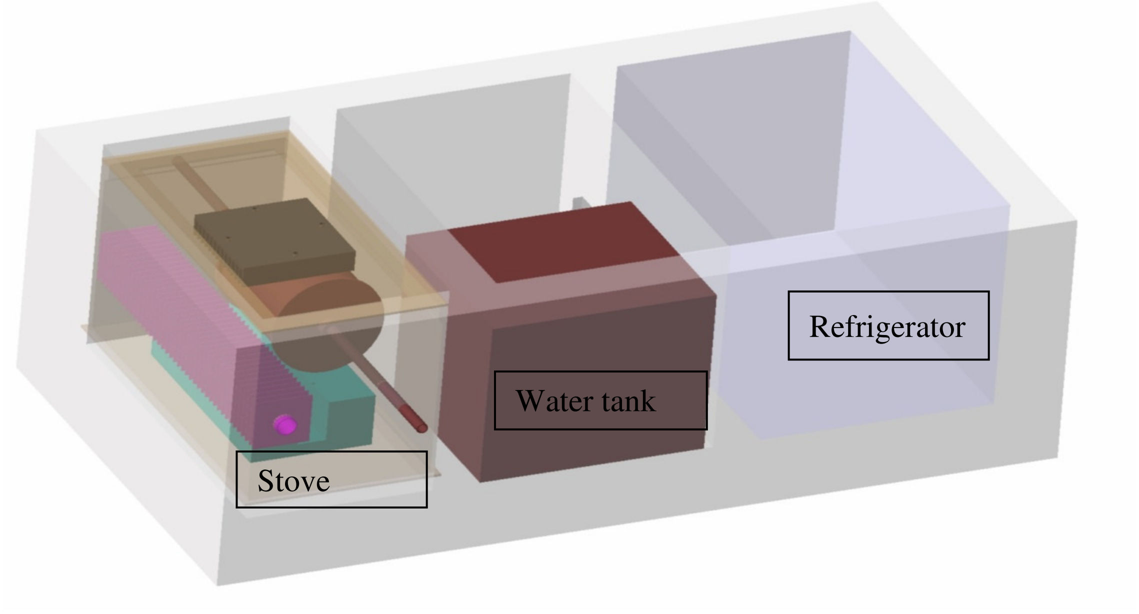

Feasibility study of low voltage DC house and compatible home appliance design

Master of Science Thesis [Electric Power Engineering]

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2011

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Cover:
A combined refrigerator & stove unit with different parts marked out in exploded view
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Abstract

In this work a low voltage direct current (DC) distribution system for a house or an apartment have been investigated. The feasibility of the low voltage DC systems for a home is investigated by evaluating the advantages and disadvantages with respect to the existing alternating current (AC) system of homes. The goal is to make a energy efficient system that would be able to cope with local electricity generation and storage systems at the end-user level, from DC sources. Data obtained from measurements of power consumption for different household appliances such as refrigerator, microwave oven, rice cooker, dish washer etc. have been used to evaluating the systems. The performance of the 230V AC system and the proposed low voltage DC system is analyzed by considering factors such as losses in the wire, internal loss of the device itself, investment cost for new wiring and energy consumption cost. From the investigation, it can be concluded that the 48 V DC system with optimized cable area is most economical system compared with the 230 V AC system and with a 20 years life time, it will save almost 13000 SEK.

In the case of a low voltage DC distribution system, there is a problem with high power loss in the feeder for high power consuming loads. The stove is one of the high power consuming kitchen appliances and it consumes large amount of energy. This project focuses on an efficient stove design for a low DC voltage supply. To decrease the energy consumption of the stove, the idea is to combine it with the refrigerator. The heat extracted from the refrigerator is stored both in the stove, to be used for cooking and in a water tank to be used for other purposes, for example providing hot water to a dishwasher. Two individual thermoelectric modules (TEM) are used for the refrigerator and the stove. A water tank is used in the middle of the refrigerator and the stove unit. Some parts of the extracted heat from the refrigerator, is stored in paraffin inside the stove and the remaining parts of that extracted heat is stored in the water tank by raising its temperature. The calculated efficiency of the refrigerator unit is 54%, the efficiency for heating up the water by storing the extracted heat is 154% and for storing heat in the paraffin is 134%. The stored heat in the water tank has the possibility to supply other devices such as a dishwasher with hot water. This would reduce the peak energy consumption of the dishwasher since it does not need to heat the water by using electricity in this case. The prototype was tested together with a dishwasher that runs on a low DC voltage and the peak power consumption was reduced by supplying hot water from water tank. The overall efficiency of the system was increased by storing the extracted heat from the refrigerator unit in a latent heat storage using paraffin and in a water tank.

Keywords: Low Voltage DC, DC households, AC system, DC system, DC Refrigerator, DC Stove, Thermoelectric Module.

Preface

This thesis was offered by CIT (Chalmers Indutriteknik), CIT is a foundation founded by Chalmers, providing knowledge on commercial terms. CIT has issued this master thesis based on a low-voltage DC distribution system for houses. This project aimed to develop solutions of energy storage in household devices connected to the system. This thesis focuses on new product concepts to be used in a low voltage DC system within a house or apartment.

In this master thesis, a prototype of a combined refrigerator and stove unit was modeled to find out a new solution for the existing AC power consuming refrigerators and stove. This unit can be connected directly to the DC system without any internal conversion inside the device. The performance of the new DC solution is compared with the existing one in terms of power consumption and losses. This work also investigated losses, investment cost of new wiring, energy consumption costs in a home area network for both a low voltage DC system and the existing 230V AC system. The results are analyzed for long run in terms of saving money and energy.

This project work comprised of two team's work where another team worked on the dishwasher to find out new solution that will operate with low DC voltage. Finally these two works were integrated and tested as a complete system. The overall efficiency of the whole system is increased by using the extracted heat from the refrigerator to the stove and the dishwasher.

Acknowledgement

This master thesis has been carried out at the Division of Electric Power Engineering in the Department of Energy and Environment, Chalmers University of Technology, in cooperation with CIT (Chalmers Indutriteknik).

We greatly acknowledge the support of our supervisor, Dr. Stephan Mangold, Project Leader, Commercial Research and Development, Stiftelsen Chalmers Industriteknik during this master thesis project with precious guidance and many good advices.

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Yasir Arafat
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Gothenburg, March 2011

Contents

1. Introduction

1.1 Problem background

During the beginning of the nineteenth century the debate between alternating current (AC) and direct current (DC) had started [1]. Tesla showed the practical advantages of alternating current. Transformers made it possible to step up an AC voltage easily, this allowed power to be transmitted over long distances with a low loss. This was not easy to achieve with Edison's DC voltage and there were huge transmission losses. Tesla's practical results were the deciding factor, at least for the time being that an AC system was to prefer [1]. This debate again came into light due to recent development in power electronics [2] which gives a better utilization of existing transmission corridors with high voltage DC connections. High voltage DC transmission allows more power to be transmitted over a long distance with less losses compared to an AC transmission. Power electronics makes efficient and accurate control of electrical power possible. Efficient AC to DC, DC to AC and DC to DC conversion technology are now available on the market, where DC to DC conversion is more efficient than AC to DC conversion [3].

The number of devices that operate on DC continues to increase in both homes and offices. Most of the devices are using DC internally and this requires AC to DC conversion between the AC supply and the DC side of the device. Examples of these devices are PCs, radios, televisions, telephones and other electronic appliances. Energy storage devices such as batteries, mobile phones, and cordless tools, also require direct current as an energy source. They are equipped with adapters which convert 230V AC into low voltage DC [4]. The use of variable-speed motors of all sizes are increasing day by day and they also requires AC to DC conversion first and then a DC to AC conversion to obtain a AC voltage with variable frequency and magnitude [4]. All of these AC to DC conversions have losses [5].

In case of small-scale electricity generation, such as almost all new sustainable energy sources, for example from solar cells, fuel cells, osmosis batteries, and others, DC is usually the output. Energy is required to convert the source's DC into AC in order to connect to the existing 230V AC distribution network. Which further needs to be converted back to low voltage DC inside the DC power consuming apparatus. This results in a low overall efficiency of the AC system.

1.2 Low Voltage DC as a solution

By using a low voltage DC distribution network in the residence, AC to DC conversions losses can be omitted and the use of comparatively less efficient adapters can be discarded and also there will be no power factor issues [7]. Only highly efficient DC to DC converter will be needed to run some of the DC appliances. DC distribution within the home can probably also drastically reduce the number of appliance cords and also give release from keeping track of which adapter belongs to which device. A DC distribution network in the residence will facilitate to reduce the electro-magnetic interference and also the line losses due to the absence of reactive power [6][8], less current will be needed to transfer the same amount of power. Losses for distribution of electricity are mainly dependent on the current magnitude and the cable length. For safe use of DC voltage without specific insulating precautions, the voltage must not exceed 50 V [4]. The majority of the devices used in households or offices only require low power that are possible to be connected directly to the low voltage DC distribution system after removing the AC to DC conversion stage. Most of the commercially available appliances are designed with an input voltage of 12V and 24V and some of the appliances are available at input voltages of 48V [7]. As the low voltage DC appliances have demand of higher currents, it makes feeder losses considerable. As a result the overall efficiency of the appliance becomes low. Feeder losses can be decreased by using higher DC voltages and the chosen appliance voltage for a DC residence is 48V [7]. Application of DC can therefore be more advantageous.

There are some appliances with high power consumption during a short period of time where a battery can also give supply to these devices to remove the peak of the load. Low voltage application for high power consuming devices has a problem of high power losses in the feeder. Kitchen appliance such as the stove consumes high power. If the devices are supplied by low voltage then they will take more current. To decrease the energy consumption of the stove, the idea is to combine it with the refrigerator. The heat extracted from the refrigerator is stored in the stove and is used for cooking or other purposes. To run the refrigerator and stove efficiently on low voltage, this project investigated a combined refrigerator and stove unit.

