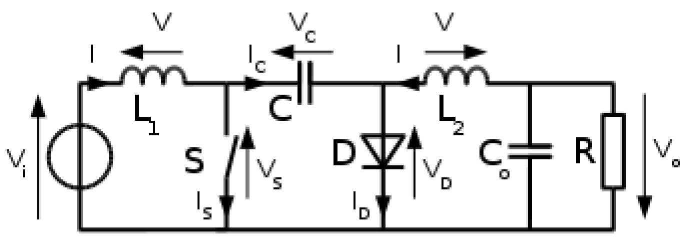
The Ćukconverter is a type of DC-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is essentially a boost converter followed by a buck converter with a capacitor to couple the energy.

The non-isolated Ćuk converter can only have opposite polarity between input and output. It uses a capacitor as its main energy-storage component, unlike most other types of converters which use an inductor. It is named after Slobodan Ćuk of the California Institute of Technology, who first presented the design.

6.8 Non isolated cuk converter

There are variations on the basic Ćuk converter. For example, the coils may share single magnetic core, which drops the output ripple, and adds efficiency. Because the power transfer flows continuously via the capacitor, this type of switcher has minimized EMI radiation. The Ćuk converter enables the energy flow bidirectionally, by adding a diode and a switch.

6.8.1 Operating principle



A non-isolated Ćuk converter comprises two inductors, two capacitors, a switch (usually a transistor), and a diode. Its schematic can be seen in figure 1. It is an inverting converter, so the output voltage is negative with respect to the input voltage.

The capacitor C is used to transfer energy and is connected alternately to the input and to the output of the converter*via* the commutation of the transistor and the diode (see figures 2 and 3).

The two inductors L_1 and L_2 are used to convert respectively the input voltage source (V_i) and the output voltage source (C_o) into current sources. At a short time scale an inductor can be considered as a current source as it maintains a constant current. This conversion is necessary because if the capacitor were connected directly to the voltage source, the current would be limited only by the parasitic resistance, resulting in high energy loss. Charging a capacitor with a current source (the inductor) prevents resistive current limiting and its associated energy loss.

As with other converters (buck converter, boost converter, buck-boost converter) the Ćuk converter can either operate in continuous or discontinuous current mode. However, unlike these converters, it can also operate in discontinuous voltage mode (i.e., the voltage across the capacitor drops to zero during the commutation cycle).

6.9 Single-ended primary-inductor converter

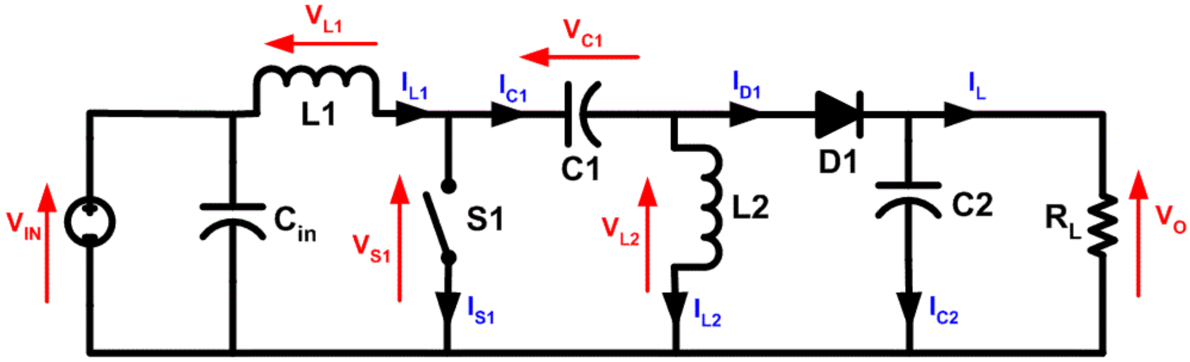
Single-ended primary-inductor converter (SEPIC) is a type of DC-DC converter allowing the electrical potential (voltage) at its output to be greater than, less than, or equal to that at its input; the output of the SEPIC is controlled by the duty cycle of the control transistor.

A SEPIC is essentially a boost converter followed by a buck-boost converter, therefore it is similar to a traditional buck-boost converter, but has advantages of having non-inverted output (the output has the same voltage polarity as the input), using a series capacitor to couple energy from the input to the output (and thus can respond more gracefully to a short-circuit output), and being capable of true shutdown: when the switch is turned off, its output drops to 0 V, following a fairly hefty transient dump of charge.

SEPICs are useful in applications in which a battery voltage can be above and below that of the regulator's intended output. For example, a single lithium ion battery typically discharges from 4.2 volts to 3 volts; if other components require 3.3 volts, then the SEPIC would be effective.

6.9.1 Circuit operation of SEPIC

The schematic diagram for a basic SEPIC is shown in Figure 1. As with other switched mode power supplies (specifically DC-to-DC converters), the SEPIC exchanges energy between the capacitors and inductors in order to convert from one voltage to another. The amount of energy exchanged is controlled by switch S1, which is typically a transistor such as a MOSFET; MOSFETs offer much higher input impedance and lower voltage drop than bipolar junction transistors (BJTs), and do not require biasing resistors as MOSFET switching is controlled by differences in voltage rather than a current, as with BJTs).



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CHAPTER 7
PULSE-WIDTH MODULATION

7.1 Introduction

Pulse-width modulation (PWM) is the basis for control in power electronics. The (**P**ulse **W**idth **M**odulation) A modulation technique that uses a digital circuit to create a variableanalog signal. PWM is a simple concept: open and close a switch at uniform, repeatableintervals. Analog circuits that vary the voltage tend to drift, and it costs more to produce onesthat do not than it does to make digital PWM circuits. In addition, control of almost everythingtoday is already in the digital realm.For example, PWM is widely used to control the speed of a DC motor and the brightness of a bulb, in which case the PWM circuit is used to open/close a power line. If the line were opened for 1ms and closed for 1ms, and this were continuously repeated, the target would receive an average of 50% of the voltage and run at half speed or half brightness. If the line were opened for1ms and closed for 3ms, the target would receive an average of 25%.Today, PWM technique has been used in wide applications, such voltage control, current control,motor control, power control, UPS, inverter.

