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Control of Power Flow in Large-Scale PV Microgrid with Load Control and Energy Storage System

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Abstract: ***Today's traditional electricity grid was built to meet less overall demand, and used to distribute power to a very large number of users or consumers from a few central generators. It can support electricity output, transmission, distribution, and control operations, In short one way communication. Micro-grid, however, is a modernized grid that allows bidirectional power and data flow using two-way communication and control technologies, leading to a whole new functionalities and applications. Furthermore, it has the potential to integrate distribution generators to form a small-scale grid called a microgrid, including renewable energy. Microgrids operate in "Grid connected mode" with the main grid, or in "Island mode" independent of utility grid or main grid. The first chapter gives introduction to Micro-grid and explains it, as well takes about inspiration its necessity and other topics. The second chapter is dedicated to the description of Micro-grid simulated in this dissertation. Distribution generators are discussed with their impact while connecting it to the Micro-grid in the third. Requirements for while connecting the distributed generators to the Micro-grid are also discussed in the third chapter. This project simulate the Micro-grid in SIMULINK, MATLAB Ra2015 and explains the key components of it in forth chapter. The last section consists of Appendix A which includes calculation of the project, conclusion, recommendation and references.***

Keywords: Power flow, Micro Grid, Matlab Simulink, Micro-grid, PV Power, Grid Power, Generator and battery

1. Introduction to Power flow in Micro-Grid

Urbanization, living standards and advancement in technology has raised the demand of electricity requirement. This made electricity consumption to levels that may no longer be manageable if its modification is ignored. This is an alarming situation for providing sustainable energy and preservation of environment worldwide. Almost 70–80% of total energy is consumed in urban areas which is responsible for more than 75% greenhouse gas emission [1, 2]. Traditional and centrally-controlled system for the distribution of electrical energy is being used for a long time. Which is named as power grid. Since the electric power grids have similar structure, dynamics and principles even with the advancement of technology. These common power grids are focused on only some basic functions like generation, distribution and control of electricity [3].Present time electricity grid is unreliable, has high transmission losses, low power quality, exposed to brownouts and blackouts, supplying un proper electricity an encouraging to integration of distributed energy sources. There is a lack of managing and real time control in the traditional non-Micro-grid systems, which creates a challenging opportunity for Micro-grids to perform as a real-time solution. Considering these issues requires a complete modification of power delivery structure. Electrical benefits and environmental aspects are the two main encouraging causes for the introduction of 'Micro-grid' concept. Efficient utilization of electricity and dependency on renewable resources will help to decrease the carbon foot print of human. Micro-grid technology has a better solution for generation of electric power and an efficient method for transmission and distribution of this power. Due to its versatility it can be easily installed, low maintenance cost and requires less space compared to traditional grids. The goal of Micro-grid design is to provide controllability of resources, enhance performance and security of power system and especially the economic aspects of operations, maintenance and planning [4]. These Micro-grids have a huge potential and could be a better solution of reliability of power distribution and transmission in developing countries which lack infrastructure. In US more than 22% of all the carbon dioxide is being emitted by transportation while generation of electricity has 45% of the carbon dioxide emitting share in it. This is due to the increased demand of electricity. Micro-grids are being considered as a key role to address this problem by distributing electric power in an efficient method and ultimately decrease greenhouse gasses and pollutants such as NOx and SOx [5]. It will also help the consumers to predict its demand and the best economical uses of energy.

2. Micro-Grid description

Photovoltaic system

Photovoltaic (PV) are designed to generate electricity from solar energy in a beneficial way. These devices generate electrical energy directly from sun radiations via an natural electronic process that take place in semiconductor materials. PV devices can be found in today many gadgets such as a calculator, road signs, transportation system even for charging vehicles, home and commercial building. The efficiency of Solar cell is still challenging due to the reflection of light and losses in the conversion process. [10].

2.1 Mircro-grid

Micro-grid is the new grid which will replace the aging electrical grid with its old infrastructure, beside that it gives monitoring, analysis, control and communication capabilities to the national power generation and distribution system, and it supports real - time measurement techniques. Furthermore, Micro-grid is more resistant to failure, more secure, more efficient and delivers power across the system at a lower cost to producers and consumers. However, it is a modernized grid that enables bidirectional flow of energy and data [7].

