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ELECTRIC POWER SYSTEM OF AN EMERGENCY ENERGY MODULE

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ABSTRACT

This thesis study is on designing and analysing the "Electric Power System of an Emergency Energy Module". KTH is running a project to create a mobile system for power supply in refugee camps and during the recovery of natural disasters. This is an independent power system comprising solar, wind and biomass based power generations and control. The design and analysis of electric power system is mainly focused on increasing the renewable energy efficiency of the system while saving excess power on the battery bank and controlling the battery discharging.

The analysis of the designed electric power system is done with using actual site data of solar irradiation and wind for one week period. Further, it has been developed a program based on MS Excel for analysing the module performances at any site in the world.

Keywords: Emergency Energy Module; Integration of wind and solar PV

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NOMENCLATURE

Abbreviations

EEM	-	Emergency Energy module
RO	-	Reverse Osmosis
PV	-	Photovoltaic
emf	-	Electro Motive force
rpm	-	Revolutions per minute
OC	-	Open Circuit
PMSG	-	Permanent Magnet Synchronous Generator
GPD	-	Gallons per Day
FRP	-	Fibreglass Reinforced Plastics
TDS	-	Total dissolved solids
GPM	-	Gallons Per Minute
AC	-	Alternating Current
DC	-	Direct Current
SOC	-	State of Charge

Parameters

Parameters			Unit
V_{oc}	-	Open circuit voltage	V
I_{sc}	-	short circuit Current	A
V_{Peak}	-	Peak Voltage	V
V_{LL}	-	Line to Line Voltage	V
ρ	-	Air Density	kg/m^3
R	-	Radius of the Wind Blade	m
u	-	Velocity of the Wind	m/s
C_P	-	Power Coefficient	
C_T	-	Torque Coefficient	
T_s	-	The period of switching frequency of the boost converter	s
t_{off}	-	The off time of the switching frequency of the boost converter	s
I_t	-	Total Irradiation on PV Panel	W/m^2
I_b	-	Beam Irradiation	W/m^2
I_d	-	Diffused Irradiation	W/m^2
θ	-	Surface Incidence Angle	rad
βc	-	Surface Tilt Angle	rad
θz	-	Solar Zenith angle	rad
$\boldsymbol{\gamma}s$	-	Solar Azimuth angle	rad
$\boldsymbol{\gamma}c$	-	Surface Azimuth angle	rad
φ	-	Latitude	rad
δ	-	Declination Angle	rad
ω	-	Hour Angle	rad
ts	-	Solar Time	hrs
α	-	The solar altitude of the sun elevation above the horizon	rad

1 BACKGROUND

KTH is running a project to create a mobile system for power supply in refugee camps and during the recovery from natural disasters. SELECT students, members of an ErasmusMundus program, have tried to develop a practical and economically viable solution for the EEM. The energy supply is considered completely renewable and is made up of 1kW wind mill, 5kW solar PV panels, 10kW Gasifier unit, 1200 Ah battery module and 600 GPD Reverse Osmosis water purification systems. The task is to design the electric power system of the Emergency Energy Module (EEM).

Furthermore, the EEM is contained in a container module so that it can be deliveredto any place upon request. The power generation modules and battery banks were selected so that they can generate electricity at any energy supply condition such as windy, sunny or availability of biomass.

Finally the controlling algorithms and electricity generating modules of the EEM is designed in order to meet energy demand of 5kW at any place in the world under the emergency requirement.

2 OBJECTIVES

The main objective of doing this project is to design the electrical system for the emergency energy module. The design of the electrical system includes to compile a specification and description of the electric system. Furthermore, it includes the schematic of the electric system in the EEM which includes the designing of power to the EEM auxiliary systems such as lighting, heating, water purification etc. In addition to that, it is required to design a startup sequence synchronizing different power sources such as wind, solar, battery bank, generator and List of apparatus.

3 METHOD OF ATTACK

1. Literature study
    - Study ofdefined Wind turbine
    - Study ofdefined Battery Bank
    - Study ofdefined Solar PV System
    - Study ofdefined Micro Gas turbine Based Power generation
    - Study ofdesigned power outputs and demands
2. Define a start-up sequence
    - Define a theoretical start up sequences with schematics based on the power input and output device's characteristics
    - Modelling the start-up sequence by using modelling software
3. Define the System and Components
    - Define variouscomponents of the system and their specifications
    - Prepare bill of material
4. Simulation and Power flow analysis

4 LITERATURE STUDY

The literature study includes studying on progress and reports of previous works. Specifically, it includes studying of Power Router, Solar PV System; Wind module and Main battery bank.

4.1 Wind Turbine and generator

A 1kW wind mill with its own controller and inverter is used for the wind power generating module for the EEM.

Figure 4.1: wind module

4.1.1 Specifications

- Model: FD1000
- Type: 3 blade upwind
- Rotor diameter: 3.0m
- Start-up wind speed: 2.5m / s (5.6mph)
- Cut-in wind speed: 3m/s (6.7mph)
- Rated wind speed: 9m/s (20.1mph)
- Rated power: 1000 W
- Maximum power: ~1300 W
- Furling wind speed: 12m/s (27mph)
- Over speed protection: auto furl
- Generator: permanent magnet alternator
- Output form: 48VDC nominal

4.1.2 Electrical Power Output Power vs. Wind Speed characteristics

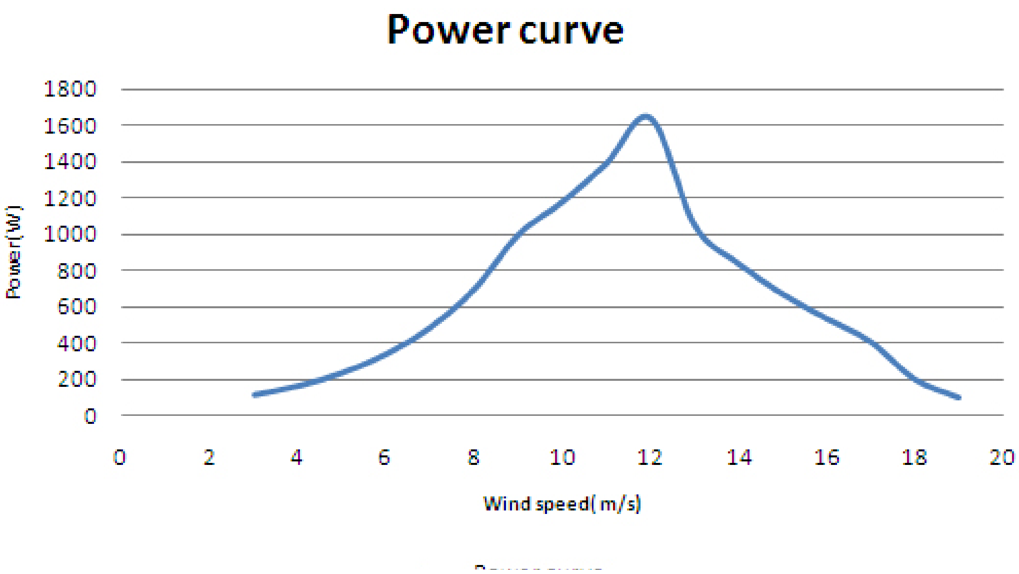

Figure 4.1.2: Electric Power Curve, Source: Manufacturer's Specification

The graph of figure 4.1.2 includes all the turbine and generator characteristics. The cut in wind speed is 3 m/s and cut off wind speed is 19 m/s.

4.1.3 Function Description

The controller and inverter module of the wind generator have the following functional characteristics;

- Automatic voltage steady output
- Automatically resuming AC output after short-voltage-protection for storage battery group
- Protection for output short circuit
- Protection to avoid storage batteries of being overcharged
- Protection to avoidstorage batteries of being reverse connected
- Damage-Protection for storage batteries

The functional description and circuit diagram is included in the chapter 5.3.

4.2 Main Battery Bank

The main battery bank of 24V and 200 Ah is formed by serially(refer Appendix 11.1) connecting two units of following battery modules. The main battery bank is formed by parallel connecting of battery cells and then serially connecting each parallel units together.

Figure 4.2: Main Battery Bank, Source: Manufacturer's Specification

4.3 Solar PV System

It is designed to install 5.5 kW solar PV modules for the Emergency Energy Module.

Figure 4.3: Solar PV Modules (Appendix 11.3 for Manufacturer's sepecifications of Solar PV Panels)

4.4 Gasifier and Three Phase Generator

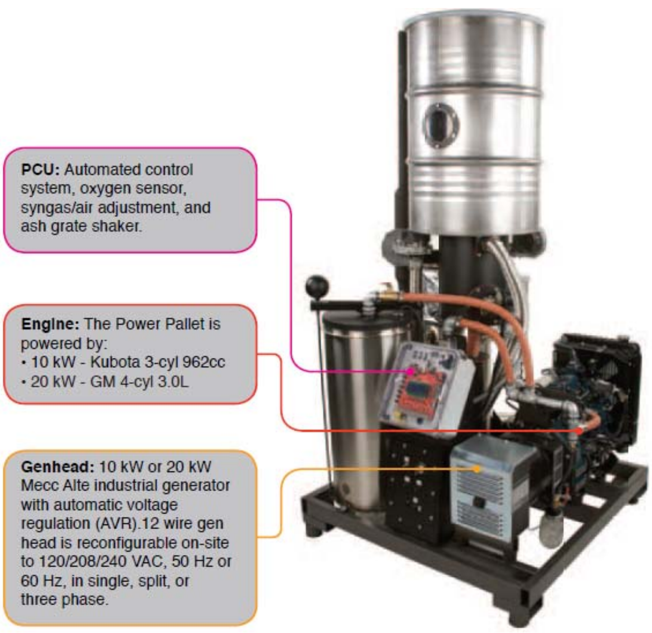

Figure 4.4: Gasifier, Engine and Generator, Source: Manufacturer's Specification

Kubota DG 972 module is used as the engine for the gasifier module.

Figure 4.5: Kubota DG 972 Engine, Source: Manufacturer's Specification

The engine is a dual fuel type engine. It can be powered by both bio gas and gasoline.

The generator is 50Hz three phase type with Delta or Star configuration. It was a problem to connect three phase generator module with existing single phase system. The generator manual is not available at the time of writing and thus the design on generator wirings has to be done later.

The fuel consumption and type of fuels that can be used in the gasifier module is described in Appendix 11.2.

4.5 Power Router

The controller module (power router) is the brain of the Emergency energy Module. It controls and monitors the power flow of the EEM.

The Wind mill cannot be interfaced directly to the current power router. Therefore, it is necessary to introduce a separate power controlling unit for the wind mill.

There is a provision to connect the Power Router to the grid power supply as shown in figure 4.5. The EEM is designed to work at remote sites where grid electricity supply is not appearing. Even ifthere is a grid power supply, we cannot expect a reliable and quality power supply under any emergency situation. Thereforethe grid interconnection of the Power Router modulehas not been utilized.