DC application has some limitations. Fault currents in DC distribution systems are comparatively higher than in AC distribution systems due to the absence of limiting self inductance [11]. Problem can arise during switching of DC circuits [12]-[14] and hence special consideration is required for interruption of DC. Interruption of a DC arc is more difficult than interruption of an AC arc due to absence of zero current crossing for the DC current. The arc is cleared by increasing the voltage to a point at which the arc is unstable and where the conductivity of the arc is low [11]. DC system in open air has a typical problem of corrosion and the corrosion problem is comparatively larger than in AC system [11]. Several factors have increased the recent interest in DC power system. According to [4], one of them is the increasing number of microprocessor based electronic devices which use DC power internally. Another factor is the increasing number of distributed resources such as solar photovoltaic arrays and fuel cells which produce DC power and batteries or other technologies store it in DC form. Batteries of plug-in hybrid vehicles (PHEV) store DC power, which is coming more in near future. Less complicated conversion system with less waste heat of DC distribution network would result in lower maintenance requirement, longer life of system components and lower cost of operation. Moreover, solid state switching can quickly interrupt the faults in DC distribution system and results in better reliability and power quality. Edison may be proven as winner after more than a century [4].

1.3 Purpose

This project investigates the feasibility of using a low DC voltage for the distribution system in houses. In this work, 48V DC is used due to the fact that the user can handle this voltage level without any problem. This DC voltage can come from different sources such as a large central rectifier that converts 230VAC to 48V DC or/and renewable energy sources such as solar cells and batteries. A low DC voltage wiring system of a house is investigated and compared with the wiring of the traditional 230V AC system to observe the economical impact in terms of losses in the cable and cost of installation for long run.

Most of the household appliances use DC internally except some appliances such as stove, refrigerator, and microwave oven. Resistive loads can run on DC supply easily. This work also investigated on DC solution for some major AC power consuming devices to run all the home appliances from low voltage DC outlets at home. The main goal is to reduce the energy consumption by using low DC voltage. As the stove consumes high power, thermal energy storage was investigated for the stove to reduce the peak power consumption of the stove. A completely new model of combined refrigerator and stove unit is analyzed and designed in this project to run on a low DC supply. The idea is to store the extracted heat of the refrigerator in thermal energy storage in the stove. Two thermoelectric modules are used for this unit. The thermoelectric module (TEM) creates temperature difference between the sides of it by extracting heat from one side to the other side when it is supplied by electric power. The refrigerator side TEM extracts heat from the refrigerator and transmit it to a water tank. The Stove side TEM is capable of extracting some energy from the extracted heat of refrigerator and the remaining energy is stored into the water. To store the extracted heat from the stove side TEM, paraffin is used, which has the capability of latent heat storage by changing its phase from solid to liquid at 100°C.
Another group working in parallel with this project investigated a system for the dishwasher to run on low DC voltage. The refrigerator, stove and dishwasher units are proposed as a combined unit which has inter related functionality. The other group of this project work investigated on dishwasher to run on low DC voltage. Energy consumption of the dishwasher is reduced by using hot water from the combined stove and refrigerator unit. Main expected benefit from this system is the increased overall efficiency of the system. Storing extracted heat from the refrigerator into the water and the paraffin, helps to increase the overall efficiency.

2. Feasibility of the low voltage DC distribution system for houses

In this chapter, the energy consumption, losses and the voltage drop across the feeder cable for different household appliances are calculated for a 230V AC distribution system and for the proposed DC distribution system with different voltage levels, 24V and 48 V. The losses in the household appliances [26] and in the distribution system is an important issue in the context of energy saving. Electronic appliances such as TV, DVD, Personal Computer, Laptop, etc. operate internally on DC. Some appliances need variable output frequency e.g., in a machine drives. They convert AC to DC and DC to variable frequency AC by Power Electronics Converters. The energy conversion from AC to DC involves inherent energy losses. The electronics appliances that operate on a low DC voltage need a step down transformer which consumes some energy, even when the appliances are not performing its primary function in standby mode [27]. The energy conversion losses and the standby losses can be minimized by using a DC system. To demonstrate the difference between AC and DC system, Energy consumption and losses are calculated for some common household appliances for the existing AC system as well as different systems with low DC voltage.

2.1 The investigated household and appliances

Earlier household appliances mainly relied on three sources of energy- electricity, natural gas and fuel oil [15]. Nowadays most of the households are designed based on only electricity as energy source. It makes the life comfortable, easy and enjoyable. Figure 2.1 shows a wiring diagram of a house. The high power consuming appliances such as stove, microwave oven, dish washer, rice cooker, coffee maker etc. are located in the kitchen. The Laundry appliances are also high power devices. The wiring of a house is done in such a way that main power supply is kept close to the high power devices.

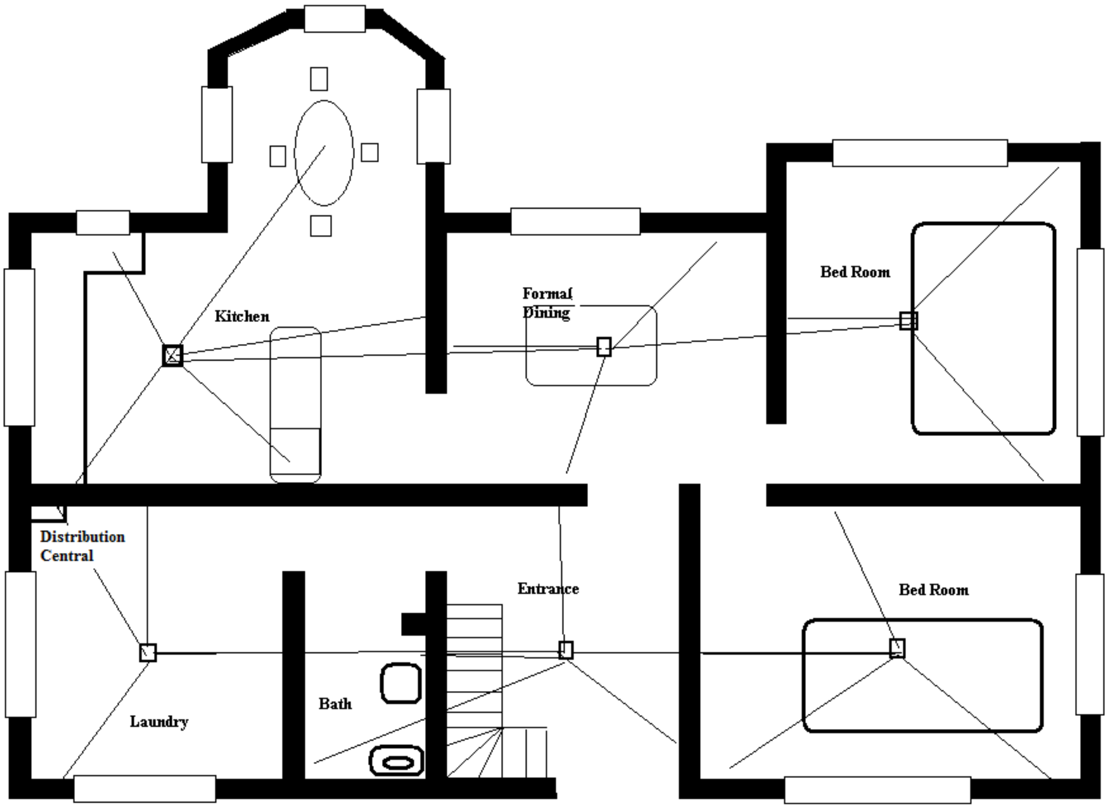

Figure 2.1 Wiring diagram of a house.

The length of feeder cables in a house depends on the size of the room and power rating of the appliances. The feeder length for the different loads varies between 12 m and 80 m [20]. In this investigation feeder length is selected as an average length. For the appliances whose power rating less than 200 W, feeder lengths is considered 50 m (phase and neutral) and feeder length is 20 m for the appliances with power rating greater than 200 W. The feeder length of the refrigerator is 20 m as it is located in the kitchen. Conductor area of the feeder is selected according to the Table 2.1.

Table 2.1 Current rating of Cables [21]

core size, mm^2	current (A)	wattage at 240v (kW)
1.0	14	3.25
1.5	18	4.25
2.5	24	5.75
4.0	32	7.75
6.0	40	9.75
10	53	12.9
13.3 [33]	101	--------

2.1.1 Investigated loads

Examples of household appliances that is used in daily life can be found in [16]-[18] with their ratings. The most significant energy consuming appliances are electric space heating (in cold country e.g. Sweden) or air conditioning (in warm country) and the refrigerator. Kitchen and laundry appliances accounted for about one-third electricity consumption in US [15]. Refrigerator is the biggest energy consuming device in kitchen appliances [15]. Microwave oven, stove, coffee machine, dishwasher etc. also consume large amount of energy. Incandescent lamps are used for lighting in both indoors and outdoors [22] which are highly inefficient as 90% is lost as heat [15]. Home electronics e.g. TV, DVDs, Computer runs on DC voltage internally. Most of the digital systems operate on DC. It necessitates converting the AC voltage to DC voltage. The devices which are selected to be studied are mainly household devices that are needed in our daily life. Number of appliances in a house is different. In this study, the kitchen appliances and electronics appliances are investigated. Appliances with different power ratings are available in the market [16]-[18]. The investigated devices are refrigerator, stove, microwave oven, rice cooker, coffee maker, dish washer, washing machine, light bulb, vacuum cleaner, iron, window unit AC, laptop, personal computer, external modem and 32” LCD television. The power rating of the investigated loads are in the range of 7 W to 2000 W. The on-duration of household appliances is obtained from a survey in some houses in Bangladesh and Sweden. The running hour of the appliances varies from house to house, season to season and country to country. For example, some houses use the washing machine for less than 50 cycles in a year and some houses use it for more than 750 cycles per year [22]. The uses of washing machine are 230 cycles per year in average [22]. For lighting, the bulb is on more than 12 hours during winter and during summer it is not on for that long time. In Bangladesh people use the stove more than 2 hours in a day, in Sweden it is less than 1 hour. Table 2.2 shows the power rating, standby power, feeder length and on-duration in a day of the investigated appliances. It is obtained that the dishwasher runs for 200 cycles per year and the washing Machine runs for 230 cycles per year [22].