2.1.1 Micro-grid abilities

1) Allow using of renewable plug-and-play.
2) Optimize quality, efficiency, and reliable supply by:
   a) Better balancing of supply and demand.
   b) The use of smart meters.
   c) Demand side management
3) Incorporates self-correction, Self-monitoring, and restoration. a. Better monitoring achieved by using sensor networks and communications.
4) More customer choices [7].

2.2 Integration of distribution generators (DG) with Micro-grid

Basically Distributed Energy (DG) is the power produced near the consumers. It sources consists of small-scale, eco-friendly technologies such as wind energy, solar energy, and biomass plants installed to serve a single end user's site. But due power reliability and power quality distributed energy resources consist of traditionally used fossil fuel and gas turbine [8].

A) Distributed Energies can be connected to utility when the conditions of having:
1) Similar frequency rotation with the grid.
2) Similar output voltage.
3) Similar phase angle with utility grid.

B)Types of microgrid:
Microgrids can be categorized into 3 classes, the classification based on the method in which the AC and DC buses are connected.

AC microgrids

AC microgrids can be easily combined to the traditional AC gridssince most of loads and grid are AC. They have a common AC bus which is generally connected by mixed loads, distributed generation resources, energy storage devices such batteries. DC sources and energy storage devices are connected to the AC bus via DC/AC inverter, so a lot of DCC/AC conversions take place that causes a tremendous reduction in efficiency due to the use of power electronics components.

DC microgrids:

The operation principle of DC microgrid is same with AC microgrid. Actually DC microgrid has advantage compared with AC microgrid, DC microgrid is a better solution to decrease the power conversion losses. It has got higher system efficiency, less cost and system size.

Hybrid AC/DC microgrids:

Hybrid AC/DC microgridis the combination of AC and DC microgrids in same distribution grid, providing possibility of the direct integration of both AC and DC.

2.1.4 Operation modes of microgrid

2.1.4.1 Grid mode

Connected to utility grid, in grid-connected mode, the microgrid operator can take economic decisions, such as to sell or buy energy depending on generation capability, its cost, and the current prices on the energy market.

A) Island mode:

Though out the world, a remarkable figure of villages have no access to electricity due to their remoteness. Luckily, in many of these places, there are renewable energy resources, specifically solar, wind and biomass energies. These energy resources can be utilized to create isolated microgrids to address local energy needs.

Island microgrid means that the microgrid continues to work on its own when disconnected from the utility grid, it is not difficult to island it, by opening the circuit breaker at PCC we can disconnect the. in this mode high proportion consist of renewable energy generation, where the major technical challenges are found.

B) Fundamental challenges of islanded mode:

Power converter control of electrical storage systems.

Control design method that is Decentralized.

Improvement of power quality in grids deteriorated by the disturbances that are generated of renewable.

2.3 Energy Storage System

For better operation of standalone microgrid requires some kind of energy storage system (ESS), battery banks have been used mainly due to economic reasons. In general, a backup energy source must be used during the lack or disturbances occurred in the primary renewable distributed energy sources or when the generation system is going under maintenance process.

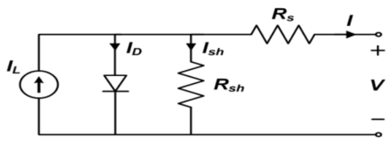
Energy storage apparatus can be categorized into three categories. As electrochemical systems (batteries and flow batteries), kinetic energy storage systems (flywheel) and potential energy storage systems (pumped hydro and compresses air storage) [8].

Batteries:

The most used energy storage devices, the life cycle and the capacity of the battery depends on its type.

3. PV Modelling

The ideal solar cell circuit consists of a DC current source that models the solar irradiance, a diode in parallel but opposite direction models the p-n junction, as observed in Figure 3.1[11]. When the photovoltaic cells exposed to sun irradiation, the direct current is produced, the current changes with the solar irradiance. The model is improved with shunt resistor and series resistor to represent the losses [12]-[13].