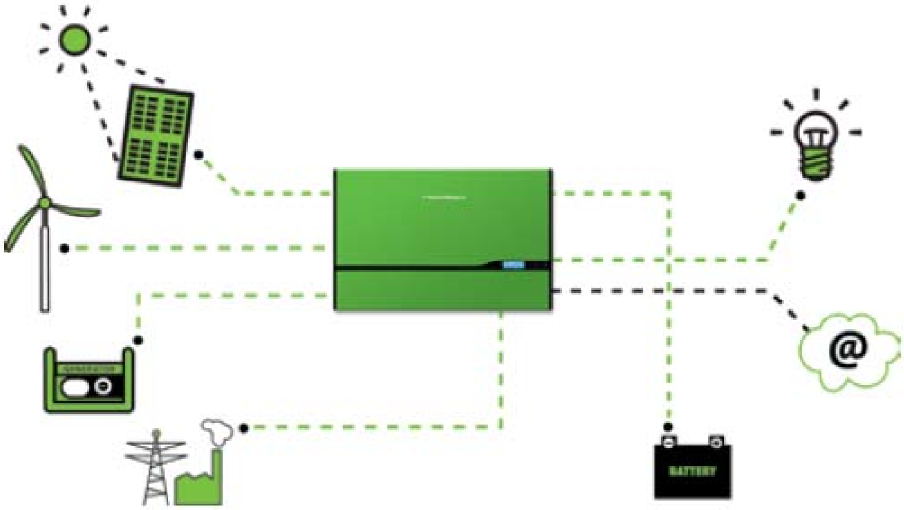

Figure 4.5: schematic connections to the Power Router, Source: Manufacturer's Specification

4.6 Reverse Osmosis System

Reverse osmosis (RO) is a membrane-technology filtration method that removes many types of large molecules and ions from solutions by applying pressure to the solution when it is on one side of a selective membrane. The result is that the solute is retained on the pressurized side of the membrane and the pure solvent is allowed to pass to the other side [1]. When the applied pressure exceeds the osmotic pressure, reverse osmosis will take place. This process purifies the water, often reducing total dissolved solids content by 99%.

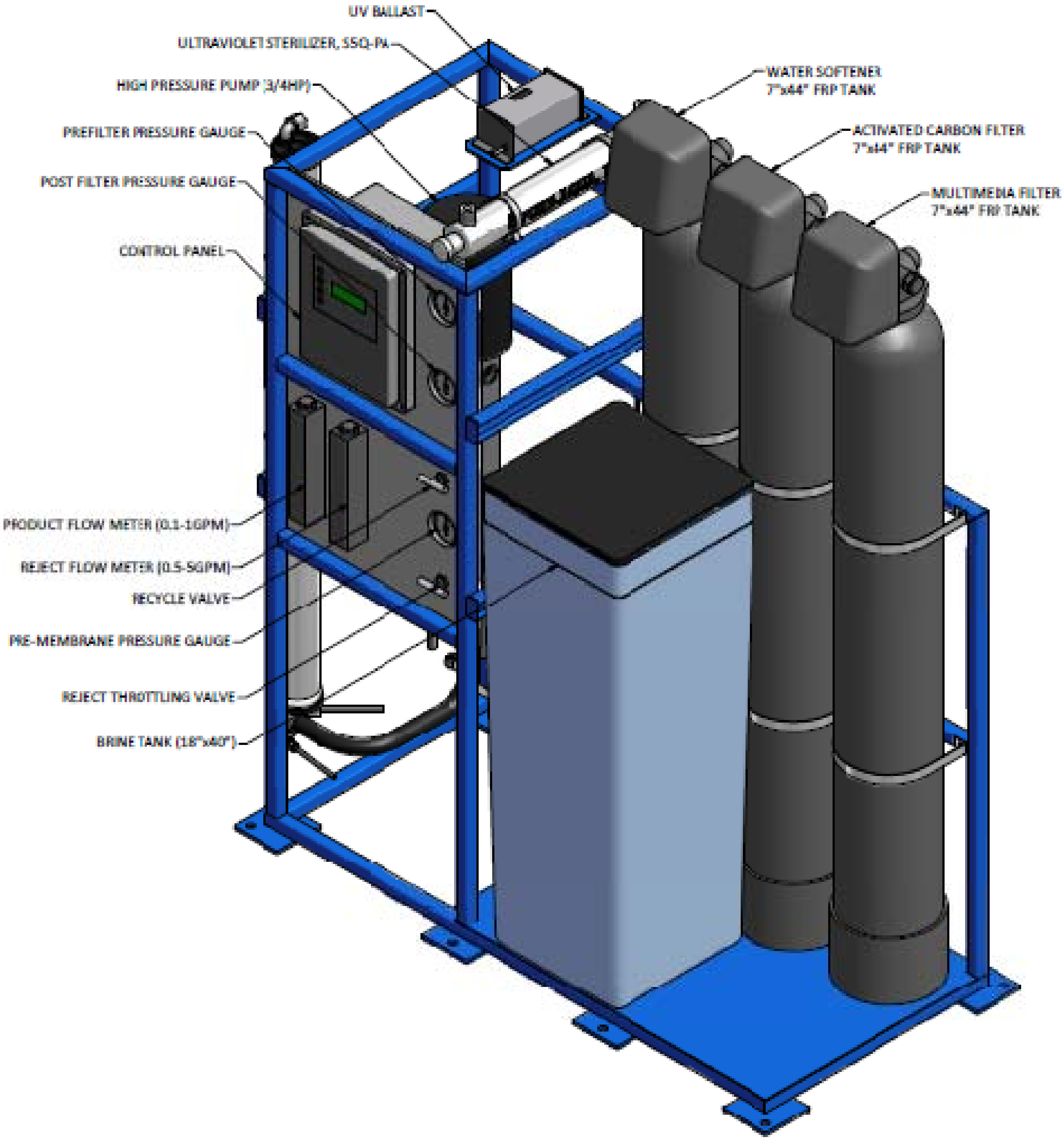

Figure 4.6: reverse Osmosis System, Source: Manufacturer's Specification

The 600 GPD Reverse Osmosis System consists of the following components,

4.6.1 Pre-treatments

- 7 inch FRP tank multimedia filter complete with media, 5600 Fleck valve, ¾ inch pipe size, 220V/1ph/50Hz.
- 7 inch FRP tank activated carbon filter complete with media, 5600 Fleck valve, ¾ inch pipe size, 220V/1ph/50Hz.
- 7 inch FRP tank water softener complete with media, 5600 Fleck valve, ¾ inch pipe size, 220V/1ph/50Hz.

4.6.2 RO System

- Reverse Osmosis System to produce 600 GPD at maximum 1000 ppm feed water TDS, 220V/1ph/50Hz.

4.6.3 Post-treatment

- UV sterilizer, 5 GPM, 220V/1ph/50Hz

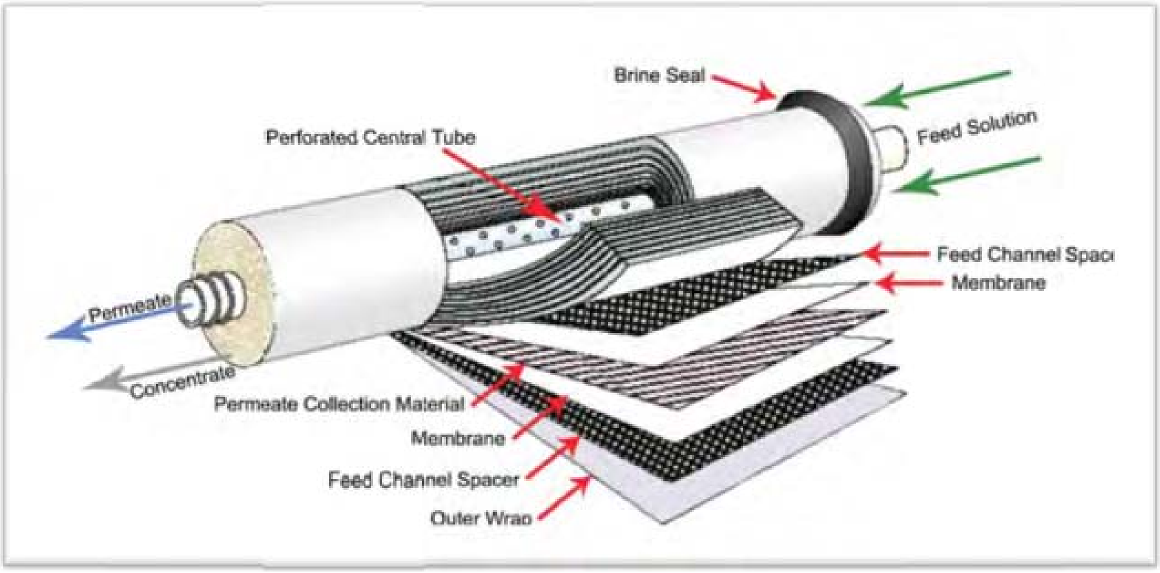

Figure 4.6.3: Membrane element exploded view, Source: Manufacturer's Specification

4.6.4 Electrical data of RO System

Rated Power	:	0.3728kW
Motor Operating Voltage	:	230V
Motor Amps at 230V	:	5
Locked Rotor Motor Amps	:	24
Thermal Overload Protector	:	Automatic Reset

5 ELECTRICAL SYSTEM OF EEM

The following figure shows the connection of the different power sources and load to form the electrical network of the Emergency Energy Module.

Equipment for the prototype of the EEM has been purchased. There were some shortcomings of interfacing them. Therefore, a special electrical wiring system has been defined to interconnect that equipment. Furthermore, it is recommended equipment for future development and general wiring system for interconnections has been designed.

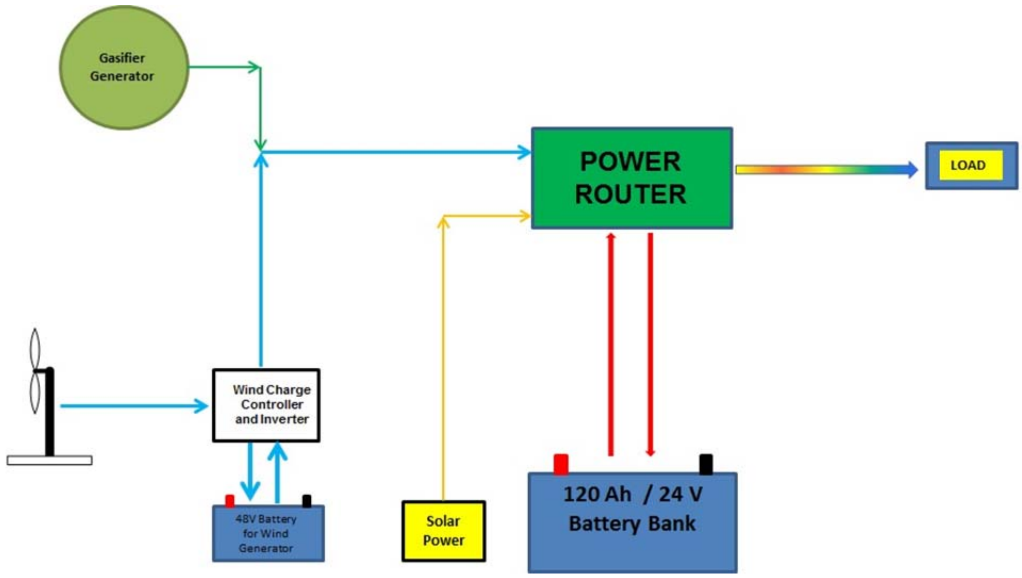

Figure 5.0: Schematic electrical connection of the network

5.1 Special Problems encountered when designing the Wiring System for the prototype

5.1.1 Mismatch of Number of Phases of Components

The major modules of the EEM had been purchased by the SELECT MSc students. The GEK Power Pellet Gasifier has a three phase power output while the all the other electrical components are single phase units. Therefore, the problem of interfacing the three phase engine with single phase modules was faced. Therefore, when the three phase generator is working, the phases are star connected. In addition to that the load of the phases are balanced and supposed to be used separately. This is achieved by introducing two three phase circuit breakers for Generator and Power router respectively with an interlocking mechanism for each other.