Table 2.2 The investigated appliances and the power rating, feeder length and estimated on time per day

Product name	Power W [16]-[18]	Standby power W [23]-[28]	Current at 230 V AC A	Wire length m	On duration in a day
Light bulb	60	------	0.26	50	12 hrs
	100	-------	0.435	50	
Microwave oven	800	2.8	3.49	20	1 hr
Induction Stove	2000	--------	8.74	20	1.5 hrs
Rice cocker	500		2.18	20	0.75 hr
Coffee maker	990	---------	4.323	20	0.5 hrs
Refrigerator	125	10	0.544	20	12 hrs
Dishwasher	1500	1.2	6.56	20	0.55 hr (200 cycle per yr)
Washing machine	500	2	2.17	20	0.95 hr (230cycle)
Vacuum cleaner (200-700W)	300	------	1.30	20	2 hrs in week
Iron	1000		4.37	20	3 hrs in a week
Window unit AC	900	6	3.91	20	12 hrs
Laptop	50	4.5	0.22	50	7 hrs stand by 5hrs
CPU & LCD monitor	270	3.5	1.17	20	5 hrs
External modem	7.2	1	0.031	20	5 hrs
32" LCD television	156	4.5	0.68	50	5 hrs

The standby losses of the appliances vary for different appliances from different producer [9][10]. For the calculation of standby losses, the data of standby power is taken from [23]-[28].

A microwave oven is a kitchen appliance that is used to cook or heat food. The input voltage and current for a 800 W microwave oven were measured for 3 different power modes with the observation time 3 minutes. For 800 W input power mode, the microwave oven took 800 W power continuously. At 650 W mode, it took 800 W power for 81% of the total time and average power was 650W. For the 450 W power mode, it took 800 W for 56 % of total time and the average power was 450 W. The Figure 2.2 shows the measured voltage, current and power of the microwave oven.

The RMS value is calculated from the measurement as

$$X_{RMS}(t) = \frac{1}{T_s} \int_{t-T_s}^{t+T_s} x(\tau) d\tau \tag{2.1}$$

And the power as

$$P(t) = \frac{1}{T_s} \int_{t-T_s}^{t+T_s} u(\tau)\, i(\tau)\, d\tau \tag{2.2}$$

For the 800 W mode the RMS voltage was 230 V, the current 3.4 A and the power 795 W.

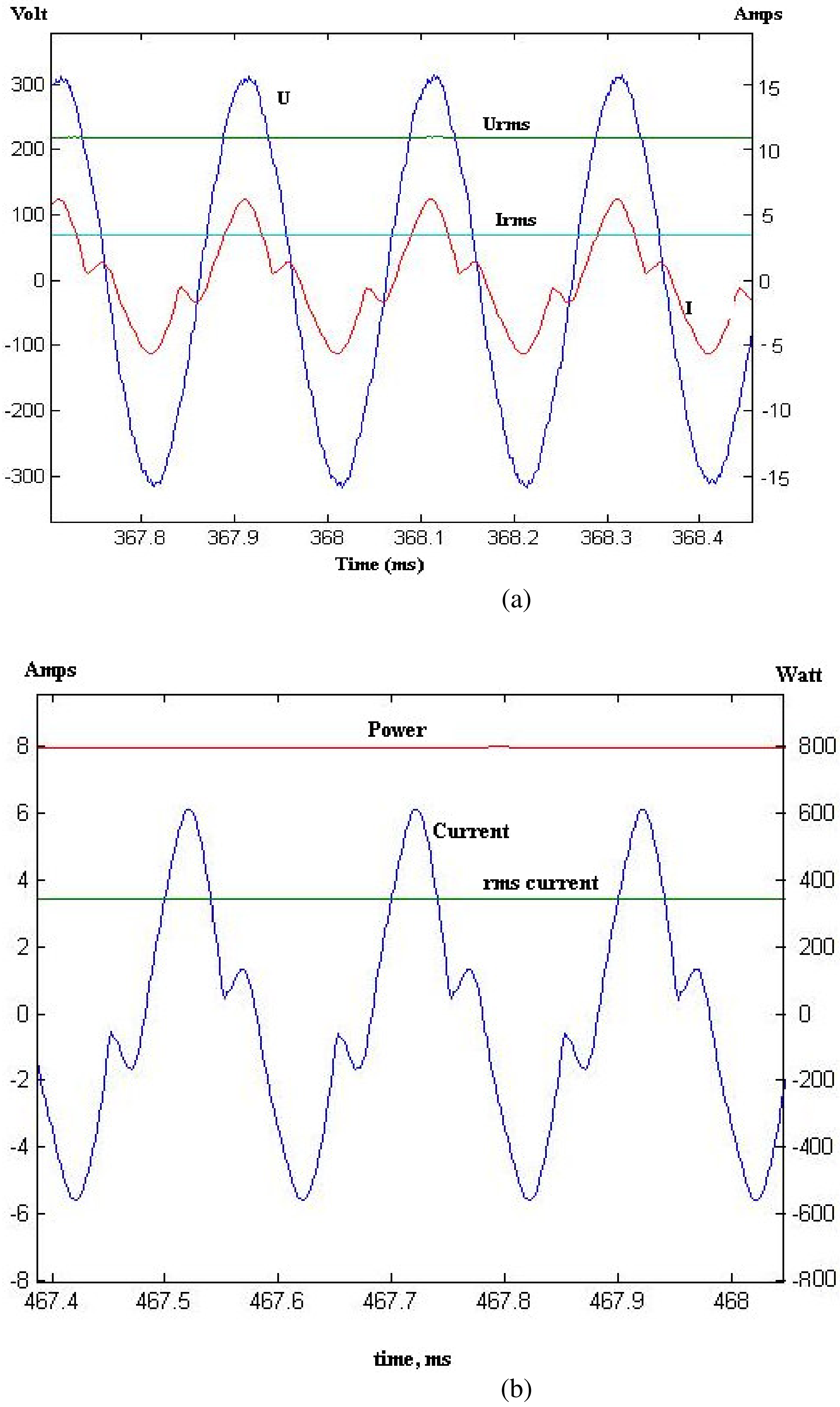

Figure 2.2 Measurement on a microwave oven for 800 W operation mode (a) AC input voltage and current, (b) Current and Power.

The first technology used resistive heating coils for the electrical stove. Now induction stoves are using which heat the cookware directly through electromagnetic induction and require pots and pans with ferromagnetic bottoms. From the survey, on-duration of electric stove is 1.5 hrs per day. A Rice cooker is a resistive load. It consumes power at a constant rate. The power rating of the rice cooker measured in the lab was 500 W and on-duration is 0.75 hrs per day. A coffee maker is also a resistive load and the on-duration in average is half an hour per day. It consumes constant power when the heater is on. For the coffee maker measured on, the power consumption is 990 W. The compressor of a refrigerator does not operate for 24 hours in a day. For the refrigerator measured on in this work, the compressor was on for 12 hours and was left off for 12 hours. When the compressor is operating, it is taking 125W in average and 10W when it is off. The speed of the compressor's motor is controlled by varying the frequency [29]. The LCD monitor consumes power depending upon operation of the personal computer. In this measurement it takes 44 W when a video is playing, and it takes 41 W without any video playing. Figure 2.3 presents the current and voltage wave shape of a monitor.

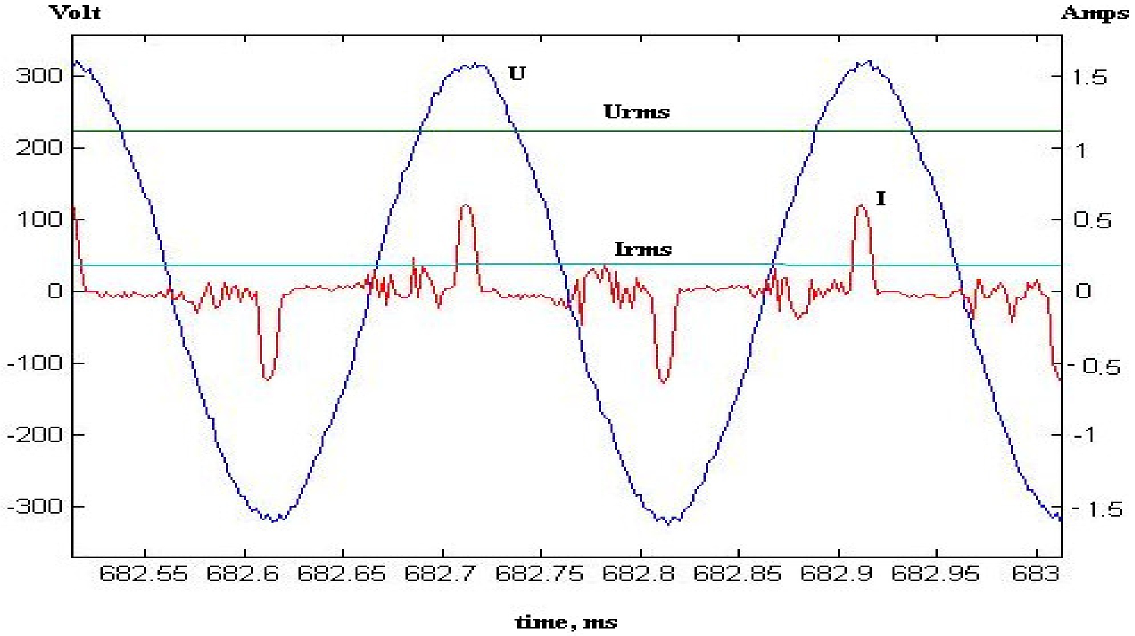

Figure 2.3 AC input voltage and current measurements for a LCD monitor

2.2 The 230 volt AC House

2.2.1 AC distribution system for the house

The Figure 2.4 shows a scheme of 230 volt AC system including distributed generation sources and sensitive loads. The DC power sources such as solar cell, fuel cell can be connected with the AC distribution system of a house. For solar cell and fuel cell, a DC to AC converter is required in this power system. Utilizing solar energy in this way involves two stages of energy conversion and wind energy (micro turbine) needs three stages of energy conversions with inherent energy losses. For the micro turbine, a full scale frequency converter is needed to connect with the AC bus. For the sensitive loads, uninterruptable power supply (UPS) is required. The efficiency of dc-ac inverter is up to 85% [19]. There are some losses in this conversion. These losses could be minimized by introducing DC grid.