We use Kirchhoff's current law to to find photovoltaic output current. The final equation [14]

$$I_{pv} = I_{ph} - I_d - I_p \qquad (1)$$

Where Ipv is the cell current, Iph is the photovoltaic output current, Id diode current, Ip is the parallel resistor current

$$I_d = I_0[e^{\frac{V+IR_s}{V_T}} - 1] \qquad (2)$$

I0 saturation current, Rs serial resistor, VT thermal voltage K is electron charge constant, Tc is actual cell temperature.

$$V_T = \frac{KT_c}{q} \qquad (3)$$

$$I_{ph} = \frac{G}{G_{ref}}(I_{ph,ref} + \mu_{sc}\Delta T) \qquad (4)$$

Where G the irradiance, G_{ref} is the irradiance at standard test condition (STC), I_{ph}, r_{ef} is the photo current at standard test condition, T is the cell temperature at (STC).where Iph depends on the temperature degree and irradiance flux.

$$I_p = \frac{V+R_s I}{R_p} \qquad (5)$$

is the resistor current in the equivalent circuit shown above.The PV system's final equation can be seen below.

$$I = \frac{G}{G_{ref}}(I_{ph,ref} + \mu_{sc}\Delta T) - I_0[e^{\frac{V+IR_s}{V_T}} - 1] - \frac{V+R_s I}{R_p} \qquad (6)$$

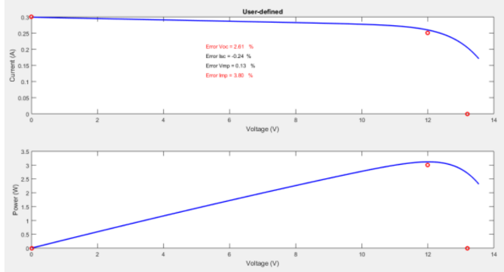
This equivalent circuit shown is for a single cell, thus requires modification in Np (number of parallel cells) which increases the amount of current and Ns (number of series cells) which correspond for voltage, that them into accounts then array current is given below:

$$I_{pv} = N_p I_{pv} - I_0[e^{(q\frac{\frac{V_d}{RI} + \frac{R_s I}{R_p}}{N_s KF T_{pv}})} - 1] - \frac{\frac{N_p V_d}{N_s}}{R_p} \qquad (7)$$

3.2 PV Simulation

In this study, the sizing for the PV module was done in according with DC bus requirements that are based the battery nominal, and charging voltage, as well as considering the output voltage of other renewable distributed energy resources .We can adjust the voltage and current by increasing and decreasing the the number of the parallel modules and series strings [16].The most relevant values are calculated and given Table 3.1.

Open Circuit Voltage	Voc	13.2
Short Circuit Current	Isc	0.3
Voltage, Maximum Power	Vm	12
Current, Maximum Power	Im	0.25
Maximum Power	Pm	3



3.3 Maximum Power Point Tracking (MPPT)

An MPPT controller, or maximum power point tracker is a DC/DC converter that optimizes the output voltage of solar array (PV panels), and the battery bank or utility grid (ESS). MPPT operates the photovoltaic arrays with a method that maximizes their power output [17].

A) Incremental Conductance MPPT Algorithm

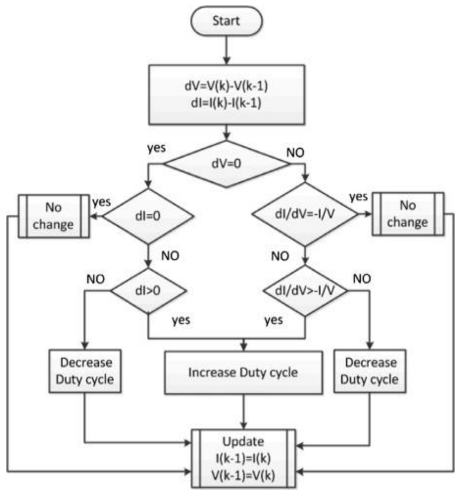
Incremental Conductance method uses the data of source voltage and current to find the optimized desired operating point. From the P-V curve of a PV module shown in Fig 3.2 it is understandable that slope is zero at maximum point[[20]-[22]], so the formulas are as follows.

$$\frac{dP}{dV}mpp = \frac{d\,(VI)}{dV} \qquad (8)$$

$$0 = 1 + V\left(\frac{dI}{dV}\right)mpp \qquad (9)$$

$$\left(\frac{dI}{dV}\right)mpp = -\frac{1}{V} \qquad (10)$$

Equation 10 is the condition to achieve the maximum power point, when the variance of the output conductance is equal to the negative of the output conductance, the module will work at the maximum power point [21]. The flow chart of the incremental conductance is shown in Fig 3.3.