Aninduction motor is used for the water purification system. Three-phase induction machines face three kinds of problems due to unbalance [2].However all the electrical loadsare single phase. Therefore the phase unbalances of three phase system will not be affected to the electrical network of EEM.

5.1.2 Phase unbalances while charging the main battery bank

Battery charging current changes with thecharge level, Thusthe dedicated phase current of the three phase system is changing with the charging status of the Battery Bank. The maximum charging current for the battery bank is 60 A at 24V, so the maximum loading of the phase is below 3 kW. Therefore, it is not difficult to maintain the phase balancing of the system even at the highest charging current.

Unbalance is a serious power quality problem, mainly affecting low-voltage distribution systems, as for instance encountered in office buildings with abundant PCs and lighting. However, it can be quantified in a relatively simple manner resulting in parameters that can be compared to standardized values.
It is acceptable for the prototype of EEM and we can avoid such problems in future development.

5.1.3 Starting current of the RO System

The starting current requirement of the RO system is 24A. The maximum power handling capacity of the Power Router is 5kW i.e. 22A. But it can beseen from the specification that the peak current handling capacity of the Power Router is 25A for a few seconds. Therefore, the RO system is directly connected to the system and precautions were given to switch off every other electrical equipment of the network while switching on the RO system. Furthermore, the RO system is connected to the load, so that it does not switch off while switching the system to GEK Generator as well.

5.2 Electrical Wiring of the EEM

IEC 364:electrical Installations of buildings is used as the basis for designing the wiring system inside the container. Sweden also agreed to the above standard and there is a special chapter for “Electrical Installation in Caravan”.

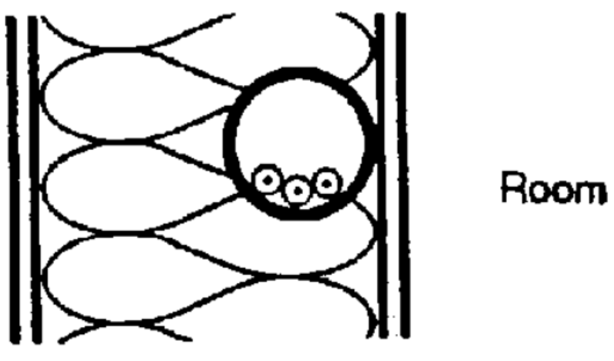

Figure 5.2: wiring in the insulation of the wall, Source: IEC

The insulated conductors in conduits are embedded in thermally insulated wall. The cross sectional areas of the conductors are selected considering their maximum current flow. In addition to that a safety margin is addedas well. The neutral conductor has a higher cross sectional area than the phase conductors to withstand for any unbalanced current due to unbalances of the three phases and harmonic currents.

5.3 Interfacing Different Power Generating Sources to the Network

All the electrical components of the EEM such as Power Router, 1kW Wind Generator, Solar Panels, GEK Gasifier, and RO System were already purchased. Therefore, the focus has been to integrate all those devicesassuring reliable and efficient operation of the system.

5.3.1 Interfacing a 1kW Wind Turbine to the System

The interfacing of the 1kW wind turbine to the mini electricity network was one of the important issues. The wind generator is a Permanent Magnet Synchronous Generator. The inherent electrical characteristics of a permanent magnet generator result in a poor match between a standard rectifier/battery combination and a wind turbine generator.
The main technical challenge in the interfacing of a wind-electric generator to the main battery bank is to come up with a system configuration and control algorithm that maximizes wind energy production from the turbine and also provides favourable charging conditions for batteries. This task is complex because of the variability of the wind: continual wind speed variations result in varying wind turbine power output. Furthermore, there is not any provision to connect the wind generator to the same DC bus asthe Power Router. The regulated DC voltage of the wind system is 48V, while the voltage of the main battery is 24 V. Therefore, it requires an additional DC to DC converter to interface to the main battery.

Ideally, the system configuration and its controller should optimize the match between the wind rotor and load, thereby allowing the maximum available power from the wind to be used, while at the same time charging the batteries with an optimum charge profile(for a given type of battery).

Therefore, a separate battery bank of 48V and 60 Ah has been added to the wind system with its own charging controller and inverter. When the voltage of the storage battery group is between 90% to 125% rated voltage, the controller and inverter system generates a steady AC output of220+/-8 V. When the voltage of the storage battery group is lower than 90% of rated voltage, the output AC voltage will decline following the battery group voltage. When the battery group is reduced to 80% of rated voltage, the short voltage protection function will work, automatically cutting off AC output to avoid the battery group to be deep discharged.

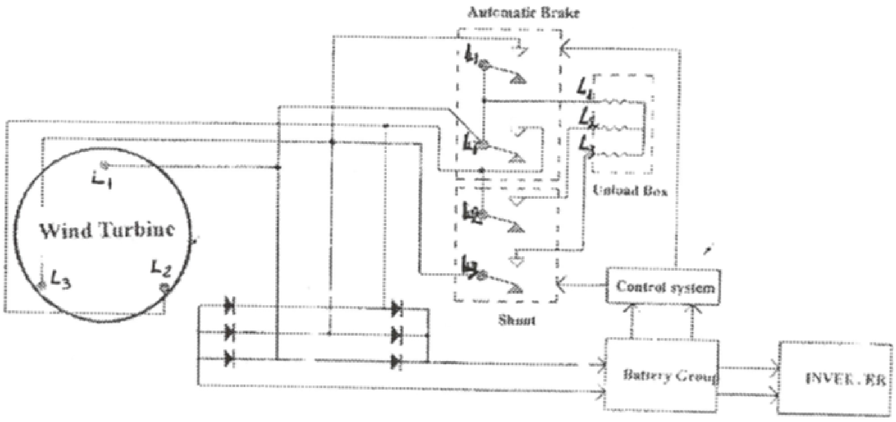

Figure 5.3: Power routing diagram of the wind controlling module, Source: Manufacturer's Specification

The electrical configuration of the 1kW wind generator is shown in the figure 5.3. The generated three phase electricity will be rectified and sent to the battery bank. Then, the controller system monitors the state of charge of the battery bank and if the battery is being fully charged then three phase generated electricity will be routed to a three phase dummy load to protect the overcharging of the battery. Furthermore, an inverter module converts the stored energy in the battery bank to 230V AC.

5.3.2 Interfacing the 5.5 kW Solar PV System and the Battery bank

The Solar PV system is directly connected to the Power Router through its dedicated MC4 connectors. The solar PV maximum power is absorbed to the system through its maximum power point tracking functions. Then, it is connected to the internal 400V DC bus of the power router to work together with the backup battery bank.

5.4 Load Forecasting of the EEM

The electrical power in Emergency Energy Module is going to be used for the following applications;

- Water purification
- Thermal comfort ventilation
- Indoor and Outdoor lighting of the camp area
- Communication units for the EEM including power supply to laptops and mobile phones
- Food preparation
- Refrigeration of medicine, etc.

The first four items of applications are being considered for the prototype of the EEM. Therefore, we can analyse the phase balancing of the three phase system of the prototype as follows.

6 START UP SEQUENCE OF EEM

First of all, controller module finds the available sum of solar and wind energy. If the sum of solar and wind energy equals to the current load then EEM continuously is supplying the load from solar and wind power. Furthermore, if EEM faces energy shortage from solar and wind modules due to fluctuation of wind speed and solar irradiation, then it retrieves stored energy in the battery to fulfil the shortage of energy.

If the sum of solar and wind energy still falls short of current load, then EEM starts the gasifierand generator which havethe capability of producing 3kW to 10kW electrical power output.

At the same time, it disconnects the wind power supply from the main electricity network and the wind module starts storing energy in its own battery bank. The reason for disconnecting the wind module after starting the generator is to maximize the efficiency of the generator. It is not required to change the output of the gasifier with changing wind speed. It can be kept at constant value so that it increases the efficiency. In addition, the green wind energy is stored in its own battery bank and there is no waste of energy except charging losses. Therefore, it increases the total energy efficiency of the EEM.

The electrical connection of the solar energy system remains connected, also after starting the generator. That is because the produced power from solar PV is stored in the main battery bank. The excess power of the generator is also stored in the main battery bank.

Even after the full charging of the main battery bank the EEM calculates the availability of sum of solar and wind energy. If the sum of the solar and wind energy is below the load then it is still remaining supplying electricity from the generator. If there is not sufficient energy coming from solar and wind, then the main battery bank will be discharged quickly.

Assumed Power Requirement	=	5000kW
Battery Voltage	=	24V
Battery Discharging Current	=	5000/24 DC
	=	208A [DC]

Battery Discharge Characteristics	Capacity (Ah)
20 hour rate (10 A - 10.5 V)	200 Ah
10 hour rate (19.6 A - 10.5 V)	196 Ah
5 hour rate (36.7A - 10.5 V)	183.5 Ah
1 hour rate (138 A - 9.6 V)	138 Ah

Figure 6.0: Battery discharge characteristics (Source: Manufacturer’s Specification)

According to the above figure no. 6.0; If the battery bank delivers 208.33 A the battery bank will be dischargedin less than hour period. This is not good for battery life time because of higher current capacity. In addition to that the system is not designed to handle such a big amount of current level.

In such situations it will require restarting of the generator. Frequent starting and stopping of the generator causes inefficiency of the electricity system. The frequent energy storing from the generator to battery and subsequent discharging the battery is not efficient because of inefficiency of energy storage of the battery.
If there is sufficient amount of solar and wind power then system hand over the network to solar and wind power by switching offthe generator module. Even though there are fluctuations in wind energy due to fluctuations of wind speed, it doesn’t matter for the electricity system because some energy is stored in the dedicated battery bank of wind. In addition to that, the solar energy is much predictable for at least several hours once the shining has started.