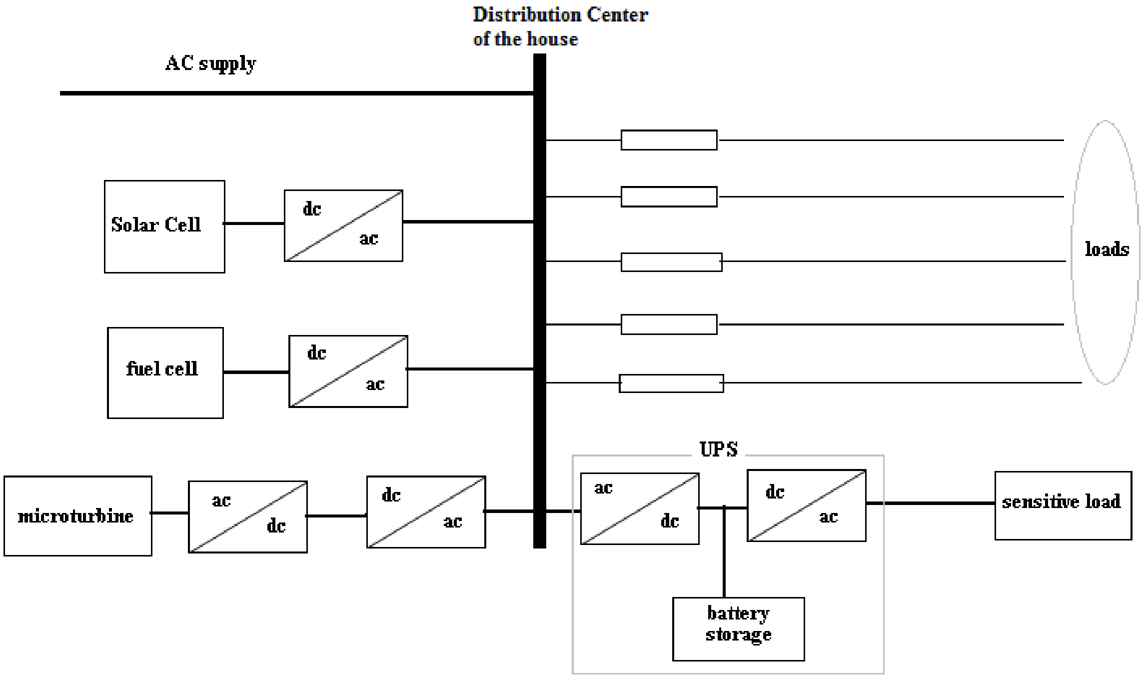

Figure 2.4 Scheme of 230 Volt AC system including distributed generation sources and sensitive loads.

The losses and voltage drop over the feeder cable can be calculated for a single phase load by using the circuit in Figure 2.5.

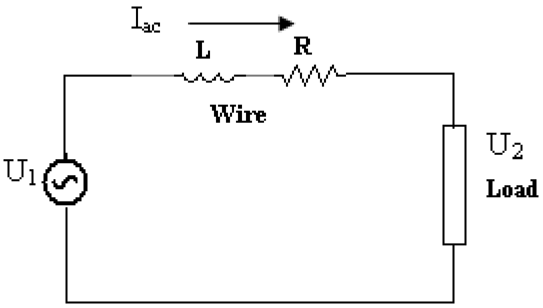

Figure 2.5 simple AC circuit

The voltages in the circuit can be calculated by using the phasor diagram method.

$$\underline{U}_1 = \underline{U}_2 + (R + jX)\underline{I}_{ac} = \underline{U}_2 + \underline{Z}\,\underline{I}_{ac} \tag{2.3}$$

where $\underline{U}_1$ is the RMS voltage at the distribution central of the house. $\underline{I}_{ac}$ is the current in the circuit and R is the resistance of the cable, $X = 2\pi f L$ is the reactance of the cable. L is the cable inductance and f is the grid frequency.

If the load voltage $\underline{U}_2$is selected as reference phasor the current can be expressed as

$$\underline{I}_{ac} = |\underline{I}_{ac}|\cos\varphi - j\,|\underline{I}_{ac}|\sin\varphi \tag{2.4}$$

where φ is the angle between the load voltage and the current.

The voltages can be expressed as

$$\underline{U}_1 = \underline{U}_2 + (R + jX)\left(|\underline{I}_{ac}|\cos\varphi - j\,|\underline{I}_{ac}|\sin\varphi\right) \tag{2.5}$$

$$\underline{U}_1 = \underline{U}_2 + \left(R\,|\underline{I}_{ac}|\cos\varphi + \mathrm{X}\,|\underline{I}_{ac}|\sin\varphi\right) + \mathrm{j}(\mathrm{R}\,|\underline{I}_{ac}|\sin\varphi - \mathrm{X}\,|\underline{I}_{ac}|\cos\varphi) \tag{2.6}$$

The active power consumed by the load is $P_2 = |\underline{U}_2|\,|\underline{I}_{ac}|\cos\varphi$ $(2.7a)$

And the reactive power$Q_2 = |\underline{U}_2|\,|\underline{I}_{ac}|\sin\varphi$ $(2.7b)$

this gives

$$\underline{U}_1 = \underline{U}_2 + \frac{RP_2 + XQ_2}{|U_2|} + j\frac{XP_2 - RQ_2}{|U_2|} \tag{2.8}$$

Since many of the investigated loads are operating with unity or close to unity power factor at least the high power consuming loads, unity power factor is used for all loads in this work. Unity power factor means that$Q_2 = 0$, this gives that the load voltage can be calculated as

$$\underline{U}_1 = \underline{U}_2 + \frac{RP_2 + jXP_2}{|U_2|} = \underline{U}_2 + \frac{\underline{Z}P_2}{|U_2|} \tag{2.9}$$

$$|U_1||U_2| = |U_2|^2 + \underline{Z}P_2$$

$$|U_2|^2 - |U_1||U_2| = \underline{Z}P_2$$

$$|U_2| = \frac{|U_1|}{2} \pm \sqrt{\frac{|U_1|^2}{4} - |\underline{Z}|P_2} \tag{2.10}$$

$$Voltage\ drop = \frac{U_1 - U_2}{U_1} \times 100\ \% \tag{2.10a}$$

And the current as

$$|\underline{I}_{ac}| = \frac{P_2}{|U_2|} \tag{2.11}$$

The losses in the feeder cable is calculated as

$$P_{loss} = R|\underline{I}_{ac}|^2 \tag{2.12}$$

The resistance of the feeder cable can be calculated as

$$\mathrm{R} = \rho \frac{l}{A} \tag{2.13}$$

Where $\rho = 1.7 \times 10^{-8}\ \Omega m^{-1}$ is the resistivity for copper, l is the length of the feeder and A is the area of the feeder. The inductance can be calculated by assuming that the phase and neutral feeder conductors two parallel uses as [11]

$$L = 0.05 + 0.2\, ln\frac{d}{r} \quad [\mu\mathrm{H/m}] \tag{2.14}$$

where, r is the radius of wire and d is the separation between phase and neutral. From equation it can be noticed that the inductance varies with the distance between the two conductors. Normally PVC pipes are used in house wiring. The distance between the two conductors inside the PVC pipe varies at different positions. The variation of inductance is investigated inside a PVC pipe with an inner diameter of 13 mm and outer diameter of 16 mm. The variation of inductance for wires with different cross sectional area is shown in Figure 2.6. It can be observed from the figure that the wire of cross- section area of 10 mm^2 has the lowest inductance compared to the other cables with lower cross section area. In the case of a 1.5 mm^2 cable, the variation of inductance inside the PVC pipe is between 0.12 to 0.58 μH whereas for the wires of 10 mm^2, it is between 0.07 to 0.26 μH.