7.2 PWM techniques

Because of advances in solid state power devices and microprocessors switching power converters are used in more and more modern motor drives to convert and deliver the required energy to the motor. The energy that a switching power converter delivers to a motor is controlled by Pulse Width Modulated (PWM) signals applied to the gates of the power transistors. PWMsignals are pulse trains with fixed frequency and magnitude and variable pulse width. There is one pulse of fixed magnitude in every PWM period. However, the width of the pulses changes from pulse to pulse according to a modulating signal. When a PWM signal is applied to the gate of a power transistor, it causes the turn on and turn off intervals of the transistor to change from onePWM period to another PWM period according to the same modulating signal. The frequency of a PWM signal must be much higher thanthat of the modulatingsignal, the fundamental frequency, such that the energy deliveredto the motor and its load depends mostly on themodulating signal [2].

7.3 Advantages and disadvantages of pulse width modulation

Advantage of PWM:

The advantage of PWM based switching power converter over linear power amplifier is:

- Easy to implement and control,
- No temperature variation-and ageing-caused drifting ordegradation in linearity,
- Compatible with today's digital microprocessors,
- Lower power dissipation, and
- It allows linear amplitude control of the output voltage/current from previously not present.

Disadvantage of PWM:

- Attenuation of the wanted fundamental component of the PW Med waveform, in this case from **1.1-0.866**^Pu.
- Drastically increased switching frequencies (in this case from 1 pu to 21 pu)-this means greater stresses on associated switching devices and therefore derating of those devices, and
- Generation of high-frequency harmonic components. The following are some major concerns then comparing different PWM techniques:
- Low switching losses.
- Good utilization of DC power supply that is to deliver a higher output voltage with the same DC supply.
- Good linearity in voltage and or current control.
- Low harmonics contents in the output voltage and or currents, especially in the low-frequency region. The basic PWM techniques are:

a) Single Pulse Width Modulation
b) Multi Pulse Width Modulation
c) Sinusoidal Pulse Width Modulation

But when the technology progresses some advanced modulation techniques [3] is also proposed by the different researcher like:

1. Trapezoidal Modulation
2. Staircase Modulation
3. Stepped Modulation
4. Harmonic Injection Modulation
5. Delta Modulation
6. Space vector Modulation (SVPWM)

7. Random PWM

7.4 Form and Function

Theoretically zero rise and fall time of an ideal PWM waveform represents a preferred way of driving modern semiconductor power devices. With the exception of some resonant converters, the vast majority of power electronic circuits are controlled by PWM signals of various forms. The rapid rising and falling edges ensure that the semiconductor power devices are turned on or turned off as fast as practically possible to minimise the switching transition time and the associated switching Losses. Although other considerations, such as parasitic ringing and electromagnetic interference (EMI) emission, may impose an upper limit on the turn-on and turn-off speed in practical situations, the resulting finite rise and fall time can be ignored in the analysis of PWM signals and processes in most cases. Hence only ideal PWM signals with zero rise and fall time will be considered in this chapter.

Pulse-width modulation can take different forms. The pulse frequency is one of the most important parameters when defining a PWM method and can be either constant or variable. A constant-frequency (CF) PWM signal can be produced simply by comparing a reference signal, r(t), with a carrier signal, c(t), as depicted in Fig. 6.1a. The binary PWM output can be mathematically written as
Where ‘sign’ is the sign function.

Three types of carrier signals are commonly used in constant-frequency PWM:

1. Saw tooth Carrier, reported in Fig. 5.1b: The leading (rising) edge of PWM output occurs at fixed instants in time while the position of the trailing (falling) edge is carrier signal modulated as the reference signal level varies. Hence the method is also called constant-frequency trailing-edge modulation.
2. Inverted Saw tooth Carrier, reported in Fig. 6.1c: The trailing (falling) edge of PWM output occurs at fixed instants in time while the position of the leading (rising) edge is modulated as the reference signal level varies. The method is usually referred to as constant-frequency leading-edge modulation.
3. Triangle Carrier, reported in Fig. 6.1d: Both the leading edge and the trailing edge of the PWM output is modulated. The rising and falling edge of the triangle are usually

symmetric so that the pulse is centered within a carrier cycle when the reference is a constant. The method is called constant-frequency double-edge modulation.