6.1 Flow Chart Representation of Start Up Sequence of EEM

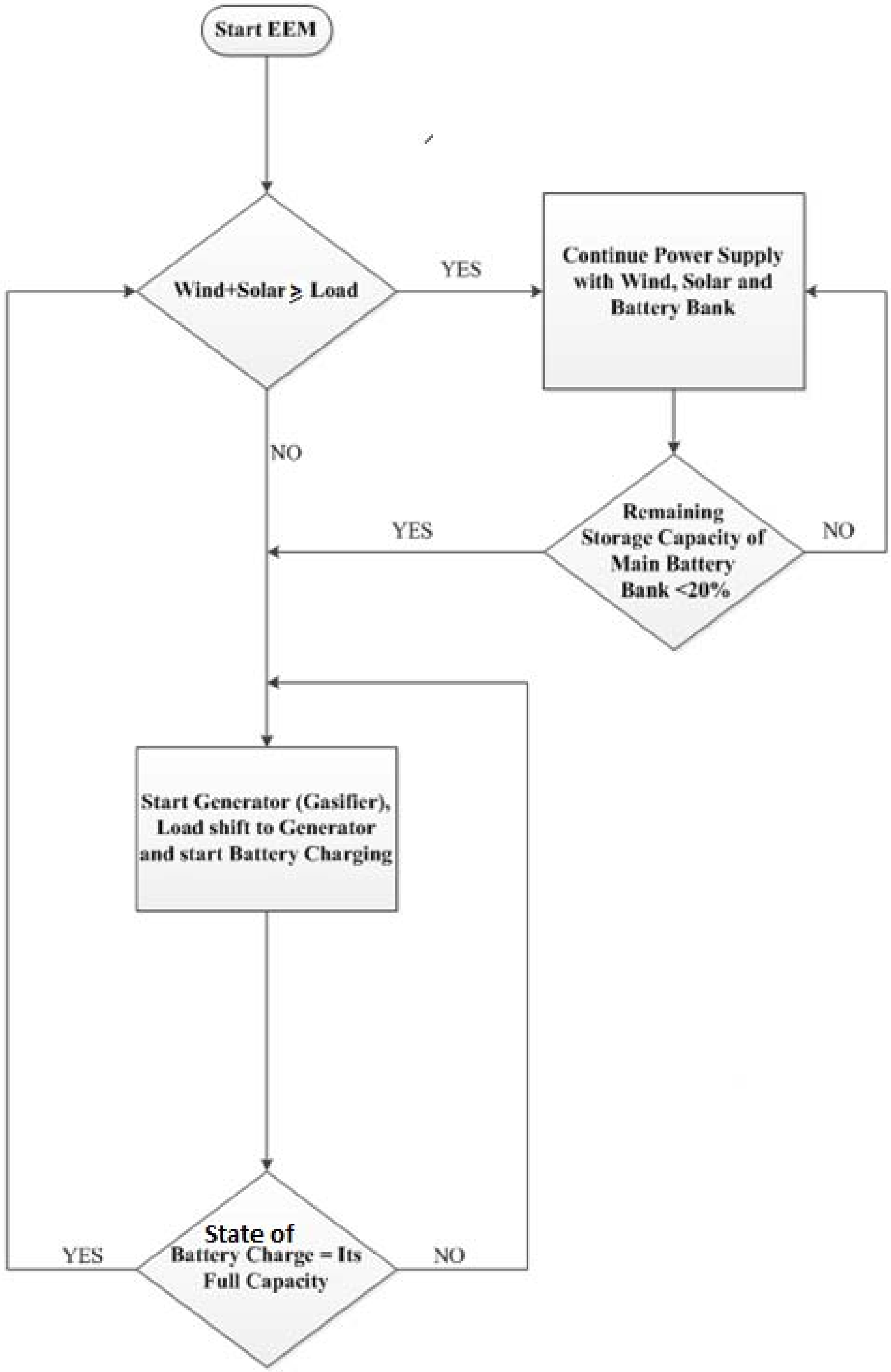

Figure 6.1: Flow chart representation of Start-up Sequence of EEM

6.2 Electrical configuration for start-up sequence

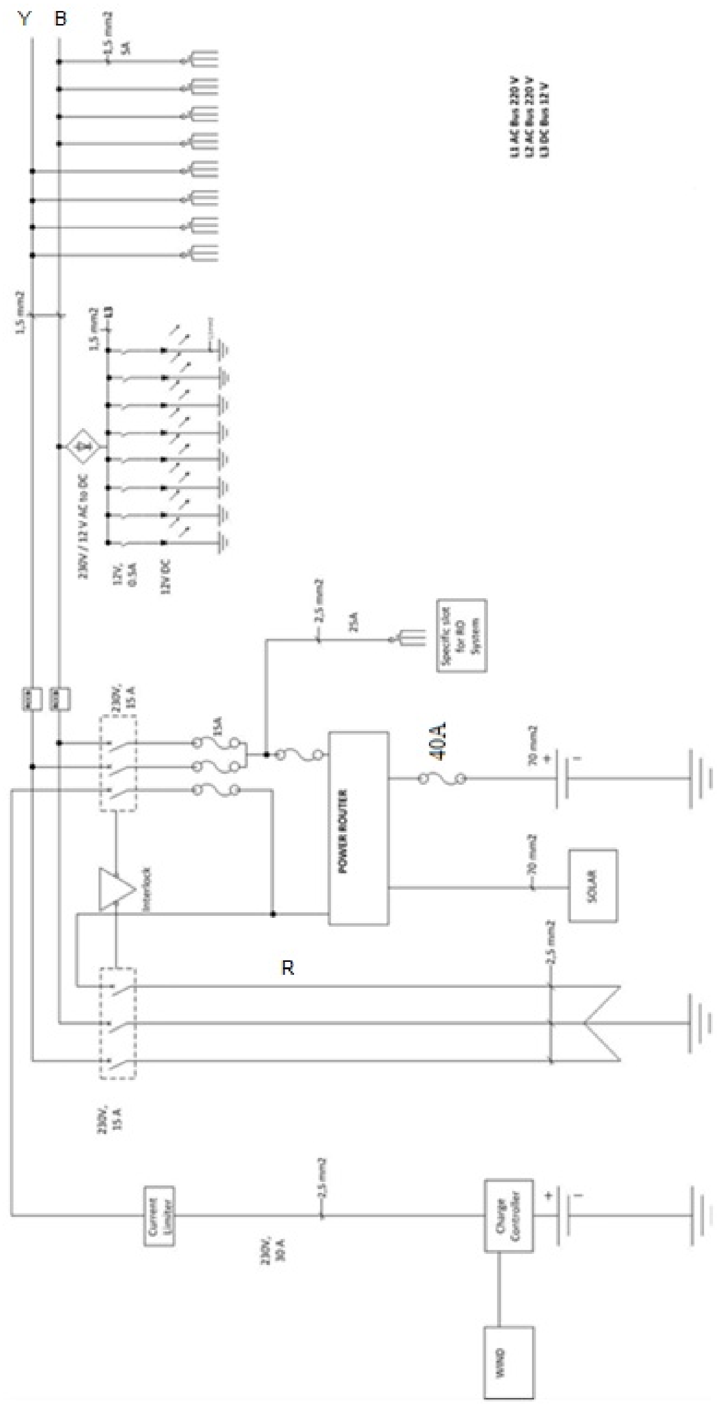

Figure 6.2.1: Electrical wiring for prototype of EEM

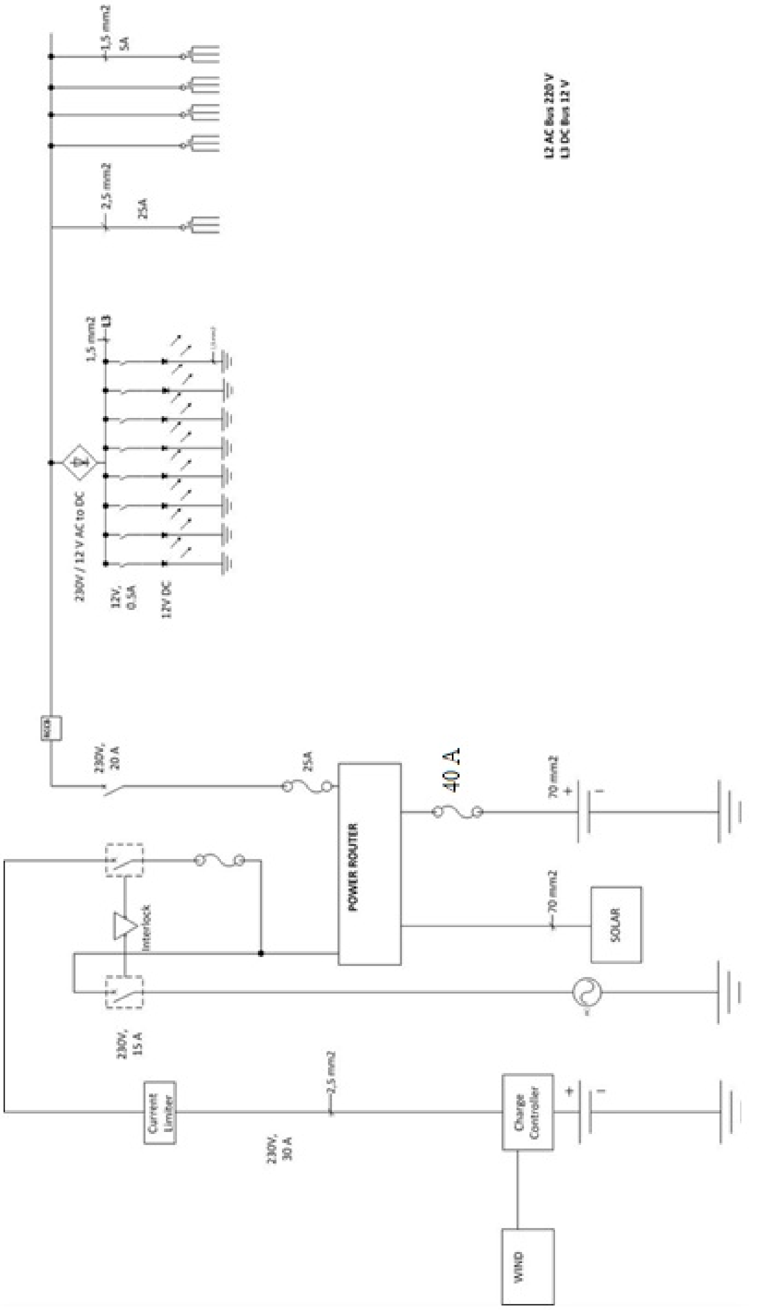

Figure 6.2.2: Electrical wiring for Generalized EEM

6.3 Transient Analysis of Variation of Load during the Battery Charging

Once the main battery bank is below 20% charge capacity of the rated value, then the gasifier is started. The power output of the gasifier is 3kW – 10kW capacity which go beyond the power requirement of 5kW. Therefore, once the gasifier is operated the total load is shifted to the gasifier through the interlocking switching mechanisms. The gasifierhas a three phase generator based power generation system. Therefore, it is necessary to maintain the phase balancing while supplying the power. Otherwise it may cause to some serious problems.

The manual phase balancing is achieved as follows while dedicating one phase of the three phase system for the charging of the main battery bank through the power router. The power flow to the battery is changing with the charged capacity of the battery. Further, it leads to dynamic phase unbalances. Therefore, the battery charging characteristics are analysed as follows to improve the balanced three phase system.

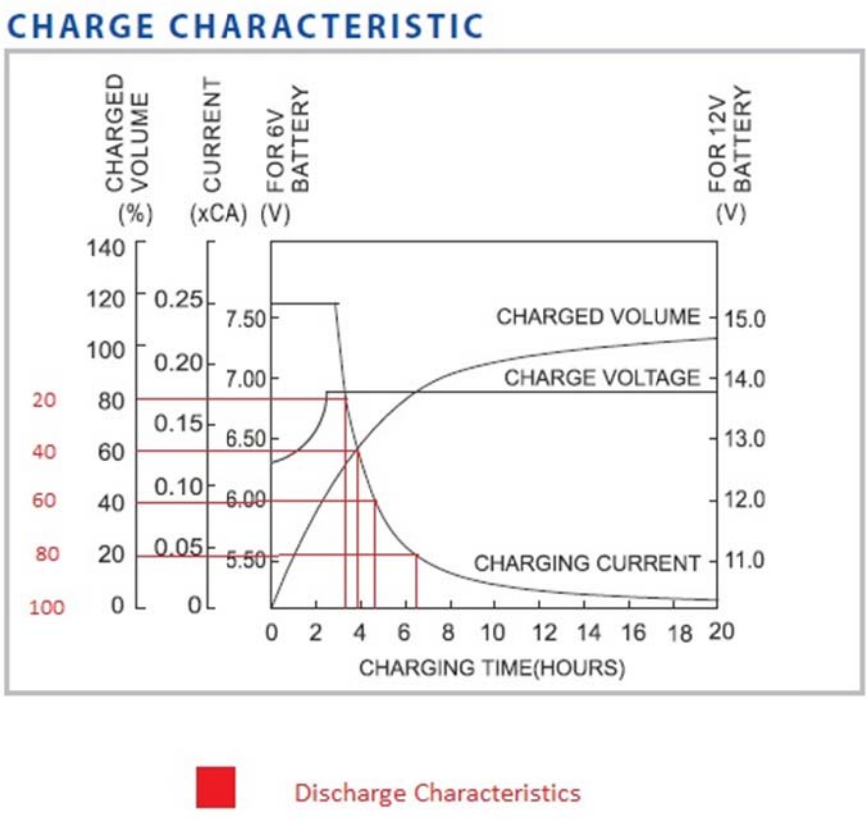

Figure 6.3.1: Battery discharge characteristics

N.B: It is assumed that the current level is constant for particular charging interval.