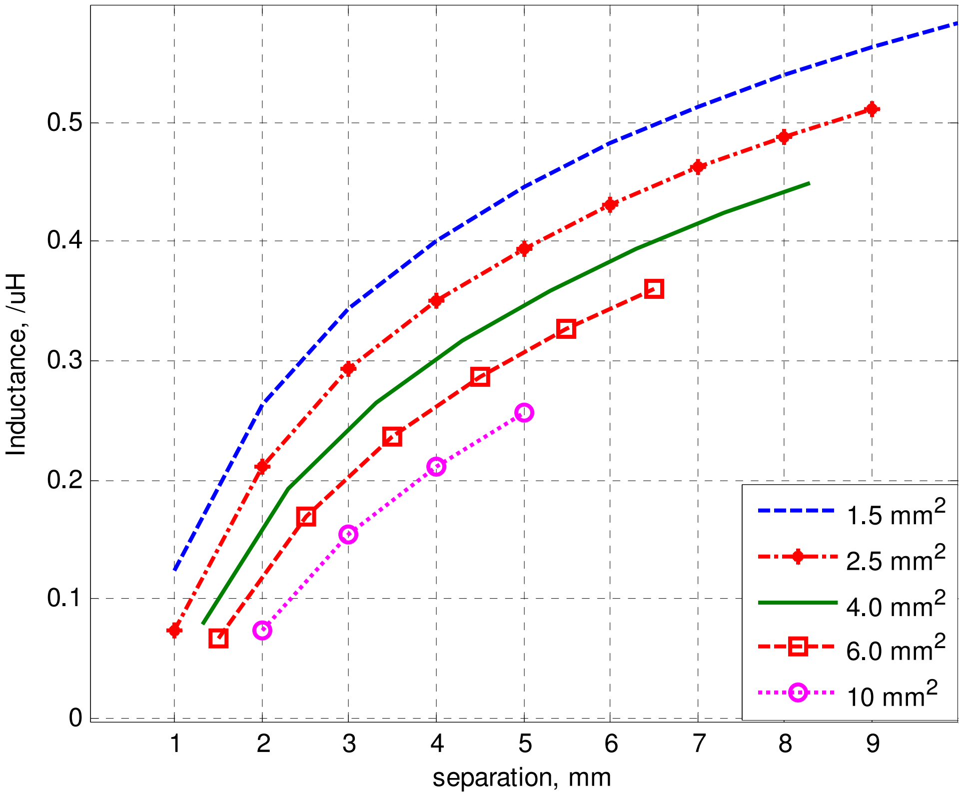

Figure 2.6 Variation of inductance for different conductor areas.

In this work the values of inductance and resistance for different cross section areas of the wire presented in Table 2.3 are used.

Table 2.3 inductance and resistance for core size

core size, [mm^2]	Inductance, L [µH/m]	Resistance, R [Ω/m]
1.0	0.6224	0.0170
1.5	0.5767	0.0113
2.5	0.5170	0.0068
4.0	0.4595	0.0043
6.0	0.4070	0.0028
10	0.3354	0.0017
13.3	0.2916	0.0013

2.2.2 Energy consumption and load loss calculation

The energy consumption of a house in a year can be obtained by summing up the energy consumption of all appliances. The amount of energy consumed in year by an appliance is given by

$$\text{Energy consumption} = \text{On energy consumption} + \text{Standby energy consumption} \qquad (2.15)$$

where

$$\text{On energy consumption} = \frac{\text{On Power x On time per day x 365 day}}{1000} \text{ kWh/yr} \qquad (2.16)$$

$$\text{Standby energy consumption} = \frac{\text{Standby Power x Standby time per day x 365 day}}{1000} \text{ kWh/yr} \qquad (2.17)$$

The power and times are taken from Table 2.2 for these calculations. One of the aims of this thesis is to compare the estimated losses for the 230V AC system with the estimated losses for the low voltage DC system. For the appliances that internally run on DC voltage, it is assumed that when they are used in DC distribution system they are connected directly to the 48 V DC without any converting stage. If the appliance is supplied with DC the losses in the AC to DC rectifier can be eliminated. As an example, a block diagram of a microwave oven is shown in Figure 2.7 [32]. There are some losses in the AC to DC rectification and moreover there is a small transformer (step down magnetic) that causes no load losses though it is not performing its primary function in standby mode. These losses can also be eliminated when using the DC distribution system. To demonstrate the comparison between the AC system and the DC system, the losses and energy consumptions are calculated. In case of the AC system, the losses in the rectifier and the standby losses are included. This is due to the fact that, if the main power supply is DC, then there is no rectification losses and small or negligible amount of standby losses.

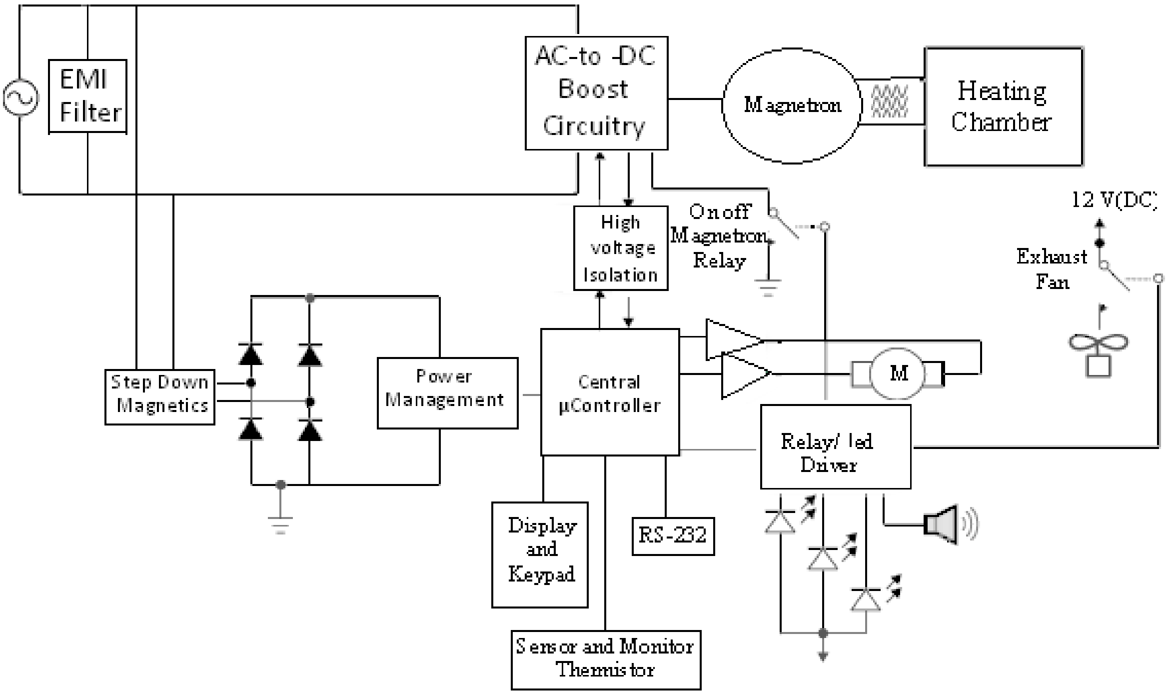

Figure 2.7 Block diagram of a microwave oven

The losses in the rectifier shown in Figure 2.8 depend on the forward voltage drop, V_F and the on resistance, R of the diode and load current. The forward voltage drop of a diode is different for different types of diode e.g. the forward voltage of the diode no. 1N4007 is in the range of 0.8 volt to 1.1 V [28]. The V_F is taken 0.9 V for the calculation of losses in the diode. The diode is assumed zero switching losses. Losses in a diode can be calculated as

$$P_{diode\_loss} = V_F \; I_{rms} \tag{2.18}$$

In a full wave rectifier shown in Figure 2.8, two diodes are always on. The losses in the rectifier diode can be calculated by

$$P_{rectifier\_loss} = 2 \; V_F \; I_{rms} \tag{2.19}$$

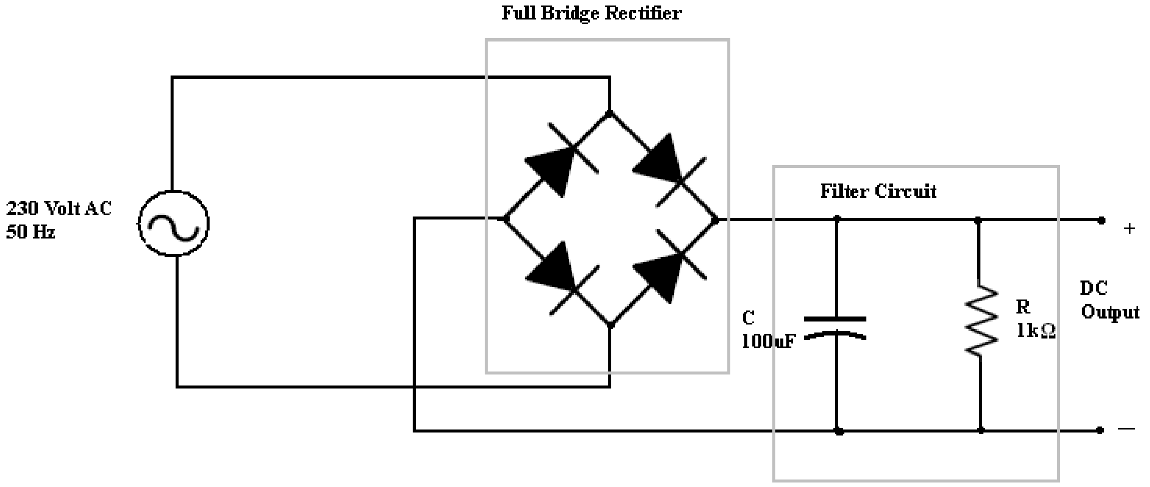

Figure 2.8 Full wave rectifier with RC filter

The energy losses in the AC system are calculated as the sum of the feeder cable losses and rectifier losses (if the appliances have a rectifier).

$$Energy\ losses = \frac{(Feeder\ losses + rectifier\ losses) \times on\ time \times 365}{1000}\ kWhr \qquad (2.20)$$

where the feeder losses are calculated with (2.12) and the rectifier losses with (2.19)

2.2.3 Energy consumption and loss calculation for the 230 V AC system

In Table 2.4 the voltage drop and power losses for the AC distribution system calculated with (2.10a) and (2.12) are presented. In the table also the rectifier loss for the appliance must have a rectifier is calculated with (2.19)

Table 2.4 Losses and voltage drops across the cable for 230 V AC system.