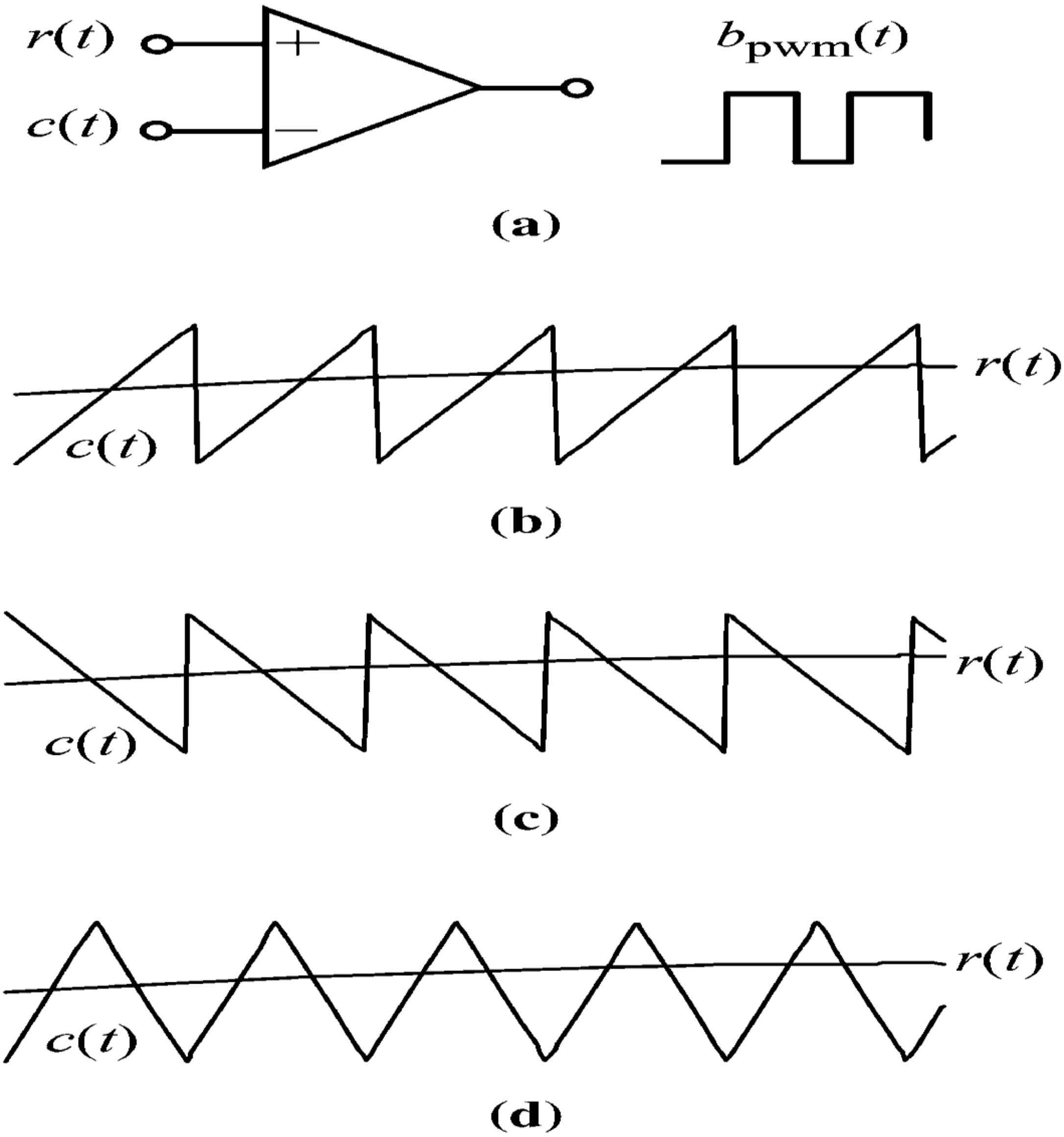


Figure 7.1 Constant-frequency PWM implemented by a comparator with different

Trailing-edge modulation is most common in DC–DC converters. As will be discussed in the next section, double-edge modulation eliminates certain harmonics when the reference is a sine wave, and is a preferred method for AC–DC and DC–AC converters where the PWM reference contains a sinusoidal component. A combination of synchronised leading-edge and trailing-edge modulation has also been used to control a boost single-phase power factor correction (PFC) converter and a buck DC–DC converter to reduce ripple in the intermediate DC bus capacitor.

The illustrations in Fig. 6.1 assumed analog implementation. When digital implementation is used, the reference is usually sampled at a regular frequency and the carrier can be replaced by a counter/timer. To avoid multiple switching transition within a carrier cycle, the reference should be sampled at the point where the carrier reaches its peak or valley. Pulse-width modulation using such sampled references is called regular-sampling PWM. To distinguish from such sampled PWM,

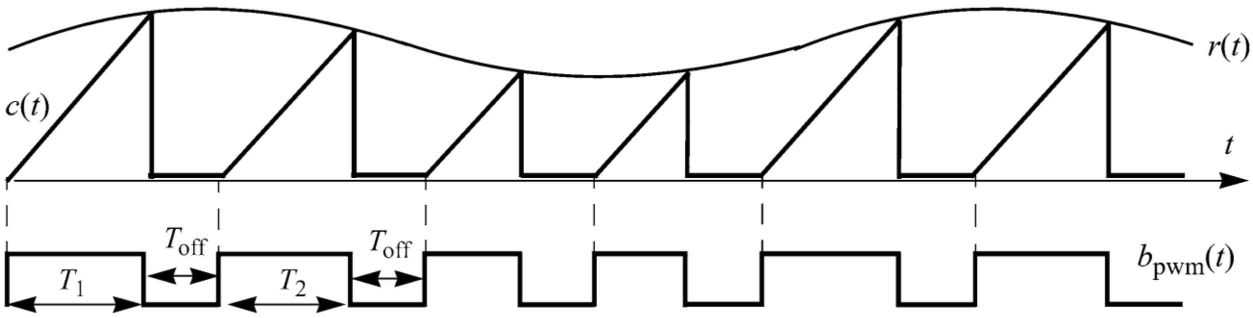


Fig. 7.2 Variable-frequency PWM with constant OFF-time

The analog version discussed before is also called natural-sampling PWM in the literature. With a saw tooth or inverted saw tooth carrier, samples are usually taken at the beginning of a carrier cycle. With a triangle carrier, on the other hand, the reference can be sampled either once at the peak of the triangle or twice at both the peak and the valley of the triangle; the former is referred to as symmetrical sampling, while the latter is called asymmetrical sampling due to the fact that the rising and falling edge of the triangle are compared with different samples of the reference.

Regular-sampling PWM is usually used in high power inverters and rectifiers and will not be further discussed in this chapter. On the other hand, the effects of sampling can be incorporated into the PWM spectral models by modifying the double Fourier integral to be presented in the following sections.

Variable-frequency (VF) PWM, although not as popular as CF PWM, has also been used in practice. Three common variations of VF PWM are: (a) constant OFF time, variable ON-time; (b) constant ON-time, variable OFF-time; and (c) hysteretic control. Figure 6.2 depicts constant OFF-time, variable ON-time PWM using a saw tooth-like carrier signal. The switch is turned on after a fixed OFF-time, T_{off}, at which point the saw tooth signal also starts to rise at a constant rate. The switch is turned off again when the saw tooth signal intersects with the reference, at which point the carrier signal is reset to zero. The switch is then kept OFF for a fixed time(T_{off}) again before the next switching cycle starts. As can be seen, the ON-time changes with the reference and the switching frequency increases with the decrease in the reference level, resulting in a variable frequency operation when the reference varies. Constant ON-time, variable OFF-time can be implemented in a similar manner.

A popular application of the VF PWM is in boundary-mode control of boost power factor correction (PFC) converters, where the switch operates with a constant ON-time and is turned on as soon as the diode current reduces to zero, resulting in an average input current that is proportional to the input voltage. Hysteretic control is usually applied in conjunction with a current or voltage regulator, and doesn't involve an explicit PWM process. It will not be further discussed in this chapter.