The minimum charge level of the main battery bank is 20 % of its rated charge capacity. That corresponds to 3.2 hours of charging time according to the Figure 6.3.1 of Battery discharge characteristics. Therefore the transient analysis is carried out from 3.2 hours of its charging time.

Time, h	Charging Current, A	Power for Charging, W	Ro System,W	Power Router Consumption, ,W	Total Load for the Phase ‘R’ , W
3.2 to 4	18	432	375	20	827
4 to 4.8	13.2	316.8	375	20	711.8
4.8 to 6.2	8.4	201.6	375	20	596.6
6.2 to 10	3.6	86.4	375	20	481.4
Above 10	<3.6	<86.4	375	20	395

Table 6.3.1: Load calculation for phase ‘R’

Item	Power Consumption, Y
Laptop	40
Venitilation Fan	60
Heating	300
Total	400

Table 6.3.2: Load calculation for phase ‘Y’

Item	Power Consumption, B
Indoor Lighting	40
Table Lamp	60
Heatimg	300
Total	400

Table 6.3.3: Load calculation for phase ‘B’

	Load On the Phase, W		
Charging Time	R	Y	B
3.2 hrs to 4 hrs	827	400	400
4 hrs to 4.8 hrs	712	400	400
4.8 hrs to 6.2 hrs	597	400	400
6.2hrs to 10 hrs	481	400	400
Above 10 hrs	395	400	400

Table 6.3.4: Loads for phase ‘R”Y”B’

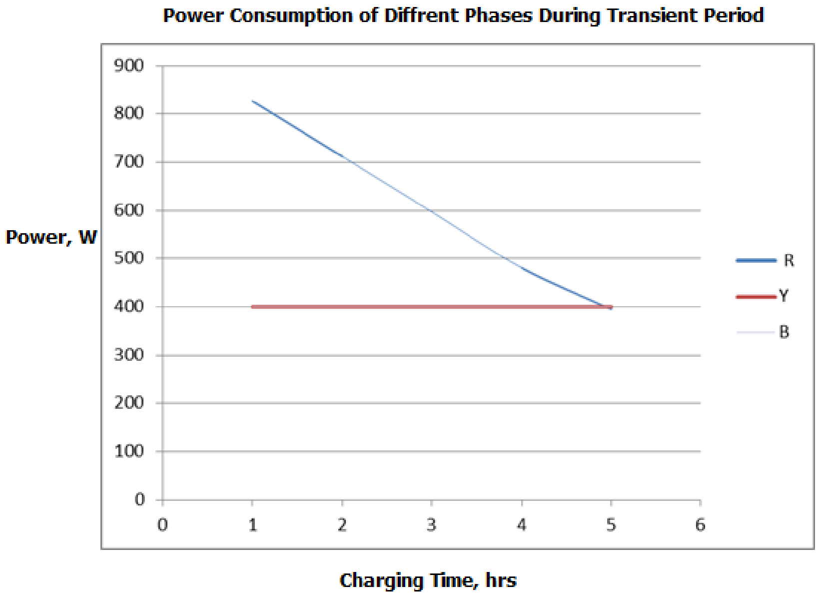

Figure 6.3.2: Load variation of three phases

Note: In the figure no 6.3.2. The Yand B phases are coincides to the same line.

There is a load unbalance in the three phase system during the charging of the main battery bank. But, it is balanced after the charging period, which can take five hours from 20 % State of charge

7 MODELLING AND SIMULATION WORKS

7.1 Modelling and Simulation of wind Turbine

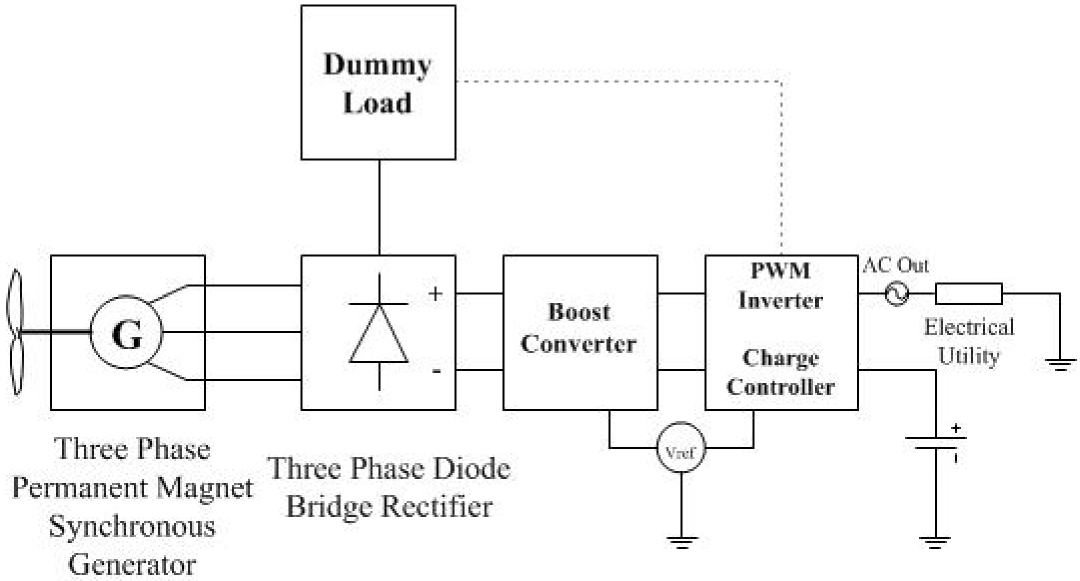

Figure 7.1.1: Block Diagram of Wind GeneratorSystem– Source: Manufacturer's Specification of Wind Generator System

The mechanical power generated from wind turbine is given by the following equations.

$$P_m = \frac{1}{2} C_p \, \rho \, A u^3$$ …Eq. 7.1.1, Source CompEdu

$$P_m = \frac{1}{2} C_p \, \rho \, \pi \, R^2 u^3$$ …Eq.7.1.2, Source CompEdu

The mechanical torque generated from wind turbine is given by the following equation.

$$T_m = \frac{1}{2} C_T \, \rho \, \pi \, R^3 u^2$$ …Eq.7.1.3, Source CompEdu

Where;

ρ	:	Air Density
R	:	Radius of the Wind Blade
u	:	Velocity of the Wind
C_P	:	Power Coefficient
C_T	:	Torque Coefficient

When the wind speed changes then in order to go for further analysis, we should find a relationship between the rotational speed of the wind turbine (ω_m) and the wind speed. The tip speed ratio is the ratio of the turbine tip speed $R\omega$ to the wind speed u. Then;

Tip Speed Ratio,

$$\lambda = \frac{Blade\ Tip\ Speed}{Wind\ Speed} \qquad \text{…Eq.7.1.4, Source CompEdu}$$

$$\lambda = \frac{R\ \omega_m}{u} \qquad \text{…Eq.7.1.5, Source CompEdu}$$

The relationship between CP, CT and λ is shown in the figure no 7.1.2.

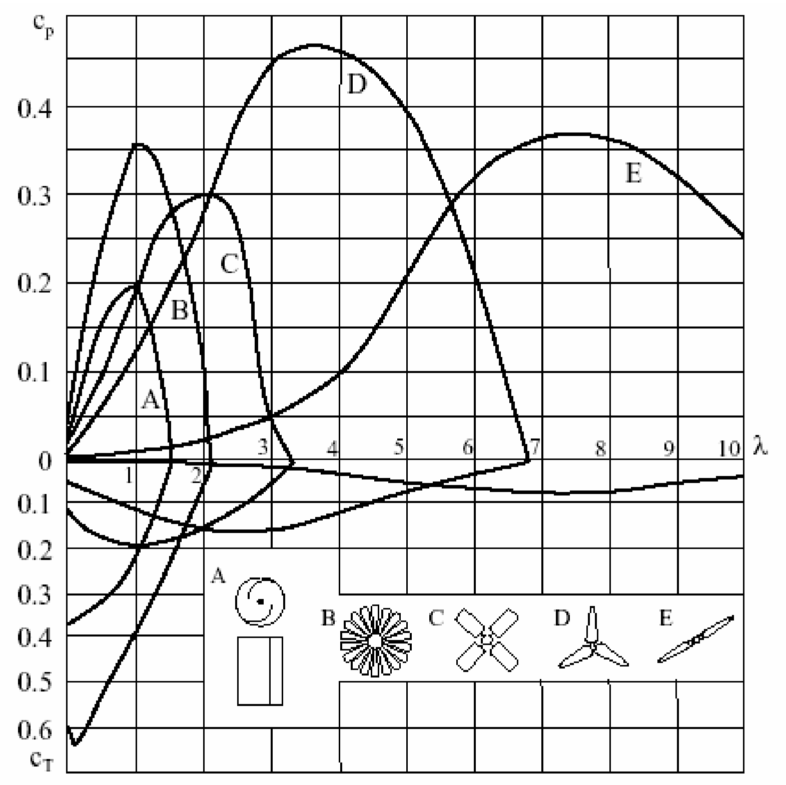

Figure 7.1.2: The relationship between CP, CT and λ, Source: Boyle – Renewable Energy, Power for Future

It is very clear that there exists a point where the power coefficient of performance is maximal according to figure no. 7.1.2. If we consider the curve D (wind turbine with three blades) for the simulation for different wind speeds then we have to vary the rotational speed to operate close to λ = 3.8.

7.1.1 Boost Converter

A boost converter or step-up converter is a type of DC-to-DC power converter with an output voltage always greater than its input voltage. It is used to regulate the output voltage ($V_{d,out}$) to constant value in this wind turbine model. The duty ratio 'D' varies according to the input voltage ($V_{d,in}$). The relation between the input and output voltage of the boost converter is shown in equation7.1.1.1. And the relation between the input and output currents of the boost converter is shown in equation 7.1.1.2.

$$\frac{V_{d,out}}{V_{d,in}} = \frac{t_s}{T_{off}} = \frac{1}{1-D}$$ …Eq.7.1.1, Source: Chapman, Electrical Machinery Fundamentals

$$\frac{I_{d,out}}{I_{d,in}} = (1-D)$$ …Eq.7.1.1.2, Source: Chapman, Electrical Machinery Fundamentals

Where;

T_s: is the period of switching frequency of the boost converter
t_{off}: is the off time of the switching frequency of the boost converter

The duty ratio D can be defined for the continuous conduction mode as the equation 7.1.1.3.

$$D = 1 - \frac{V_{d,in}}{V_{d,out}}$$ …Eq.7.1.1.3,Source: Chapman, Electrical Machinery Fundamentals

7.1.2 Measuring Synchronous Generator Model Parameter

The equivalent circuit of a synchronous generator that has been derived contains three quantities that must be determined in order to completely describe the behavior of a real synchronous generator.

1. The relationship between field current and flux
2. The synchronous reactance
3. The armature resistance [4]

The rotor has a fixed magnetization in a Permanent Magnet Synchronous Generator. Therefore, there is no any requirement of above first component and it is measured the second and third components. In addition, the armature electro motive force (emf) (E_A) was measured at the rated speed.