Product name	Power W	Current A	Wire area mm^2	Wire resistance Ω	Inductance μH	Power loss W across the cable	Voltage drop %	Rectifier loss W
Light bulb	60	0.26	1.5	0.5667	0.417	0.039	0.064	-------
	100	0.435	1.5	0.5667	0.417	0.107	0.107	-------
Microwave oven	800	3.49	1.5	0.2267	0.417	2.760	0.344	6.283
Induction Stove	2000	8.74	2.5	0.1360	0.367	10.391	0.517	15.734
Rice cocker	500	2.18	1.5	0.2267	0.417	1.076	0.215	-------
Coffee maker	990	4.32	1.5	0.2267	0.417	4.236	0.426	-------
Refrigerator	125	0.544	1.5	0.2267	0.417	0.067	0.054	0.979
Dishwasher	500	2.17	1.5	0.2267	0.417	1.076	0.215	3.920
Washing machine	500	2.17	1.5	0.2267	0.417	1.076	0.215	3.920
Vacuum cleaner (200-700W)	300	1.30	1.5	0.2267	0.417	0.387	0.129	-------
Iron	1000	4.37	1.5	0.2267	0.417	4.323	0.430	-------
Window unit AC, medium	900	3.91	1.5	0.2267	0.417	3.498	0.387	7.071
Laptop	50	0.22	1.5	0.5667	0.417	0.027	0.054	0.40
Personal computer	270	1.17	1.5	0.2267	0.417	0.313	0.116	2.116
External modem	7.2	0.031	1.5	0.2267	0.417	0.00	0.000	0.056
32” LCD television	156	0.68	1.5	0.5667	0.417	0.262	0.167	1.224

In Table 2.5 the energy losses in the feeder and rectifier, the standby energy consumption, the on energy consumption and the energy consumption are calculated for the investigated appliances.

Table 2.5 Power consumption and energy losses for 230 V AC system

Product name	Power W	Energy loss in Feeder kWh/yr	Rectifier kWh/yr	Standby energy kWh/yr	On energy kWh/yr	Loss of energy in a year kWh/yr	Total energy consumption kWh/yr
Light bulb	60	0.63	00	00	700	0.63	700
	100						
Microwave oven	800	10.11	2.30	23.50	292	12.41	315.5
Induction Stove	2000	5.69	8.61	00	1095	14.30	1095
Rice cocker	500	0.30	00	00	136.88	0.30	136.88
Coffee maker	990	0.77	00	00	180.68	0.77	180.68
Refrigerator	125	0.30	4.29	43.80	547.50	4.59	591.3
Dishwasher	500	0.22	0.79	10.27	100.34	1.01	110.60
Washing machine	500	0.37	1.36	16.83	173.38	1.73	190.21
Iron	1000	0.674			156	0.674	156
Window unit AC, medium	900	15.32	30.97	26.28	3942	41.6	3968.28
Laptop	50	0	1.00	11.50	127.75	1.00	139.25
Personal computer	270	0.60	3.86	24.27	492.75	4.46	517.00
External Modem	7.2	00	00	7.00	13.14	00	20.14
32” LCD television	156	0.50	2.23	31.20	284.7	2.73	315.90
Total		35.48	55.41	194.65	8242.12	86.20 kWh	8436.74 kWh

For the AC system the total losses can be divided into 3 types, the losses due to stand-by mode, resistive losses in the feeder and losses due to the rectification. From the calculation of losses for the appliances above, it is observed that the resistive losses are 35.48 kWh per year, standby losses are 194.65 kWh per year and losses for AC to DC rectification in electronic appliances is 55.41 kWh per year. Figure 2.9 presents the loss component in the AC system, here standby losses are 68 % of the total losses and it is 56 % higher than resistive losses and 48 % higher than rectifying losses.

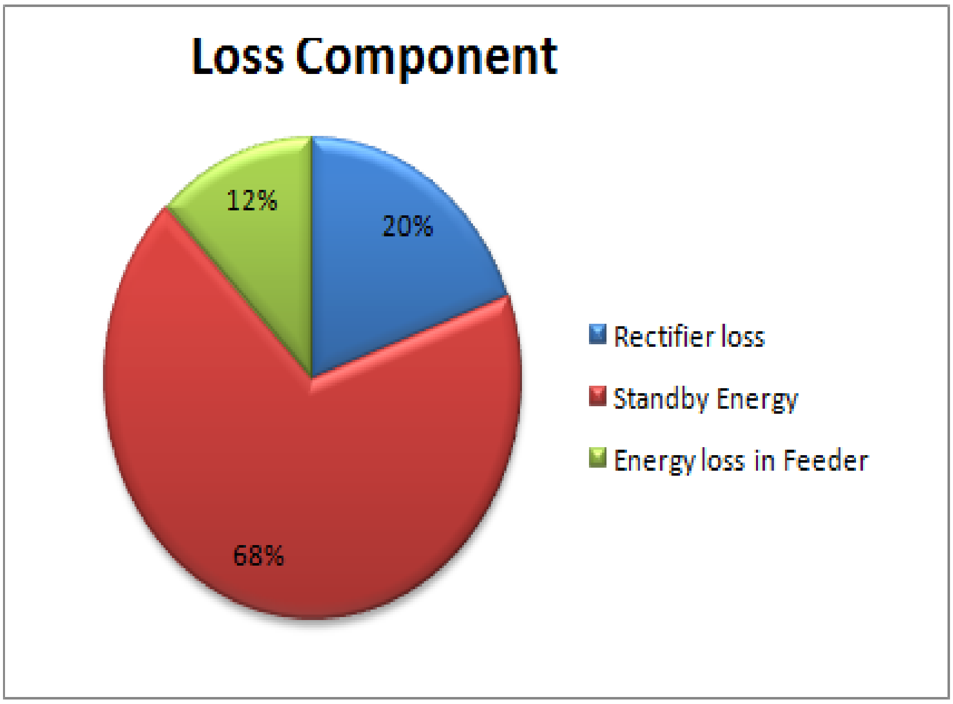

Figure 2.9 Percentage of different losses for 230V AC system.

2.3 The DC house

2.3.1 DC distribution system for the house

Many household appliances operate internally on DC voltage where an alternating voltage of about 230V is transformed to a low DC voltage. The scheme of proposed DC system presents in Figure 2.10. The solar cell is connected to the DC bus with DC/DC converter. Compared to AC system, the DC energy sources (fuel cell, micro turbine) have eliminated one DC to AC conversion stage. The energy storage system can be connected directly with the DC bus without any converter. To connect the DC distribution system with the existing AC system an additional AC to DC converter is required which is a drawback. As mention before, many household appliances operate internally on DC and when supplied with AC "high" voltage AC is transformed and rectified to a low voltage DC. In this work it is assumed that these loads can be connected directly to 48 V DC supply without any conversion. In reality may be a DC to DC converter can be needed to adapt the voltage level.

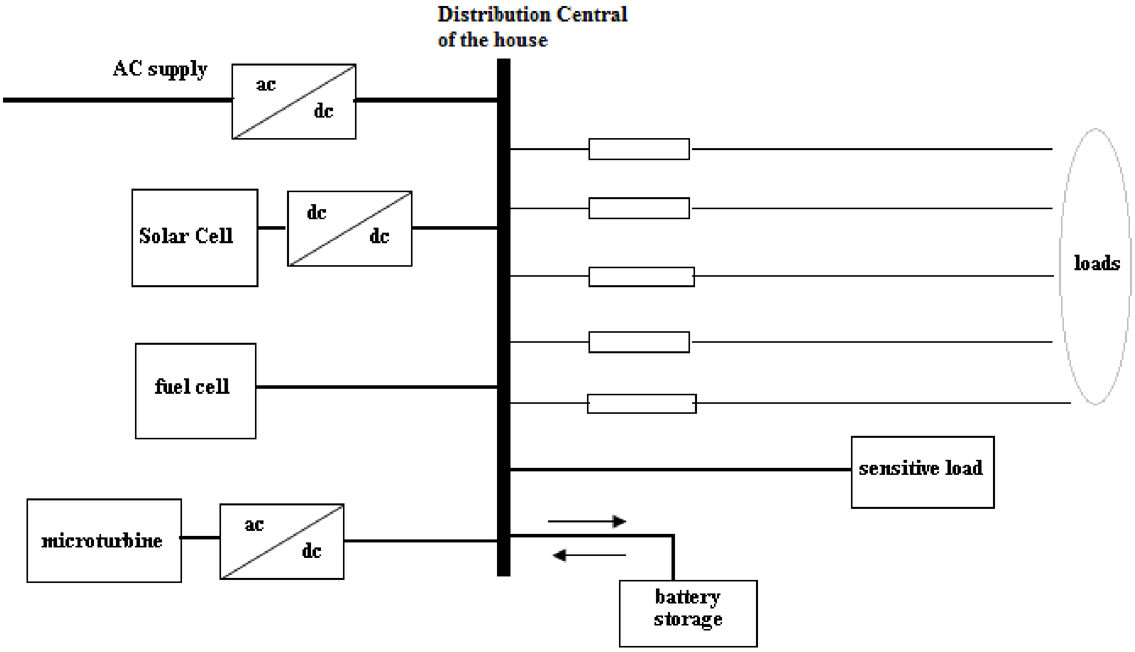

Figure 2.10 Scheme of the proposed DC distribution system for the house

With this assumption the circuit diagram of the appliances can be changed to adapt with the DC system. For example, a block diagram of the Microwave oven for DC supply is proposed in Figure 2.11. Compared with the block diagram for AC supply, Figure 2.7, many advantages can be seen such as, the rectifier circuits are eliminated (which avoid the rectification losses), step down magnetic (transformer) is eliminated (which reduces no load or standby losses). This results in reduced losses of the appliances.