One common concern about VF PWM is the difficulty associated with the design of input and output filters. The filter corner frequency would have to be selected based on the lowest possible switching frequency in order to provide the required attenuation for ripple and EMI under all operation conditions. This usually leads to a conservative design with significant volume and cost penalties. On the other hand, both constant ON-time and constant OFF-time VF PWM exhibit a leading phase angle in their small-signal dynamic transfer functions. Since the modulator is part of the feedback control loop, such a leading phase boosts the phase angle of the loop at high frequencies, thereby improving the stability.

The reference signal depends on the application and is usually independent of the modulation method. For DC–DC converters, the PWM reference is a constant when the converter operates in a steady state but varies whenever the converter goes through a transient. The spectral characteristics of such a PWM waveform with constant frequency and constant duty ratio can be readily determined by Fourier analysis. To characterise the dynamic behaviour of a modulator in DC–DC converters, the reference can be assumed to consist of a DC value corresponding to thesteady-state duty ratio and a sinusoidal component representing a small-signal perturbation. A small-signal model can be obtained for the modulator by computing the component in the PWM output at the frequency of the sinusoidal perturbation.

For AC–DC and DC–AC converters, the reference signal typically contains at least one sinusoidal component at the fundamental frequency of the AC input or output of the converter. For poly-phase (e.g. three-phase) converters, each phase will have a separate reference and their sinusoidal components are shifted from each other by the same phase angle that separates the input or output phase voltages. Often, the PWM references also contain harmonics of the fundamental component. This is the case, for example, in three-phase converters where triple harmonics can be purposely injected into the PWM references to increase the utilisation of the DC voltage, that is, to maximise the AC voltages that can be produced from a given DCvoltage source before the modulator saturates.

CHAPTER 8

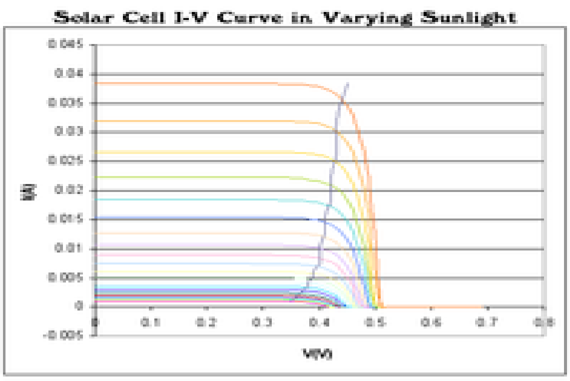
MAXIMUM POWER POINT TRACKING

8.1 Introduction

Maximum power point tracking (MPPT) is a technique that grid connected inverters, solar battery chargers and similar devices use to get the maximum possible power from one or more photovoltaic devices, typically solar panels,[1] though optical power transmission systems can benefit from similar technology.[2] Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency which can be analysed based on the I-V curve. It is the purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions.[citation needed] MPPT devices are typically integrated into an electric power converter system that provides voltage or current conversion, filtering, and regulation for driving various loads, including power grids, batteries, or motors.

- Solar inverters convert the DC power to AC power and may incorporate MPPT: such inverters sample the output power (I-V curve) from the solar cell and apply the proper resistance (load) so as to obtain maximum power.
- MPP (Maximum power point) is the product of the MPP voltage (V mpp) and MPP current (I mpp): some solar panels have a higher maximum power than others.

8.2 VI curve



- Photovoltaic cells have a complex relationship between their operating environment and the maximum power they can produce. The fill factor, abbreviated *FF*, is a parameter which characterizes the non-linear electrical behavior of the solar cell. Fill factor is defined as the ratio of the maximum power from the solar cell to the product of Open Circuit Voltage V_{oc} and Short-Circuit Current I_{sc}. In tabulated data it is often used to estimate the maximum power that a cell can provide with an optimal load under given conditions, $P=FF*V_{oc}*I_{sc}$. For most purposes, FF, V_{oc}, and I_{sc} are enough information to give a useful approximate model of the electrical behaviour of a photovoltaic cell under typical conditions.

- For any given set of operational conditions, cells have a single operating point where the values of the current (*I*) and Voltage (*V*) of the cell result in a maximum power output. These values correspond to a particular load resistance, which is equal to *V* / I as specified by Ohm's. The power P is given by $P=V*I$. A photovoltaic cell, for the majority of its useful curve, acts as a constant current source.[3]However, at a photovoltaic cell's MPP region, its curve has an approximately inverse exponential relationship between current and voltage. From basic circuit theory, the power delivered from or to a device is optimized where the derivative (graphically, the slope) *dI/dV*of the I-V curve is equal and opposite the *I/V* ratio (where d*P/dV*=0).[4] This is known as the **maximum power point** (MPP) and corresponds to the "knee" of the curve.
- A load with resistance $R=V/I$ equal to the reciprocal of this value draws the maximum power from the device. This is sometimes called the 'characteristic resistance' of the cell. This is a dynamic quantity which changes depending on the level of illumination, as well as other factors such as temperature and the age of the cell. If the resistance is lower or higher than this value, the power drawn will be less than the maximum available, and thus the cell will not be used as efficiently as it could be. Maximum power point trackers utilize different types of control circuit or logic to search for this point and thus to allow the converter circuit to extract the maximum power available from a cell.