7.1.3 Open Circuit Test

The first step of measuring model parameters of synchronous generator model is to perform the open circuit test on the generator. To perform this test, the generator is turned at the rated speed and the terminals are disconnected from the all loads. Then the terminal voltage (V_{LL}) is measured. The test was performed for three intermediate speeds of the generator and was the open circuit voltage.

Speed (rpm)	**OC Voltage (V)**
33	4.9
67	11
108	18.5

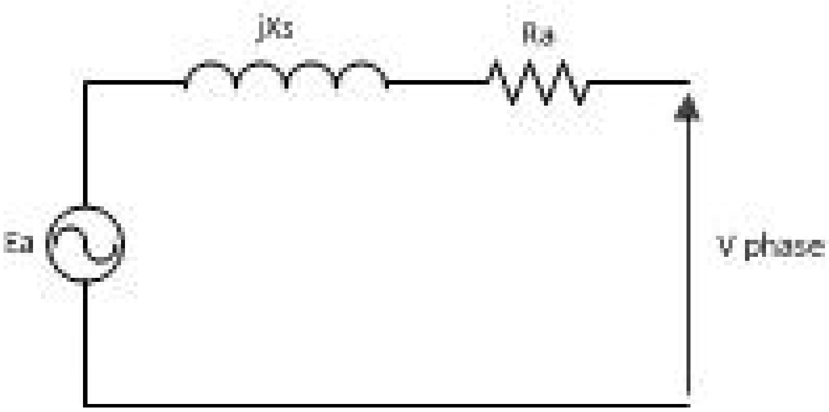

Figure 7.1.4.1 Equivalent Circuit of the Wind Generator

7.1.4 Power Curve after Permanent Magnet Synchronous Generator

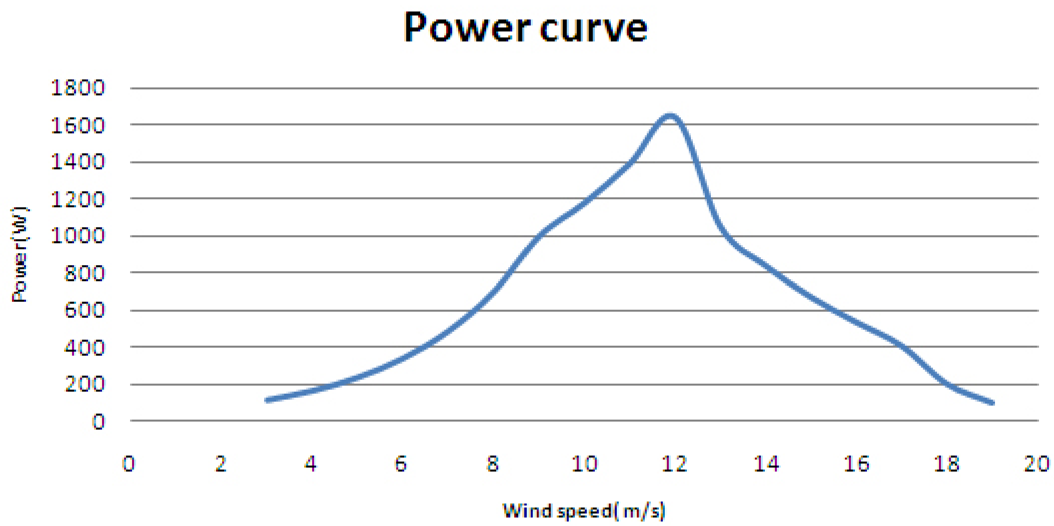

Figure 7.1.5.1Power Curve of the Wind Generator Output

Wind Speed, (m/s)	Power, (w)
<3	0
3<=x<5	160
5<=x<7	320
7<=x<9	700
9<=x<11	1200
11<=x<13	1600
13<=x<15	820
15<=x<17	520
17<=x<19	200
19<	0

Table 7.1.5.1: Discretised Values of Power Curve

The plot in the figure no 7.1.5.1 shows the power output characteristic of PMSG. It is a continuous graph. The continuous graph is split in to equal intervals and the average power output value of each interval is considered as shown in table 7.1.5.1.

The power curve at figure no7.1.5.1 is simplified as in the table no 7.1.5.1 for the simplicity of further analysis.

The power output of the wind generator is simulated and calculated based on the table no 7.1.5.1. In addition to that, the efficiencies of the different components of the controller are estimated by experience and known values.

7.2 Modelling and Simulation of Power Output of Solar PV

7.2.1 Parameters for Calculation of Solar Irradiation

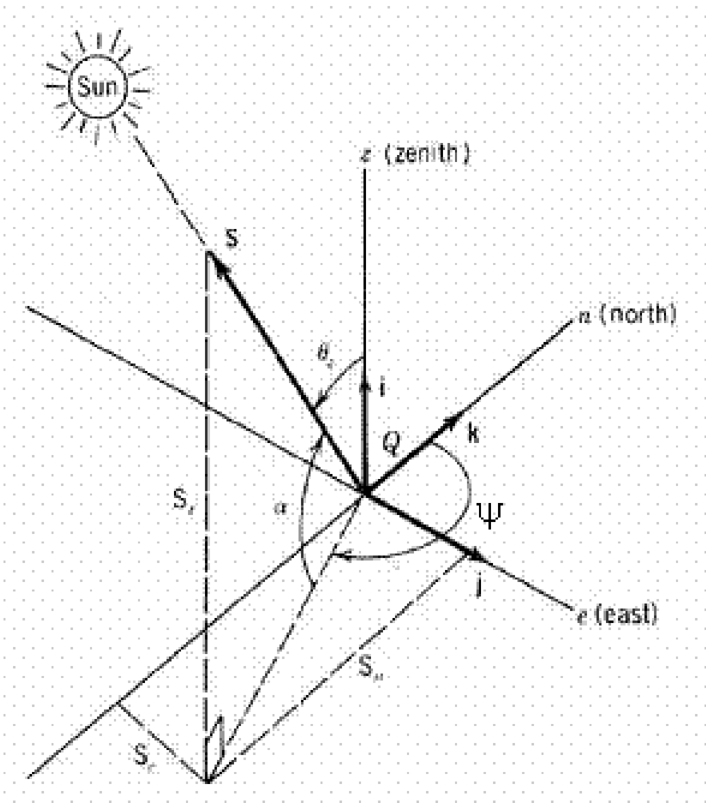

Figure 7.2.1.1Parameters for Calculation of Solar Irradiation, Source: CompEdu

The sun's position can be defined in the sky in relation to a horizontal surface for a given geographical location as in the figure 7.2.1.1.

θz	:	Zenith angle (degrees)
α	:	the solar altitude of the sun elevation above the horizon (degrees, α = 90- θz)
ω	:	hour angle
Φ	:	geographic latitude (degrees, north positive)
δ	:	the declination (degrees, north positive)
ψ	:	solar azimuth angle (degrees, northzero, east positive)

7.2.2 Calculation of Total Solar Irradiation on Solar PV Panel

The total solar irradiation on solar PV panels is needed to calculate the output power of the solar PV panels. It is calculated by using following formulas and steps.

$$I_t = I_b cos\theta + I_d \qquad \text{...Eq.7.2.2.1}$$

I_t - Total Irradiation on PV Panel (W/m^2)
I_b- Beam Irradiation (W/m^2)
I_d - Diffused Irradiation (W/m^2)
θ -Surface Incidence Angle (rad)

$$\theta = \arccos\left(cos\beta_c cos\theta_z + sin\beta_c sin\theta_z \cos\left(\gamma_s - \gamma_c\right)\right) \text{...Eq.7.2.2.2}$$

β_c–Surface Tilt Angle (rad)
θ_z– Solar Zenith angle (rad)
γ_s-Solar Azimuth angle (rad)
γ_c-Surface Azimuth angle (rad)

$$\gamma_s = \operatorname{sgn}(\omega)\left|arccos\frac{cos\theta_z sin\varphi - \sin\delta}{sin\,\theta_z cos\varphi}\right| \qquad \text{...Eq.7.2.2.3}$$

$$\theta_z = arccos\left(cos\varphi cos\delta cos\omega + sin\varphi sin\delta\right) \qquad \text{...Eq.7.2.2.4}$$

φ – Latitude (rad)
δ – Declination Angle (rad)
ω – Hour Angle (rad)

$$\omega = \frac{Pi}{12}\left(t_s - 12\right) \qquad \text{...Eq.7.2.2.5}$$

t_s – Solar Time (hrs)

$$\delta = \arcsin(0.39795\cos\left(2\,pi\frac{n-173}{365}\right)) \qquad \text{...Eq.7.2.2.6}$$

7.2.3 Simplifications and Assumptions of Calculations

The following simplification assumptions were made in order to simplify the solar PV power output calculations.

- The solar time (t_s) is taken as normal clock time.
- The diffused horizontal radiation ($I_{d,h}$) is taken instead of diffused radiation (I_d). It is assumed that diffused horizontal radiation is isentropic.
- It is considered the middle day of the week for the calculation of Declination Angle (δ, rad) and it is assumed that the variation of declination angle is negligible during the week.

7.2.4 **The following solar Irradiation data is used for the simulation**

From	:	01. 06. 2005
To	:	07. 06. 2005
City	:	Stockholm
Latitude	:	56.13 degrees
Longitude	:	13.1 degrees
References	:	http://www.soda-is.com

The middle date of the week i.e. June 4 2005 is considered for the calculation of Declination Angle.

n = 155

$$\delta = \arcsin(0.39795 \cos (2\,\pi \frac{n - 173}{365}))$$

$$\delta = \arcsin(0.39795 \cos (2\,\pi \frac{155 - 173}{365}))$$

δ = 23.4 degrees

δ = 0.409 rad

The Hour Angle is calculated considering the clock time instead of solar time. For an example, at hour one the hour angle is equal to;

$$\omega = \frac{\pi}{12}\,(t_s - 12)$$

$$\omega = \frac{\pi}{12}\,(1 - 12)$$

ω = 2.88 rad

The sample calculation of solar zenithangle, θ_z,rad for the above data set;

$$\theta_z = arccos\,(cos\varphi cos\delta cos\omega + sin\varphi sin\delta)$$

$$\theta_z = arccos\,(\cos(0.97) * \cos(\,0.40) * \cos\,(-2.88) + sin(0.97)\quad sin(0.39)\quad)$$

θ_z= 1.76

Solar panels are faced to south in the northern hemi sphere. Therefore, the Surface Azimuth Angle ($\gamma_{c,}$ rad) can be assumed to bezero degrees. The Solar Azimuth Angle (γ_s, rad);

$$\gamma_s = \mathrm{sgn}\,(\omega)|arccos\frac{cos\theta_z sin\varphi - \sin\delta}{sin\,\theta_z cos\varphi}|$$

$$\gamma_s = \mathrm{sgn}\,(2.88)|arccos\frac{cos1.76sin0.98 - \sin 1.76}{sin\,1.76\,cos0.98}|$$

γ_s= -2.90

The Surface Incidence Angle, θ is calculated as follows for the sample data set;

$$\theta = \arccos\left(cos\beta_c cos\theta_z + sin\beta_c sin\theta_z \cos\left(\gamma_s - \gamma_c\right)\right)$$

$$\theta = \arccos\left(cos0.785cos1.76 + sin0.785\ sin1.76\cos\left(-2.90 - 0\right)\right)$$

θ = 2.5

The total radiation on the solar PV panel at particular instance can be found by substituting typical values to the equation 7.2.2.