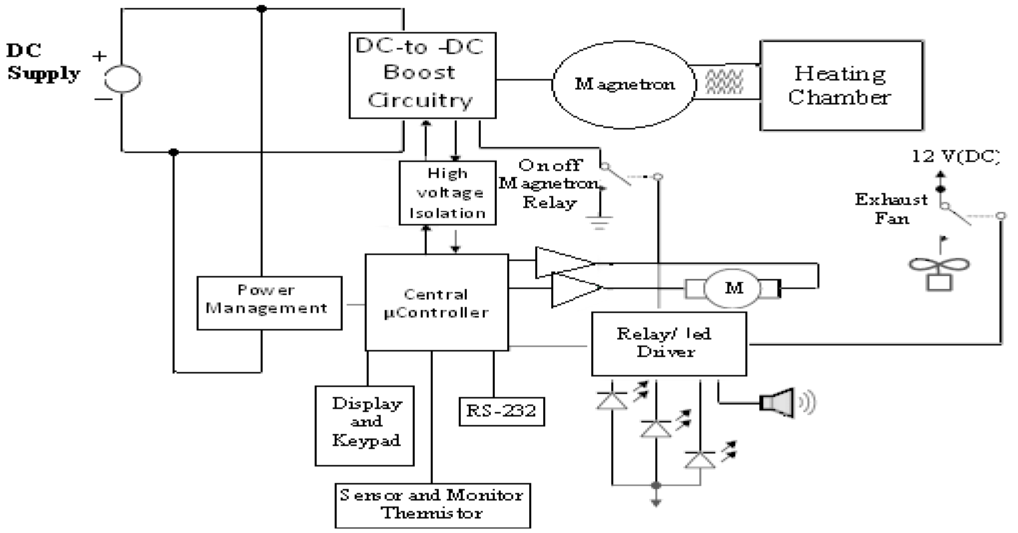

Figure 2.11 Proposed block diagram of a microwave oven for DC supply.

2.3.2 Loss and energy calculations for the DC distribution system

The voltage drop in the DC distribution system can be calculated by using Figure 2.12

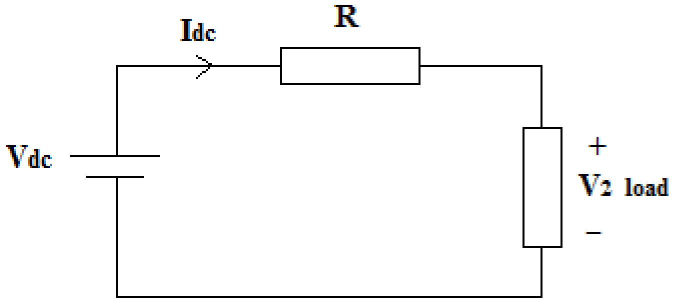

Figure 2.12 Simple DC circuit

The load voltage can be calculated as

$$V_2 = V_{dc} - I_{dc}R \tag{2.21}$$

$${V_2}^2 = V_{dc}V_2 - V_2 I_{dc}R$$

$${V_2}^2 = V_{dc}V_2 - PR$$

$$\left(V_2 - \frac{V_{dc}}{2}\right)^2 = \frac{{V_{dc}}^2}{4} - PR$$

$$V_2 = \frac{V_{dc}}{2} \pm \sqrt{\frac{{V_{dc}}^2}{4} - PR} \tag{2.22}$$

$$Voltage\ drop = \frac{V_1 - V_2}{V_1} \times 100\ \% \tag{2.22a}$$

where R is the feeder resistance and P is the load power.

In a DC system, there is no reactive current, so there is only resistive losses across the cable. The current is calculated as

$$I_{dc} = \frac{P}{V_{dc}} \tag{2.23}$$

And the feeder losses as

$$P_{loss} = R \, {I_{dc}}^2 \tag{2.24}$$

The energy loss for the DC system is calculated with (2.24). As mention before the rectifier losses are put to zero, no additional DC to DC converter with losses is considered. The on state energy consumption is calculated in the same way as for the AC system with (2.15). As also mention before the standby losses are assumed to be negligible when the appliances are supplied with DC. There are also some losses in AC to DC rectifier. The losses in this rectifier can be neglected if the solar power and microturbine is sufficient to supply required power. In this work it is assumed that they are sufficient to supply the required in the DC house.

2.3.3 Energy consumption and loss calculation for the 24 V DC system

For the 24 V DC system, the current is high and the voltage drop across the feeder cable is high. This drop depends on the length and cross section of the cable as well as the power rating of the household appliances. From the Table 2.6, it can be said that the devices whose power rating greater than 150 W, the voltage drop is greater than 5%. For example with a load of 500 W, the voltage drop is 7.38 % and power losses are 36.891W when the feeder length is 20 m and the cross section is 4 mm^2.

Table 2.6 Losses and voltage drops across the cable for 24 V DC system.

Product name	Power W	Current A	Wire area mm^2	Wire resistance Ω	Feeder Power losses W	Voltage drop %
Light bulb (LED bulb)	7	0.29	1.5	0.5667	0.05	0.68
Microwave oven	800	33.33	6	0.0567	62.95	7.86
Induction stove	2000	83.33	13.3	0.0260	180.55	9.03
Rice cocker	500	20.833	4	0.0850	36.89	7.38
Coffee maker	990	41.25	10	0.0340	57.85	5.84
Refrigerator	125	5.21	1.5	0.2267	6.15	4.92
Dishwasher	500	20.833	4	0.0850	36.89	7.38
Washing machine	500	20.833	4	0.0850	36.89	7.38
Vacuum cleaner (200-700W)	300	12.50	1.5	0.2267	35.42	11.81
Iron	1000	41.67	10	0.0340	59.04	5.90
Window unit AC, medium	900	37.50	10	0.0340	47.81	5.31
Laptop	50	2.08	1.5	0.2267	1.78	2.64
Personal computer	270	11.25	1.5	0.2267	28.69	10.63
External Modem	7.20	0.30	1.5	0.2267	0.02	0.28
32” LCD television	156	6.50	1.5	0.5667	23.94	15.35

In Table 2.7 the energy losses in the feeder and the on energy consumption are calculated for the investigated appliances for the 24 V DC system.

Table 2.7 Power consumption and energy losses for 24 V DC system.

Product name	Power W	Feeder energy loss kWh/yr	On energy Consumption kWh/yr	Loss of energy in a year kWh/yr	Total energy consumption kWh/yr
Light bulb (LED bulb)	7 (2 bulb)	0.42	61.32	0.42	61.32
Microwave oven	800	22.97	292	22.97	292
Induction stove	2000	98.85	1095	98.85	1095
Rice cocker	500	10.10	136.88	10.10	136.88
Coffee maker	990	10.56	180.68	10.56	180.68
Refrigerator	125	26.95	547.50	26.95	547.50
Dishwasher	500	7.40	100.34	7.40	100.34
Washing machine	500	12.79	173.38	12.79	173.38
Vacuum cleaner (200-700W)	300	3.68	31.20	3.68	31.20
Iron	1000	9.21	156	9.21	156
Window unit AC or electric space heater	900	209.42	3942	209.42	3942
Laptop	50	3.24	127.75	3.24	127.75
Personal computer	270	52.35	492.75	52.35	492.75
External Modem	7.2	0.022	13.14	0.022	13.14
32"LCD television	156	43.69	284.7	43.69	284.7
Total				511.65	7634.68

2.3.4 Energy consumption and loss calculation for the 48 V DC system

For the 48 V DC case the current is half for same power rating appliances compared to the 24 V DC case. As a result, the voltage drops and power losses will be decreased. For example a 500 W appliances, the voltage drop is 4.92 % and power losses are 24.611W which is 12.28 W less comparing with 24 V DC system for the same feeder area. Table 2.8 present voltage drop, power losses and power consumption for different household appliances. In the case of 48 VDC, the voltage drop exceeds 5 % when the appliance's power rating greater than 850 W.

Table 2.8 Loss and voltage drop across the cable for 48 V DC.

Product name	Power W	Current A	Wire area mm^2	Wire resistance Ω	Power loss W	Voltage drop %
Light bulb (LED bulb)	7	0.146	1.5	0.5667	0.012	0.17
Microwave oven	800	16.67	2.5	0.1360	37.79	4.72
Induction stove	2000	41.67	10	0.0330	57.31	2.8654
Rice cocker	500	10.42	1.5	0.2267	24.61	4.92
Coffee maker	990	20.625	2.5	0.1360	57.85	5.84
Refrigerator	125	2.64	1.5	0.2267	1.58	1.25
Dishwasher	500	10.42	1.5	0.2267	24.61	4.92
Washing machine	500	10.42	1.5	0.2267	24.61	4.92
Vacuum cleaner (200-700W)	300	6.25	1.5	0.2267	8.85	2.95
Iron	1000	20.833	4.0	0.0850	36.89	3.69
Window unit AC or Electric space heater, medium	900	18.75	2.5	0.1360	47.81	5.31
Laptop	50	1.042	1.5	0.2267	0.25	0.49
Personal computer	270	5.625	1.5	0.2267	7.17	2.66
External Modem	7.2	0.15	1.5	0.2267	0.01	0.07
32" LCD television	156	3.25	1.5	0.5667	5.99	3.84

In Table 2.9 the energy losses in the feeder and the on energy consumption are calculated for the investigated appliances for the 48 V DC system. The total power losses in year are 315 kWh which is 121 kWh less comparing with the 24 V system.

Table 2.9 Power consumption and energy losses for 48 V DC.