Classification

- Controllers usually follow one of three types of strategies to optimize the power output of an array. Maximum power point trackers may implement different algorithms and switch between them based on the operating conditions of the array.[5]

8.3 Perturb and observe

In this method the controller adjusts the voltage by a small amount from the array and measures power; if the power increases, further adjustments in that direction are tried until power no longer increases. This is called the perturb and observe method and is most common, although this method can result in oscillations of power output.[6][7] It is referred to as a *hill climbing* method, because it depends on the rise of the curve of power against voltage below the maximum power point, and the fall above that point.[8] Perturb and observe is the most commonly used MPPT method due to its ease of implementation.[6] Perturb and observe method may result in top-level efficiency, provided that a proper predictive and adaptive hill climbing strategy is adopted.[9][10]

8.4 Incremental conductance

In the incremental conductance method, the controller measures incremental changes in array current and voltage to predict the effect of a voltage change. This method requires more computation in the controller, but can track changing conditions more rapidly than the perturb and observe method (P&O). Like the P&O algorithm, it can produce oscillations in power output.[11] This method utilizes the incremental conductance (dI/dV) of the photovoltaic array to compute the sign of the change in power with respect to voltage (dP/dV).[12]

The incremental conductance method computes the maximum power point by comparison of the incremental conductance (I_Δ / V_Δ) to the array conductance (I / V). When these two are the same ($I / V = I_\Delta / V_\Delta$), the output voltage is the MPP voltage. The controller maintains this voltage until the irradiation changes and the process is repeated.[6]

8.5 Current Sweep Method

The current sweep method uses a sweep waveform for the PV array current such that the I-V characteristic of the PV array is obtained and updated at fixed time intervals. The maximum power point voltage can then be computed from the characteristic curve at the same intervals.[13][14]

8.6 Constant voltage

The term "constant voltage" in MPP tracking is used to describe different techniques by different authors, one in which the output voltage is regulated to a constant value under all conditions and one in which the output voltage is regulated based on a constant ratio to the measured open circuit voltage (V_{OC}). The latter technique is referred to in contrast as the "open voltage" method by some authors.[15] If the output voltage is held constant, there is no attempt to track the maximum power point, so it is not a maximum power point tracking technique in a strict sense, though it does have some advantages in cases when the MPP tracking tends to fail, and thus it is sometimes used to supplement an MPPT method in those cases.

In the "constant voltage" MPPT method (also known as the "open voltage method"), the power delivered to the load is momentarily interrupted and the open-circuit voltage with zero current is measured. The controller then resumes operation with the voltage controlled at a fixed ratio, such as 0.76, of the open-circuit voltage V_{OC}.[16] This is usually a value which has been determined to be the maximum power point, either empirically or based on modelling, for expected operating conditions.[11][12] The operating point of the PV array is thus kept near the MPP by regulating the array voltage and matching it to the fixed reference voltage $V_{ref}=kV_{OC}$. The value of V_{ref} may be also chosen to give optimal performance relative to other factors as well as the MPP, but the central idea in this technique is that V_{ref} is determined as a ratio to V_{OC}.

One of the inherent approximations to the "constant voltage" ratio method is that the ratio of the MPP voltage to V_{OC} is only approximately constant, so it leaves room for further possible optimization.

8.7 Comparison of methods

Both perturb and observe, and incremental conductance, are examples of "hill climbing" methods that can find the local maximum of the power curve for the operating condition of the array, and so provide a true maximum power point.

The perturb and observe method can produce oscillations of power output around the maximum power point even under steady state illumination.

The incremental conductance method has the advantage over the perturb and observe method that it can determine the maximum power point without oscillating around this value.[6] It can perform maximum power point tracking under rapidly varying irradiation conditions with higher accuracy than the perturb and observe method.[6] However, the incremental conductance method can produce oscillations and can perform erratically under rapidly changing atmospheric conditions. The computational time is increased due to slowing down of the sampling frequency resulting from the higher complexity of the algorithm compared to the P&O method.

In the constant voltage ratio (or "open voltage") method, the current from the photovoltaic array must be set to zero momentarily to measure the open circuit voltage and then afterwards set to a predetermined percentage of the measured voltage, usually around 76%.[12] Energy may be wasted during the time the current is set to zero.[12] The approximation of 76% as the MPP/V_{OC} ratio is not necessarily accurate though.[12] Although simple and low-cost to implement, the interruptions reduce array efficiency and do not ensure finding the actual maximum power point. However, efficiencies of some systems may reach above 95%

8.8 MPPT placement

Traditional solar inverters perform MPPT for an entire array as a whole. In such systems the same current, dictated by the inverter, flows through all panels in the string. Because different panels have different IV curves and different MPPs (due to manufacturing tolerance, partial shading,[17] etc.) this architecture means some panels will be performing below their MPP, resulting in the loss of energy.[1]

Some companies (see power optimizer) are now placing peak power point converters into individual panels, allowing each to operate at peak efficiency despite uneven shading, soiling or electrical mismatch.

Data suggests having one inverter with one MPPT for a project that has east and west-facing modules presents no disadvantages when compared to having two inverters or one inverter with more than one MPPT."Efficient East-West Oriented PV Systems with One MPP Tracker," Dietmar Staudacher, 2011.

8.9 Operation with batteries

At night, an off-grid PV power system may use batteries to supply loads. Although the fully charged battery pack voltage may be close to the PV panel's maximum power point voltage, this is unlikely to be true at sunrise when the battery has been partially discharged. Charging may begin at a voltage considerably below the PV panel maximum power point voltage, and an MPPT can resolve this mismatch.

When the batteries in an off-grid system are fully charged and PV production exceeds local loads, an MPPT can no longer operate the panel at its maximum power point as the excess power has no load to absorb it. The MPPT must then shift the PV panel operating point away from the peak power point until production exactly matches demand. (An alternative approach commonly used in spacecraft is to divert surplus PV power into a resistive load, allowing the panel to operate continuously at its peak power point.)

In a grid connected photovoltaic system, all delivered power from solar modules will be sent to the grid. Therefore, the MPPT in a grid connected PV system will always attempt to operate the PV panel at its maximum power point.

CHAPTER 9
SIMULATION RESULTS

The Simulink model of micro-grid fed by REGS is developed in Matlab. The solar panels and wind turbine are modeled using their functions. Fig. 9.2 shows the performance of the system when the wind generator is taken in an out of the system. Fig. 9.3 shows the performance of the system when solar PV system is taken in and taken out of the system. Both the above scenarios also discuss the MPPT operation through RSC and solar converter. Fig. 9.4 at unbalanced nonlinear load. Fig. 9.5 shows a scenario when stored energy and generated power are low and external charging requirement through RSC is activated.