Solar Irradiation, W/m2	Maximum Power Point, W
200	880
400	1760
600	2816
800	3850
1000	5500

Table 7.2.4.1: Solar Irradiation and Maximum Power Point

The values in the table no 7.2.4.1 is calculated referring to the manufacturer's specifications of solar PV modules at different solar iradiations.

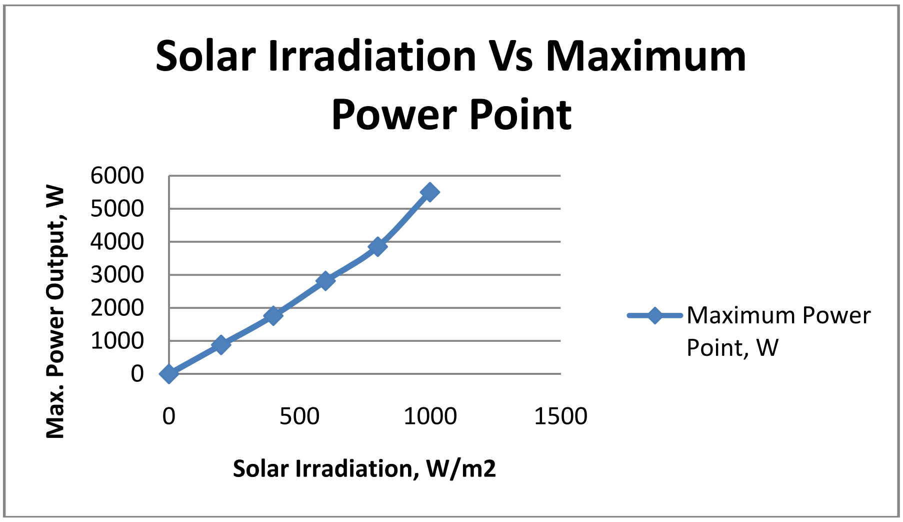

Figure 7.2.4.1Solar Irradiation vs. Maximum Power Point

The power generation from solar PV is calculated considering the figure no 7.2.3.1at a particular solar irradiation level on solar PV panel. This figure is plotted by calculating the maximum power output of the solar PV system considering the manufacturer's specification.

7.3 Analysis of the charging and discharging of the batteries

A 200 Ah, 24V battery bank is used as the main battery bank. Further, a 60Ah, 48 V separate battery bank is used for the 1kW wind mill. The charging and discharging of two battery banks are controlled by two different independent controllers.

The main battery bank is allowed to discharge until 20% of total charge capability. The value 20% is selected so that the nominal terminal voltage of the battery (12V)is not going below 12V while discharging of the battery as shown in figure 7.3.1. Furthermore, it allows the gasifierto work for long time to increase the overall efficiency.

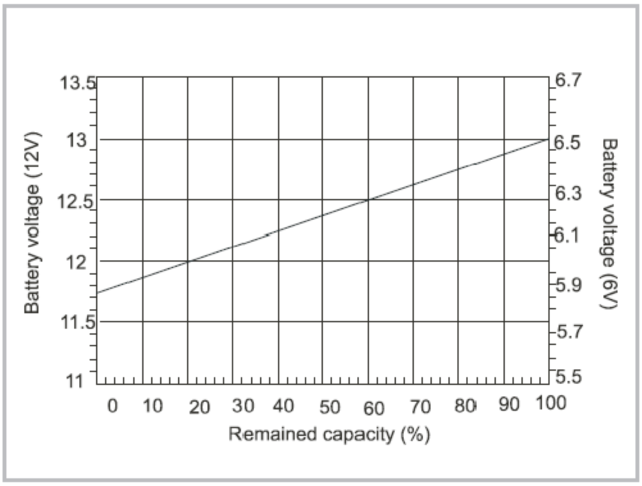

Figure 7.3.1State of Charge of Main Battery BankSource: Manufacturer's specifications of Battery bank

The controller and inverter of the wind module allows a maximum of 80% of the maximum storage capacity of the battery. Then it stops the power flow to the main battery and keeps on charging the battery bank of the wind mill. Further, it restarts the power supply to the main system when the wind mill battery reaches 100%state of charge (SOC).

8 RESULTS

The simulation work is carried out as discussed in the previous chapter. It is based on continuous electricity generation hour by hour. Therefore the energy flow (Wh) is equal to the power delivered (W) at any moment in the graph. The following results were generated for the specific site condition in Stockholm.

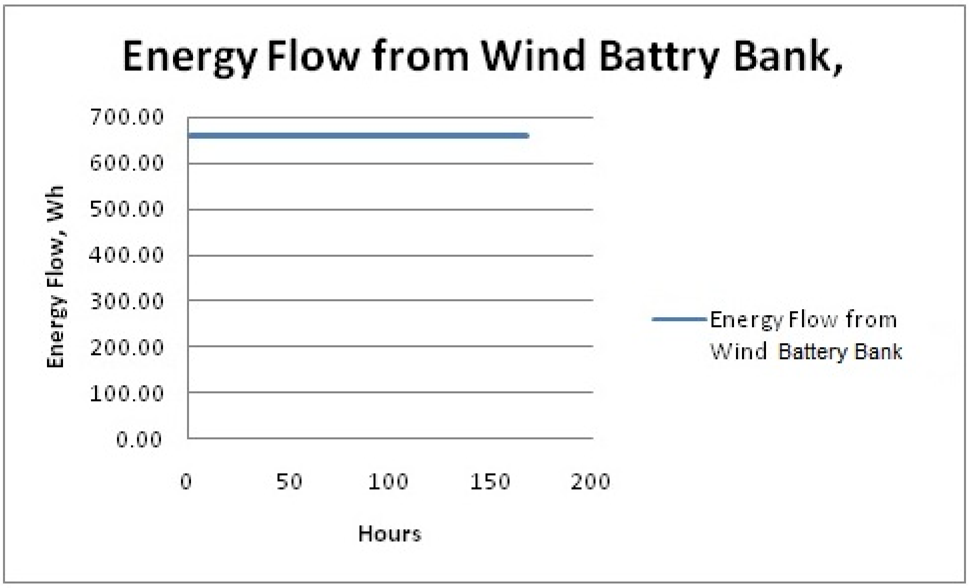

Figure 8.1: Energy delivered from wind module through out the week

It represents the delivered electricity in watts (W) at each hour continuously.

The wind power is changing frequently. Therefore, a separate battery bank is used for the wind mill to increase the flexibility of the electrical system of EEM. The electrical system is designed so that it gives continuous and constant power level to the electrical system. Therefore, it increases the flexibility to interface other electricity generating units to the EEM.

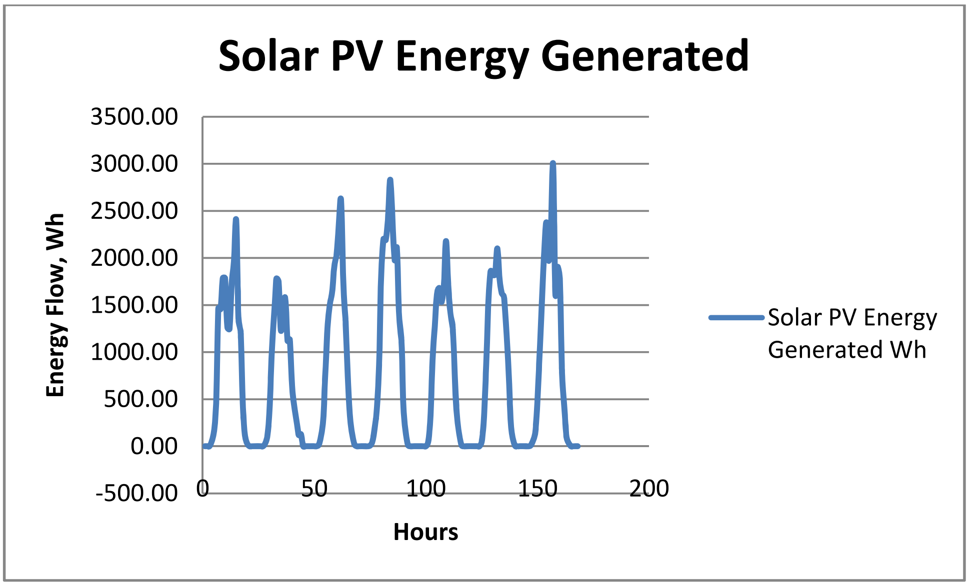

Figure 8.2: Energy delivered from solar module through out the week

The figure 8.2 shows the generated electricity (Wh) from Solar PV system at each hour. The hourly average generated energy is shown for hourly average solar irradiation. The generated electricity from Solar PV depends on the variation of solar irradiation. It can be seen seven peaks in the graph for seven day times of the week. Further, nil points are relevant to dark night times.

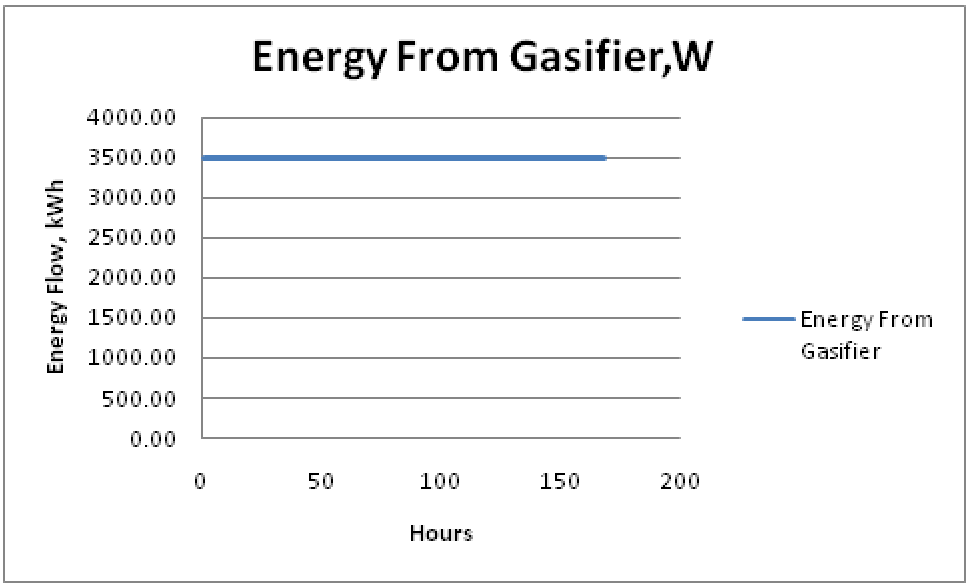

Figure 8.3: Energy delivered from gasifier module through out the week

The figure 8.3 is drawn for hourly average electricity generation. Therefore, even though the instantaneous electricity generation is 3.5kW, the energy flow can be definedas 3.5kWh for a particular hour period. The electricity output from gasifier module can be varied as we required within the specific period of 3kW to 10kW. An optimum power level of 3.5kW for this particular site condition has been selected to maximize the solar and wind energy usage. So, that is why it represents a constant line at 3.5kWh at figure 8.3.