3.4 DC-DC Boost Converter

The following figure demonstrates a DC-DC boost (step-up) converter, it is designed for the source voltage, Vs of 12V, the output voltage, Vo of 17V, output power, Po of 100 W with the efficiency η and system frequency, fs are 100% and 25 kHz, respectively. The inductance of inductor, L and capacitance of capacitor, C should be calculated to fulfill the required condition following the equations from 11 to 14.

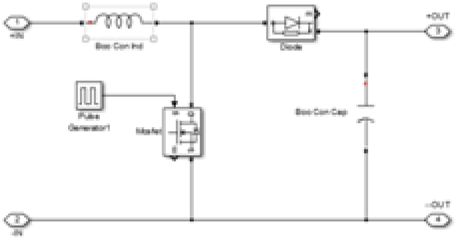


Figure 3.4: DC-DC Boost Converter

$$D = 1 - \rho\,(\frac{V_{in}}{V_o})\rho \quad (11)$$

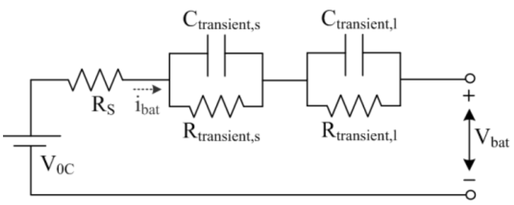
$$L >= D\,\frac{(1-D^2)R}{2f} \quad (12)$$

$$C >= \frac{D}{R\,(\frac{\Delta V_{out}}{V_{out}})f} \quad (13)$$

$$R = \frac{{V_{out}}^2}{P_{out}} \quad (14)$$

A) Battery Model

Batteries have a very significant play in the electrical systems. Recently, electrochemical batteries have become an irreplaceable device in human life such laptops, mobile phones, even in residential building such as elevators and many more different portable tools [22]. Batteries are used to store chemical energy, and then they change the chemical energy stored from chemical to electrical in a controllable manner to satisfy the load it is attached to [24]. This project includes a lithium-ion (Li-ion) battery which has been utilized widely around the world. Li-ion battery has a important benefit in comparison to other types of batteries in many aspects such as higher energy density; it manages higher voltages, and as well it has lower self-discharge rate [23]. The equivalent circuit battery is shown in Figure 3.5.



$$I = \frac{V}{R} + S_{cv} \quad (15)$$

$$I/_{sC} = \frac{V}{sCR} + V \quad (16)$$

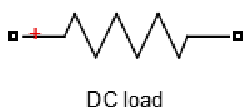
$$I_p = \frac{V+R_s I}{R_p} \quad (17)$$

3.3 Utility Grid

This Project is design for small DC load in residential apartment, where the supply is 220V from utility.

A) Load

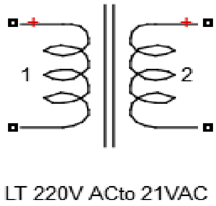
We have DC load that exist at the end of the AC supply. In this project the load is 2, 17R as per calculation done in the mentioned part.



B) Transformer

For properly feeding out load supply and without any damage to the load we have to we need two thing.

1) DC supply
2) Reducing the source voltage. Transformer will help as to reduce the power supply.