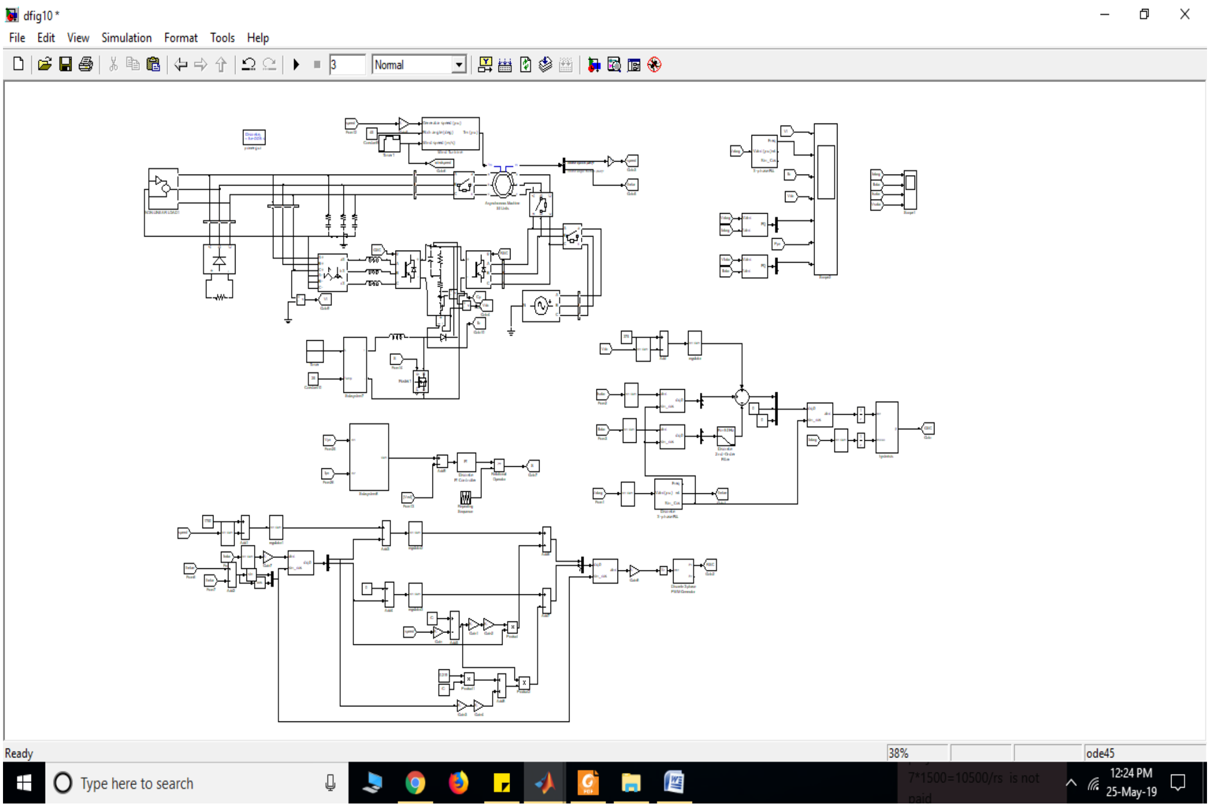


Fig. 9.1 Performance of REGS fed micro-grid with wing energy source

Performance of System at Constant Load and Cut-in and Cut-out of Wind Power

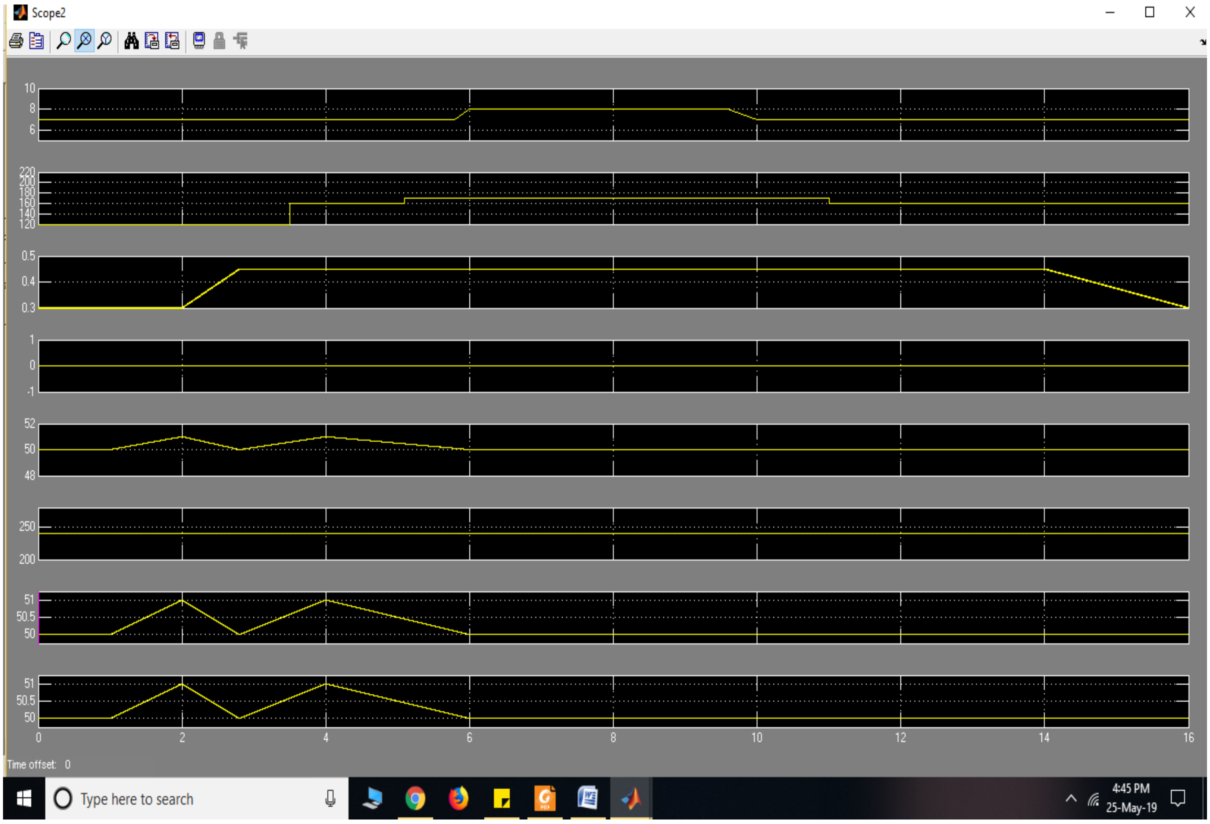


Fig. 9.2 Performance of REGS fed micro-grid with wind energy source

As shown in Fig. 9.2, the system is started with 10 kW and 6 kVAR load without wind or solar energy sources. At t=2.25 s, the wind generator at wind speed of 7 m/s, is taken in service. As a result, a momentary fluctuation in the system voltage is observed. At t=6.0 s, the wind speed of turbine is increased from 7 m/s to 8 m/s followed by reduction of the wind speed to its original value at t=10.0 s. The rotor control action, maintains the desired rotational speed as per the W-MPPT algorithm. At t=14 s, the wind generator is taken out of service. During cut-in