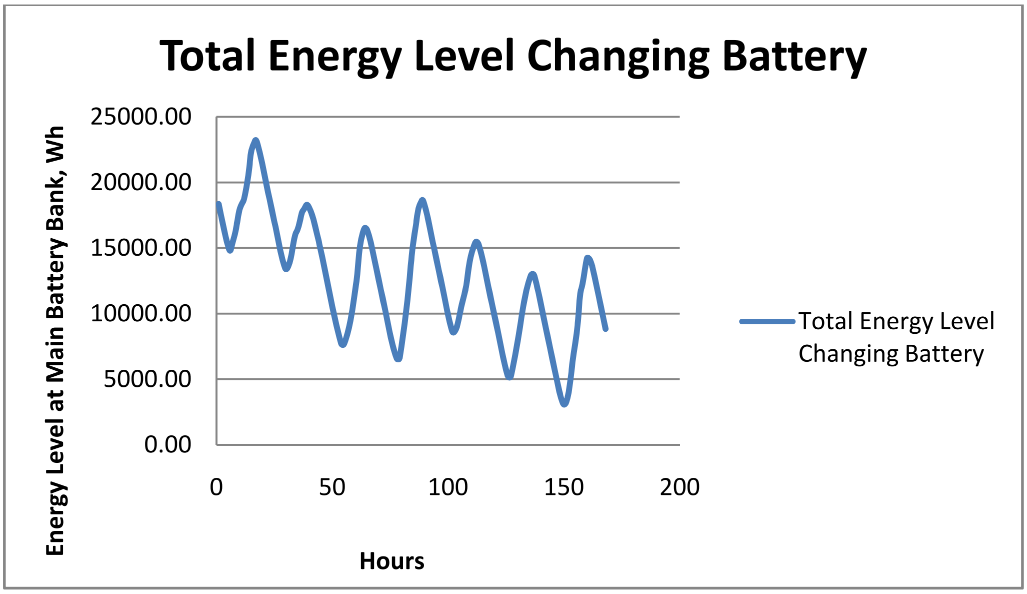

Figure 8.4: Total energy level changing at main battery bank

If the Solar, gasifier and wind cannot meet the energy requirement at any time the aditional requirement is taken from the main battery bank. It represents significant seven peaks at figure 8.4. Those peaks are represented the night or black times. At night the solar irradiation is not available, then the solar electricity generation is significantly reduced. Therefore higher level of enegy is drawn from the main battery bank at that time.

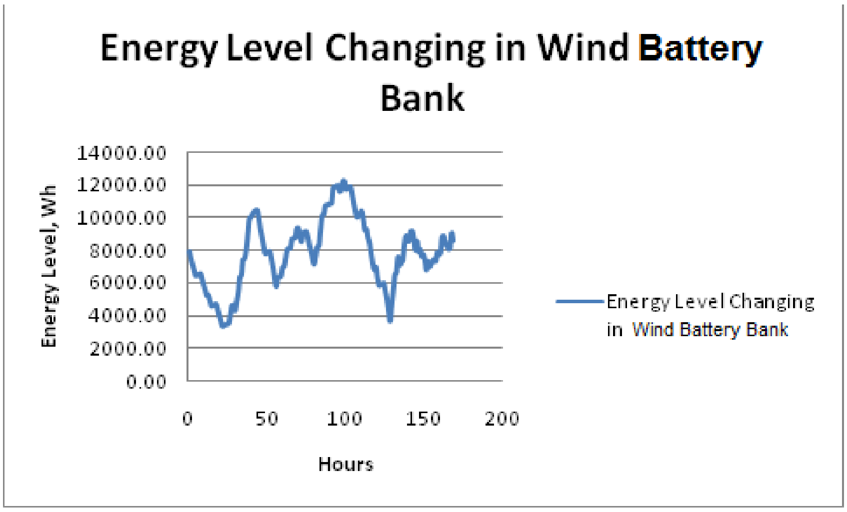

Figure 8.5: Total energy level changing at wind battery bank

The figure 8.5 shows the hourly generated wind energy for hourly average wind speed. There is a frequent fluctuation in energy produced at each hour due to rapid variation of wind speed.

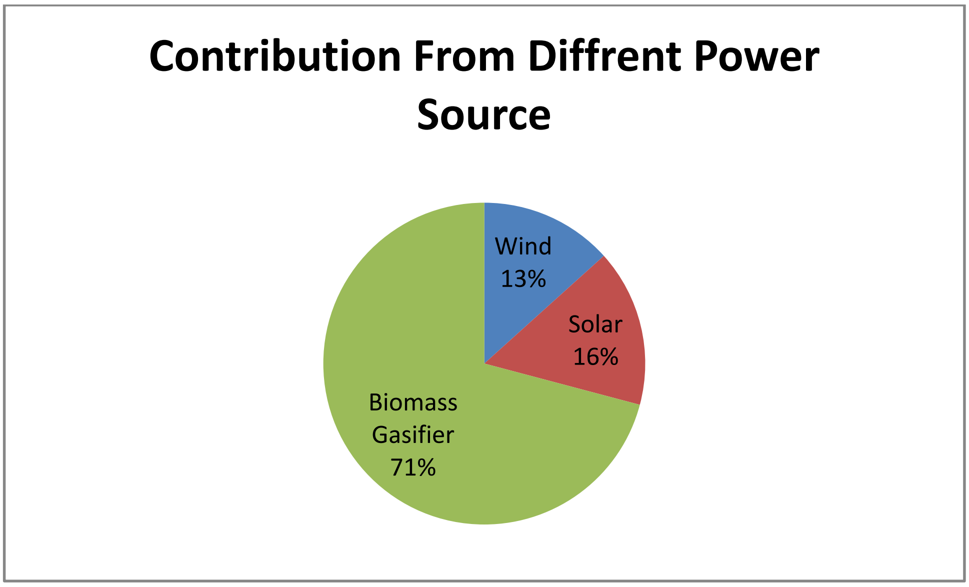

Figure 8.6: Contribution from different power sources for the week

All together the hourly generated electricity (Wh) has been calculatedat each hour for a full week period. It is calculate the total electricity generation from each source and contribution from different sources are shown in figure 8.6.

9 DISCUSSION

An integrated electricity network for an Emergency Energy Module has been designed,comprising Solar, Wind and Biomass based electricity generation. The wind energy level is changing frequently with changing wind speed. Therefore a separate battery bank is kept for the wind system to meet the frequent changing of the wind electricity output and to simplify the system. A constant energy level is taken from the wind battery bank after the calculation of the average energy level of the battery bank.

The gasifier is kept at constant power level of 3.5kW continuously. It simplifies the operation of the gasifier and increases the overall efficiency of the gasifier. The engine efficiency of the gasifier based power generation system has not been taken into account. Only the power requirement has been used. Furthermore, we can increase the overall energy efficiency of the gasifier and EEM by considering the efficiency of the gasifier at different power levels.

The produced electricity from the solar PV system is utilized totally. If there is an excess energy production, then it is stored in the main battery bank.
Increasing the solar PV capacity, wind capacity and battery capacity can minimize the requirement of gasifier power. However, this should be analyzed in economic terms and this is proposed as future work.

Electrical equipment such as Power Router and Generator have beenpurchased without designing the system in detail. Thiswill cause a reduction of the overall efficiency of the system. Designing and implementingthe controller would enablea better control of the sequence of power flow according to the requirement while maximizing the overall performances. Therefore, a sequence of execution for such a controller has been proposed. Thatcan be implementedin future development.

Since the functionality of the controller for the wind turbine is not given, it should be analyzed before the installation. Another future work would be to analyze the conversion efficiency of the controller. For now,it is assumed that the total generated wind power is sent to the battery by force to simplify the simulation.

An important observation was that the real wind speed was always below the cut-in wind speed of the wind mill. Therefore it is multiplied the actual site data by factor of ten (10) for the analysis.

It is necessary to accommodate the main battery bank of 800Ah, 24V and the wind power battery bank of 180Ah, 48V for maximum utilization of wind and solar energy and to optimize the operation of the gasifier.

10 CONCLUSIONS

Actual site data of solar irradiation and wind speed have been used for the simulation works.

This simulation work has beencarried out assuming that the systemsupplies its maximum power capacity of 5kW continuously. In reality the load is changing over time. Therefore, there will be excess energy in the system. The amount of energy produced,can be controlled by changing the power level of the gasifier engine and by increasing the battery capacity.

According to thesite conditions, the biomass based gasifier should work steady at 3500 W capacity, but for the different sites with different solar and wind conditions this can be different. The desired power levelcan be found by using the simulation worksheet. It can be adjust to any site conditions just by varying the power level.

The only controllable power source is the biomass gasifier. Solar and wind based power generations are dependent upon the site conditions. Therefore, the target is to get all the power generated from wind and solar and to minimize the operation of the gasifier.

The design challenge of an electrical power system of the EEM, is to integrate solar, wind, gasifier based power generation modules, battery bank and loads together. Such anintegration of those components as well as an estimation of the optimum capacity of the battery bank and gasifiershould be carried out as future development.

11 APPENDIX

11.1 Manufacturer's Specifications of Main Battery Bank

Model	:	CT200-12
Nominal voltage	:	12 V
Number of cells	:	6
Nominal capacity +25˚C		
20 hour rate (10 A - 10,5V)	:	200 Ah
10 hour rate (19,6 A - 10,5V)	:	196 Ah
5 hour rate (36,7 A - 10,5 V)	:	183,5 Ah
1 hour rate (138 A - 9,60V)	:	138 Ah
Internal resistance	:	3 mOhm

Self-discharge 3% of capacity decline per month at +20° C
Operating temperature range
Discharge -20 to +60° C
Charge -10 to +60° C
Storage -20 to +60° C

Max discharge current (5 sec)	:	1000 A
Short circuit current	:	3500 A
Max. charge current	:	60 A

Charging methods at +20°C
- Cycle use
  - Constant voltage charge 14,4 - 14,7 V
  - Temperature compensation -30 mV/° C
- Stand-by use
  - Constant voltage charge 13,6 - 13,8 V
  - Temperature compensation -20 mV/° C

11.2 Manufacturer's Specification of Gasifier

GEK POWER PALLET SPECS	10 kW	20 kW
Power Output	3-10 kW	5-20 kW
Biomass Consumption	12 kg / 26 lbs per hour at 10 kW	22 kg / 50 lbs per hour at 20 kW
Fuel Moisture Tolerance	Up to 30%	Up to 30%
Shipping Dimensions	1.2m x 1.2m x 1.8m 48" x 48" x 72"	1.2m x 1.3m 1.8m 51" x 52" x 72"
Weight	499 kg / 1100 lbs	658 kg / 1450 lbs

11.2.1 Type of fuel used in Gasifier Module

FUEL TYPE	WILL IT WORK	HOW WELL	COMMENTS
Hardwood Chips	Yes	Excellent	1/4" to 2" (10mm – 50mm) chips
Softwood Chips	Yes	Excellent	1/4" to 2" (10mm – 50mm) chips
Nut Shells	Yes	Excellent	Needs least preparation
Coconut Shell	Yes	Excellent	Broken into chunks
Coffee Grounds	Yes	Fair	Pelletized
Sawdust	Yes	Fair	Pelletized
Corn Cobs	Yes	Fair	Broken into chunks
Manure	Yes	Fair	Dried to 30% moisture
Rice Husks	No		Under development
Straw	No		Under development
Sugar Cane Bagasse	No		Under development
Corn Stover	No		Under development
Poultry Litter	No		Under development

11.3 Manufacturer's Specification of Solar PV Panels

Item	Characteristic
STC Power Rating P_{mp} (W)	250
Open Circuit Voltage V_{oc} (V)	37.2
Short Circuit Current I_{sc} (A)	8.24
Voltage at Maximum Power V_{mp} (V)	30.2
Current at Maximum Power I_{mp} (A)	7.26
Panel Efficiency	14.2%
Fill Factor	75.0%
Power Tolerance	-3.00% ~ 3.00%

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