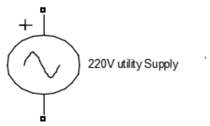


C) Rectifier

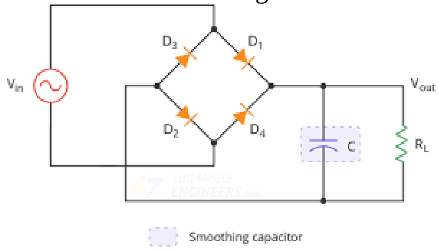
To rectify both half-cycles of a sine wave provided by the AC voltage source the bridge rectifier uses four diodes, connected together in a “bridge” configuration. The reduced output voltage of the transformer secondary winding is attached on one side (AC voltage side) of the diode bridge network and the load on the other side (DC voltage side).

This rectifier will change out AC to 14.7VDC coming out from the output of the transformer as shown in Figure 3.6.

D) Capacitor Smoothing

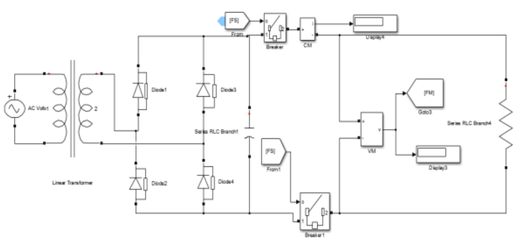


To smooth the output of the rectifier a smoother capacitor is utilized and placed across the output of the reciter in parallel manner with the load as shown in Figure 3.6.



3.4 Grid supply

This Micro-grid is designed for DC load. We have dc bus supply. We need to change AC bus supply to DC. The calculations of the transformer diode and related stuff are mentioned in the appendix A. here is the grid with the rectifier shown in the figure 1 below. The grid will the supplier to the load when PV cannot supply the load and the state of charge of the battery is less than 40%.



The PV supply for the Micro-grid and battery, in case the battery state of charge is less than 40%. The PV is working with incremental conductance MPPT control. When PV is at its maximum power production, and the PV produced power is more than load demand the extra power will be used to charge energy Stored system in this case the battery. The battery will be triggered when the PV supply is less then demand or even in of not availability. Both case are show in the figure 4.2 a and b below. Figure 4.3 is the simulation of it. The calculation are show in appendix A.

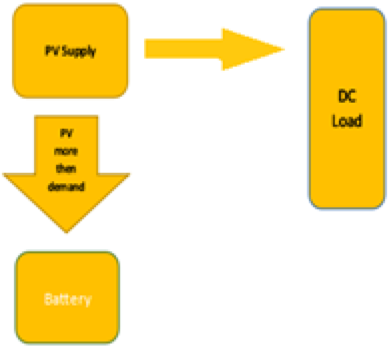


Figure 4.2 (A): shows PV supply to battery and load

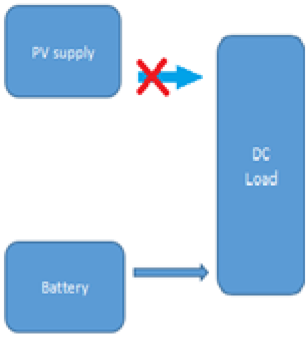
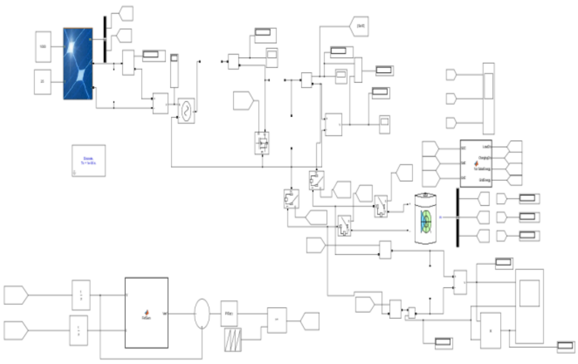
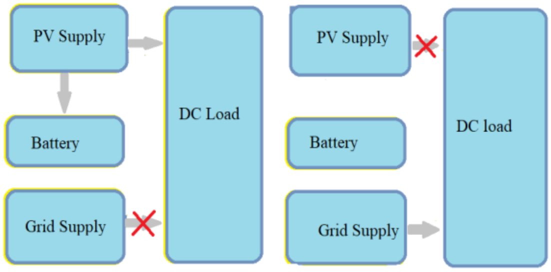