and cutout of wind generator, momentary, the voltage surge is observed. The duration and magnitude of the voltage surge, are within an IEEE 1547 standard.

Performance of System at Constant Load and Cut-in and Cut-out of Solar Power

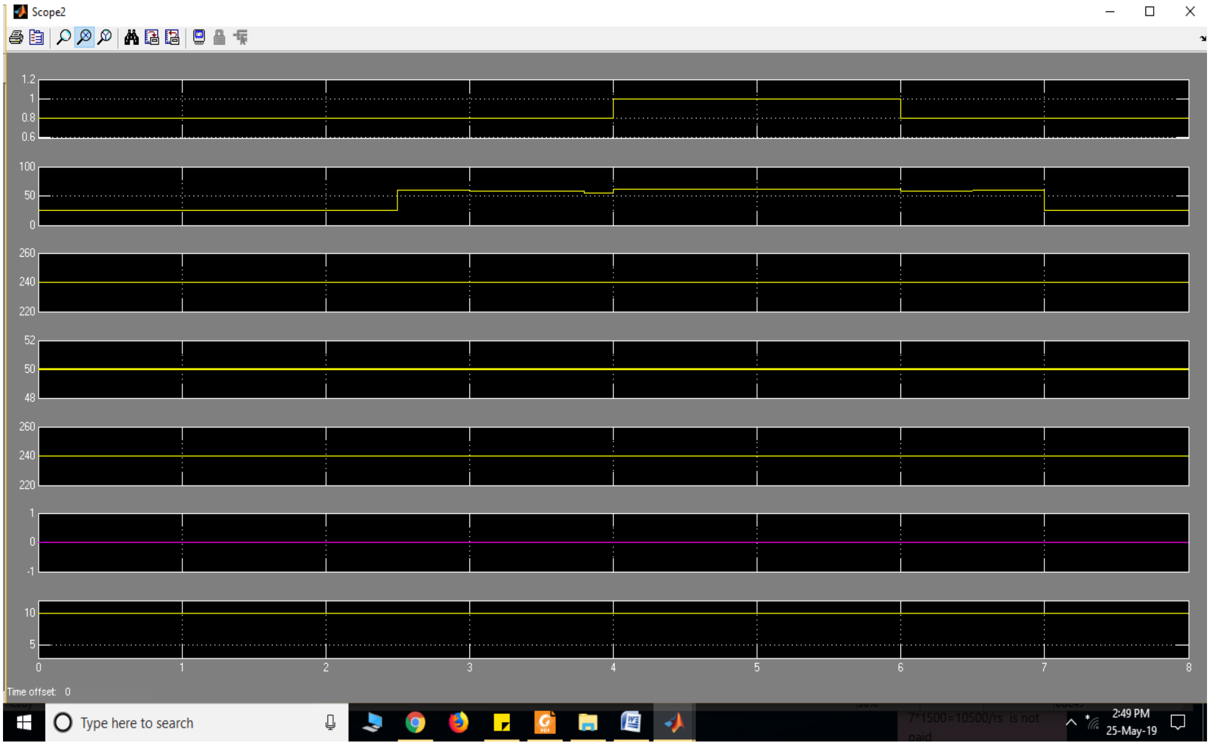


Fig. 9.3 Performance of the system without generating source and solar system is taken in the service

The system is started with a 10 kW and 6 kVAR load without wind or solar energy. As shown in Fig. 8, at t=2.25 s, solar system is taken into the service at radiation of 800 W/m2 . At t=4 s, the solar radiation is raised to 900 W/m2 and again it is reduced to 800 W/m2 at t=6 s. The solar converter adjusts the solar PV voltage and operates at S-MPPT. At t=7 s, the solar system is taken out of service. No significant variation of system voltage is observed at any transition point.