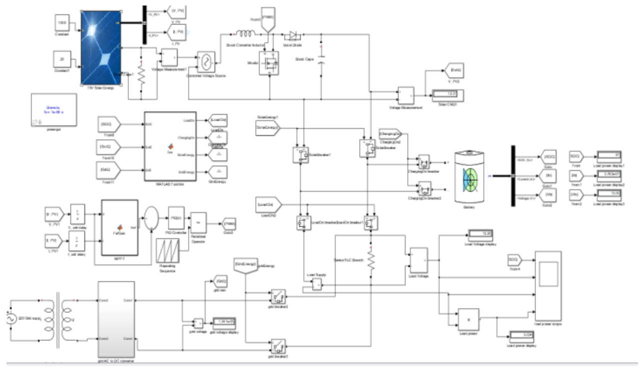
Figure 4.2 (B): Shows Battery supply to the load.



3.5 PV with Grid simulation

The Micro-grid is connected with utility supply. When the PV supply is unavailable and battery charge is below then the recommended amount by using the programable circuit breaker. As shown in figure 4.4.a and 4.4.b.

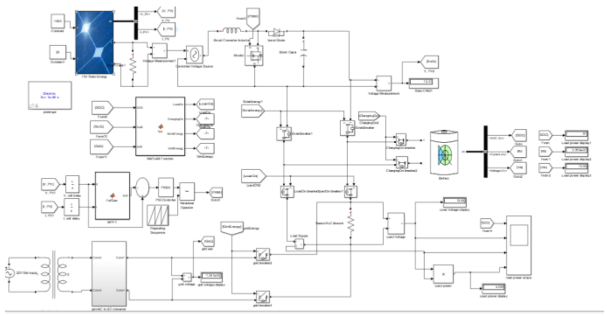




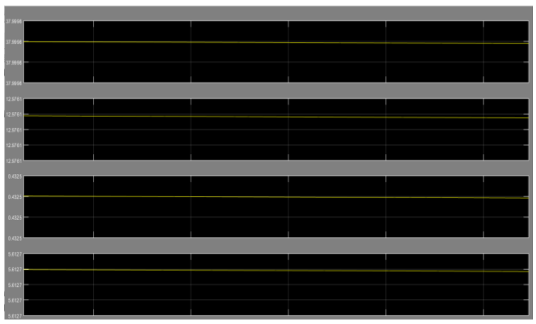
3.6 Different Scenarios by SIMULINK

1) When PV is the supplier to the battery and load grid and Generator are disconnected.
2) When grid is the supplier to the load, PV and Battery is disconnected.
3) When Generator is the supplier to the load, PV grid and battery are disconnected.

A) Case 1 PV is the supplier to Load and Battery

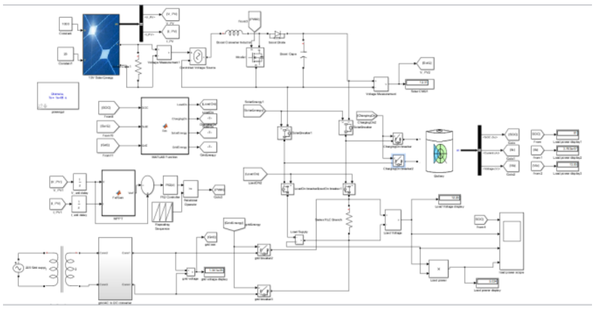


Case 1 PV is the supplier to Load and Battery

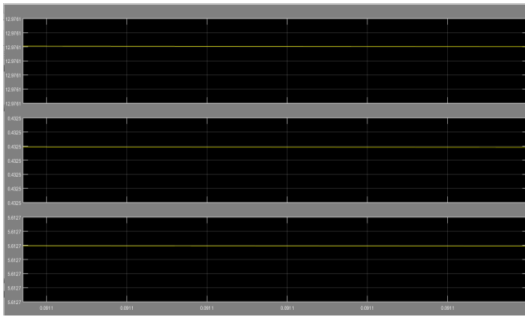


Case 1 PV supply Load and Battery Battery SOC Load Voltage Load Current Load Power Respectively

B) Case: 2 Only supply the load

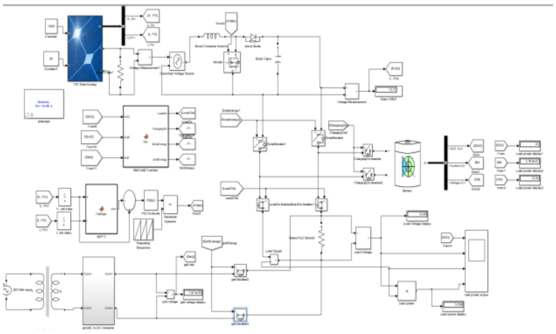


Case 2: PV Supply Load Only

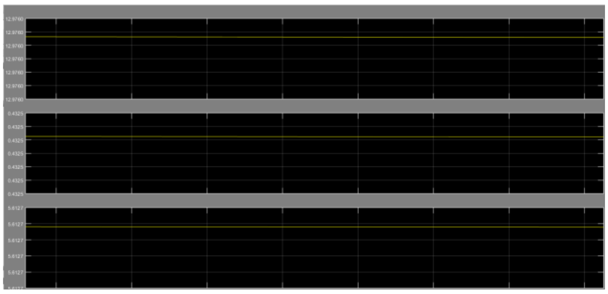


PV Supply Load Only Load Voltage Load Current Load Power respectively

C) Case 3 Grid Supply Load:

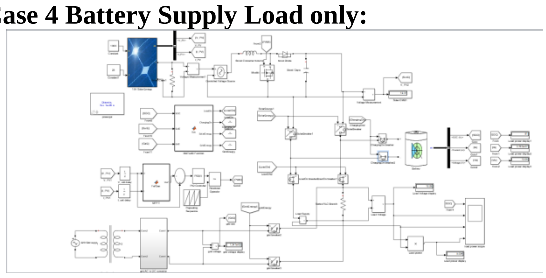


Case 3: Grid Supply Load

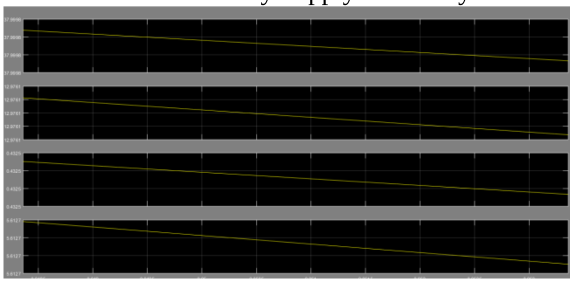


Grid Supply Load Load Voltage Load Current Load Power Respectively

D) Case 4 Battery Supply Load only:



Case 4: Battery Supply Load only



Case 4: Battery Supply Load Only Battery SOC Load Voltage Load Current Load Power

Matlab function MPPT code for PV:

```
function Vref = RefGen(V,I)

Vrefmax = 12;
Vrefmin = 0;
Vrefinit =0 ;
deltaVref = 1;

persistent Vold Iold Vrefold;

dataType = 'double';

if isempty (Vold)
    Vold = 0;
    Iold = 0;
    Vrefold = Vrefinit;
end

dV = V - Vold;
dI = I - Iold;

if (dV==0)
    if(dI==0)
        Vref = Vrefold;
    else
        if(dI>0)
            Vref = Vrefold + deltaVref;
        else
            Vref = Vrefold - deltaVref;
        end
    end
if (dV==0)
    if(dI==0)
        Vref = Vrefold;
    else
        if(dI>0)
            Vref = Vrefold + deltaVref;
        else
            Vref = Vrefold - deltaVref;
        end
    end
else
    if(dI/dV == (-I/V))
        Vref = Vrefold;
    else
        if(dI/dV > (-I/V))
            Vref = Vrefold + deltaVref;
        else
            Vref = Vrefold - deltaVref;
        end
    end
end

if Vref >= Vrefmax || Vref<= Vrefmin
    Vref = Vrefold;
end

Vrefold = Vref;
Vold    = V;
Iold    = I;
```