Performance of System at Loss of Load

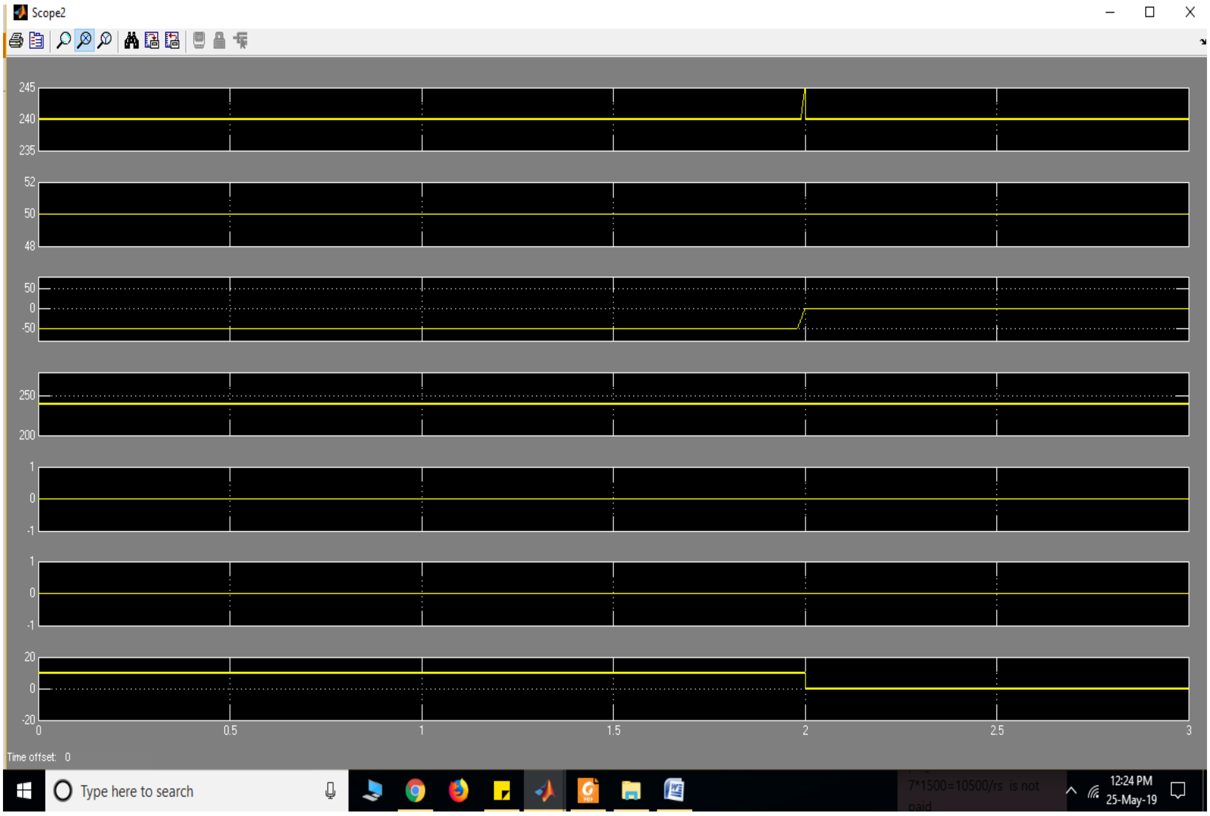


Fig.9.4 Performance of the system under loss of load at battery power

The performance of the micro-grid for loss of load, is shown in Fig. 9.4. A 10 kW and 6 kVAR load, is connected at the terminals prior to start of simulation. Neither wind nor solar power, is available and the load is fed by the battery. At t=2 s, the system load is disconnected. It is found that the system voltage and frequency remain constant of the network.

System Running without Generating Source and Battery Charged from the Grid

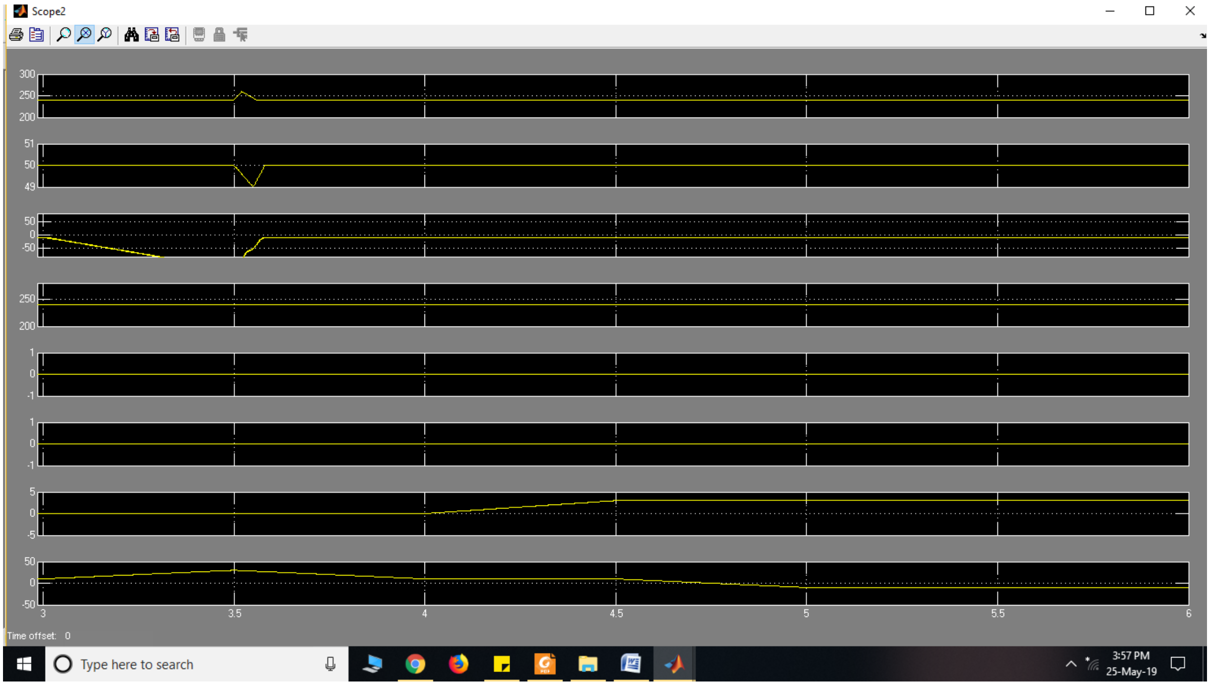


Fig. 9.5 Performance of system through external charging

Fig. 9.5 shows the scenario when there are no generating sources feeding to the network combined with low battery. External charging is required to sustain the load requirement. Charging circuit is enabled as per the logic diagram of Fig. 9.2. At t=4 s, wind generation is taken out of service and because of lower battery voltage, the charging circuit is initiated. As a result external power is injected through the RSC to cater load requirement in addition to charging the batteries.

CONCLUSION

The proposed micro-grid system fed from REGS has been found suitable for meeting load requirement of a remote isolated location comprising few households. REGS comprises of wind and solar energy blocks, which are designed to extract the maximum power from the renewable energy sources and at the same time, it provides quality power to the consumers. The system has been designed for complete automated operation. This work also presents the sizing of the major components. The performance of the system has been presented for change in input conditions for different type of load profiles. Under all the conditions, the power quality at the load terminals, remains within acceptable limit. The effectiveness of the system is also presented with test results with prototype in the laboratory. The system has also envisaged the external battery charging by utilizing the rotor side converter and its sensors for achieving rectifier operation at unity power factor.

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