3.7 Circuit Breaker control

For every circuit I have installed two programmable switches. The switches works in following manner. The first priority is to the PV energy, it means the solar energy will feed the load and if we have extra energy the it will be stored in energy storage. At the absent of PV the load will be supplied by the battery. If the battery and PV cannot arrange the power required by the load, the programable switch will change to the grid. Our last resort is generator when we have no solar energy, no battery and no grid energy. The generator will also be very beneficial in case of emergency.

```
function [LoadOn, ChargingOn, SolarEnergy,GridEnergy] = fcn(SOC,SolE,GriE)
%#codegen
LoadOn = 1;ChargingOn = 1;SolarEnergy = 1;GridEnergy = 0 ;
if(SOC>= 80) if(SolE>0) if(GriE>0)
        SolarEnergy=1;GridEnergy=0;LoadOn=1;ChargingOn=0;

        end
    end
end
if(SOC<40) if(SolE>0) if(GriE>0)
        SolarEnergy=1; GridEnergy=0; LoadOn=1;ChargingOn=1;

       end
   end
end
if(SolE<=0) if(GriE>0)
     SolarEnergy=0; GridEnergy=1;
     LoadOn=0; ChargingOn=0;
    end
end

if(SolE <= 0) if(GriE <= 0) if(SOC<40)

          SolarEnergy=0; GridEnergy=0; LoadOn =1;

        end
    end
end
```

4. Conclusion

Micro-grid is a really substantial grid that has tremendous advantages for environment, power quality and reliability, and for all contributors those that produces the power or consumes the power. The advantages and Micro-grid notion are explained using SIMULINK, MATLAB Ra2015. Micro-grid does not mean to build a new grid instead of the legacy one, it is only the improved and develop form of it to get more advanced grid utilizing communication technologies, providing way to bidirectional flow of data and electricity.

It also worth mentioning that thesis Micro-grid are extremely vulnerable to cyber crime.
Appendix

4.1 Calculations

4.1.1 Boost Converter

For boost calculations, these equations are used:

$$D = 1 - \rho\,(\frac{V_{in}}{V_o})\rho$$

$$L >= D\frac{(1 - D^2)R}{2f}$$

$$C >= \frac{D}{R\,(\frac{\Delta V_{out}}{V_{out}})f}$$

$$R = \frac{{V_{out}}^2}{P_{out}}$$

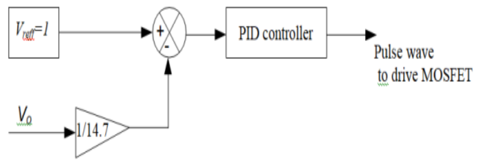
ΔV_{out} is the maximum ripple voltage desired.

F is the switching frequency which used (25 KHZ).

Batteries give 12 VDC, this voltage do need to be boosted to be as same as PV station output voltage. Capacitor is 1%, applying these equations to get:
- D= 0.5.
- L = 30.4 ×10-6 H.
- C = 3330 ×10-5 F.

4.1.2 PID controller

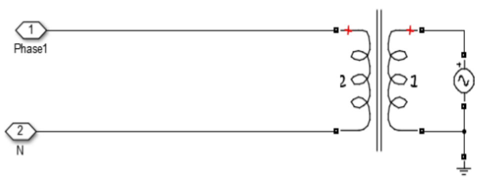
The proportional-integer-derivative controller on the DC-DC converter is to control and maintain the output voltage, Vo. Figure shown below represents a block diagram of transfer function of PID controller used in the DC-DC converter. The signal of output voltage, Vo multiplied by gain having value of 1/14.7 is a input signal is compared or added to the reference voltage, Vref. This output is as input signal of proportional-integer-derivative controller block and output signal of PID controller block goes to pulse wave generator to drive the gate port of MOSFET. domain function of PDI controller is given by equation (6)[9].



4.2 Grid Supply

The main grid supply is reduced to 220V peak voltage . The Transformer uses RMS value, so **225~=156V RMS.**

The load pure and we have to reduce the 156V RMS to bus voltage, thus we put transform's second winding as 15VRvs. Then we will change the AC to DC that is 15VdDC.



4.3 Sources Connection

1) All sources must provide same voltage.
2) All sources must be arranged to bus type. If the bus is dc, then all AC sources should be changed to AC and if bus is AC then all the source supply must be changed to AC energy.
3) If the bus is AC then all the sources mush have to same frequency.

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