Product name	Power W	Feeder energy losses kWh/yr	On energy consumption kWh/yr	Loss of energy in a year kWh/yr	Total energy consumption kWh/yr
Light bulb (LED bulb)	7 (2 bulb)	0.11	61.32	0.11	61.32
Microwave oven	800	13.79	292	13.79	292
Induction stove	2000	31.27	1095	31.27	1095
Rice cocker	500	6.73	136.88	6.73	136.88
Coffee maker	990	10.56	180.68	10.56	180.68
Refrigerator	125	6.92	547.50	6.92	547.50
Dishwasher	500	4.94	100.34	4.94	100.34
Washing machine	500	8.53	173.38	8.53	173.38
Vacuum cleaner (200-700W)	300	0.92	31.20	0.92	31.20
Iron	1000	5.75	156	5.75	156
Window unit AC or electric space heater,	900	209.43	3942	209.43	3942
Laptop	50	0.45	127.75	0.45	127.75
Personal computer	270	13.09	492.75	13.09	492.75
External Modem	7.2	0.006	13.14	0.006	13.14
32" LCD television	156	10.92	284.7	10.92	284.7
				323.5	7634.68

2.3.5 Energy consumption and loss calculation for the 48 V DC system with optimized cable area

The power losses across the cable can be reduced by reducing the wire resistance. The resistance is inversely proportional to the cross section of the wire. By increasing the cross section of the cable, the losses in the cable can be reduced. For example a load of 500 W the power losses reduces 40% if a 2.5 mm^2 cable is used instead of a 1.5 mm^2 cable. Increasing the cross section of the cable, of course it increases the copper cost. The cable area is optimized to minimize the total cost of the cable. The total cost of the cable is calculated as the sum of the investment cost of the cable and the cost of the losses in the cable. The total cost is calculated as

$$Total\ cost = Cable\ cost + Feeder\ energy\ loss/yr \times life\ time \times Energy\ cost \qquad (2.25)$$

where the life time is assumed to be 20 years and the energy cost 1 SEK/kWh

Average price of some wire and relative increment of cost compared to 1.5mm^2 wire is presented in the Table 2.10 [30]. From the Figure 2.13, it is seen that the copper wire cost increases almost linearly with the cross section of wire.

Table 2.10 Price variations with cross section variation of the cable.

Cable cross section	Price per 100 m wire (SEK)	Increases price comparing 1.5 mm^2 wire
1.5 mm^2	560	-----------------------------
2.5 mm^2	860	53.6%
4 mm^2	1250	123.2%
6 mm^2	1800	221.4%
10 mm^2	2225	297.3%

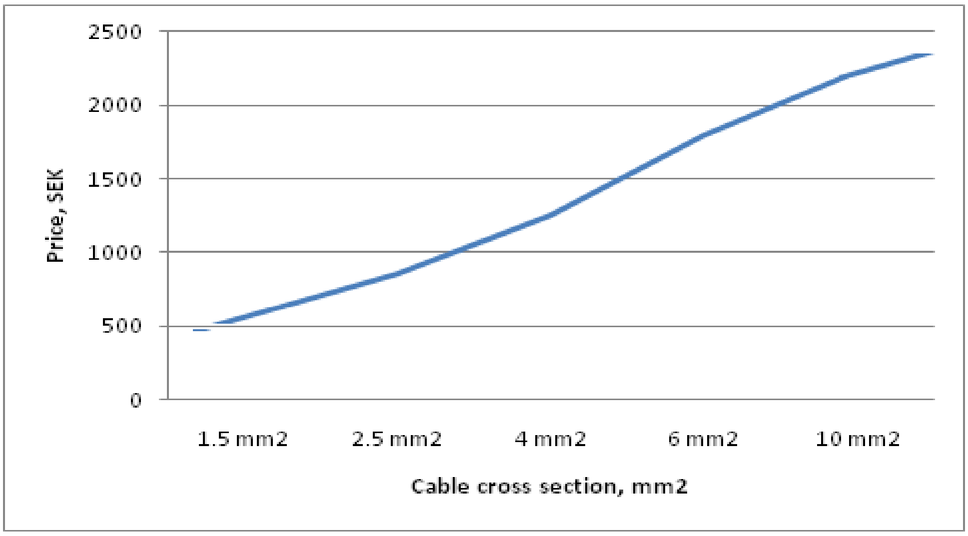

Figure 2.13 Price Vs. Copper cross section.

The wire cost shown in Figure 2.13 can be approximated as

$$Cable\ cost = 2.662 + 1.959\ A \qquad SEK/m \tag{2.26}$$

The losses in the cable can be calculated with (2.22) and (2.24)

$$P_{loss} = R\ {I_{dc}}^2 = R\frac{P^2}{{V_2}^2} = \frac{R\ P^2}{\left(\frac{V_{dc}}{2} \pm \sqrt{\frac{{V_{dc}}^2}{4} - PR}\right)^2} \approx R\frac{P^2}{{V_{dc}}^2} \tag{2.27}$$

and from this the cost of the energy loss can be calculated as

$$Cost\ of\ energy\ loss = \rho\frac{l}{A}\frac{P^2}{{V_{dc}}^2}\ On\ time.365.20.1 = \rho\frac{l}{A}\ E_{on}\ \frac{I_{on}}{V_{dc}}20.1 \tag{2.28}$$

where $E_{on} = P.On\ time.365$, is the energy consumption of the appliance for a year and I_{on} is the current consumption by the load when it is on.
The total cost can be expressed as

$$Total\ cost = \left(C_1 + C_2A + \frac{C_3}{A}\right)l \tag{2.29}$$

Where $C_1 = 2.662\ SEK/m$, $C_2 = 1.959\ SEK/mm^2.m$ and
$C_3 = 1.20\ \rho\ E_{on}\ \frac{I_{on}}{V_{dc}}\ \ SEK\ mm^2/m$

The optimum area that minimizes the total cost can be calculated as

$$\frac{d\ cost}{dA} = C_2 - \frac{C_3}{A^2} = 0$$

$$A = \sqrt{\frac{C_3}{C_2}} = \sqrt{\frac{1 * 20 * 365 * on\ time *\ \rho}{1.959}\ \frac{P}{V_{dc}}} = \sqrt{\frac{20\ \rho\ E_{on}I_{on}}{1.959\ V_{dc}}} \tag{2.30}$$

Figure 2.14 presents the optimum cable area vs. Eon.Ion for different loads. It is seen from the figure that for 10 W load such as LED bulb, the optimum cable area is 1.5 mm^2 cable and for microwave oven the optimum cable area is 16 mm^2 which is impractical. Optimum cable is selected such that it reduces feeder losses in considerable amount.

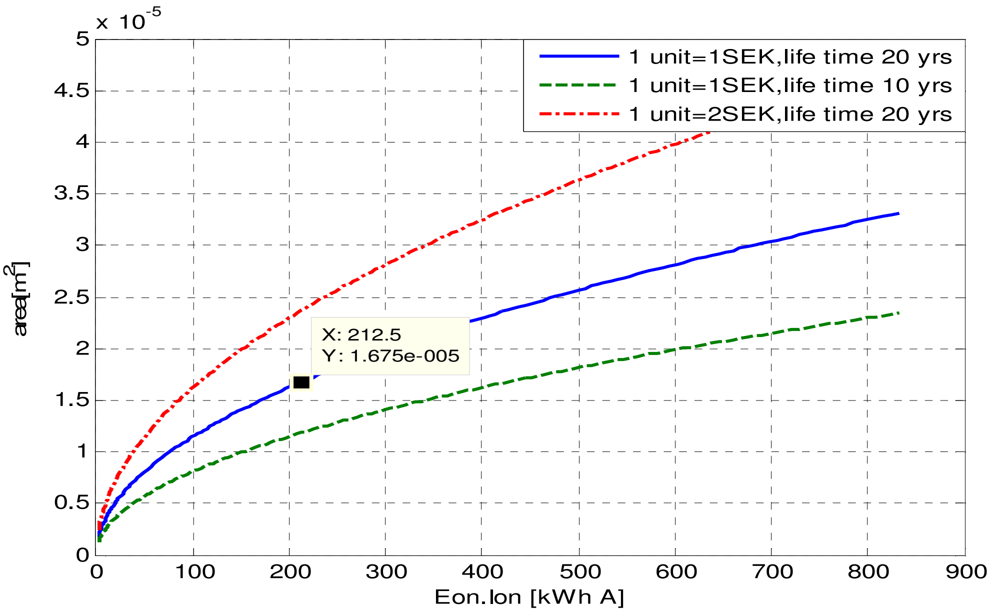

Figure 2.14 Eon.Ion vs Area

Table 2.11 Loss and voltage drop across the cable for 48 V DC optimized cable area.

Product name	Power W	Current A	Wire area mm^2	Wire resistance Ω	Power loss W	Voltage drop %
Light bulb (LED bulb)	7	0.146	1.5	0.5667	0.012	0.17
Microwave oven	800	16.67	4	0.0850	23.621	2.95
Induction stove	2000	41.67	10	0.0260	57.31	2.8654
Rice cocker	500	10.42	2.5	0.1360	14.766	2.95
Coffee maker	990	20.625	4	0.0850	36.158	3.65
Refrigerator	125	2.64	1.5	0.2267	1.579	1.25
Dishwasher	500	10.42	2.5	0.1360	14.766	2.95
Washing machine	500	10.42	2.5	0.1360	14.766	2.95
Vacuum cleaner (200-700W)	300	6.25	1.5	0.2267	8.854	2.95
Iron	1000	20.833	6	0.0567	24.594	2.46
Window unit AC, medium	900	18.75	6	0.0567	19.922	2.21
Laptop	50	1.042	1.5	0.2267	0.246	0.49
Personal computer	270	5.625	1.5	0.2267	7.172	2.66
External Modem	7.2	0.15	1.5	0.2267	0.005	0.07
32” LCD television	156	3.25	1.5	0.5667	5.985	3.84

Table 2.12 Power consumption and energy losses for 48 V DC modified wire cross section.

Product name	Power W	Feeder energy loss kWh/yr	On energy consumption kWh/yr	Loss of energy kWh/yr	Total energy consumption kWh/yr
Light bulb (LED bulb)	7 (2 bulb)	0.11	61.32	0.11	61.32
Microwave oven	800	8.62	292	8.62	292
Induction stove	2000	31.38	1095	31.38	1095
Rice cocker	500	4.04	136.88	4.04	136.88
Coffee maker	990	6.60	180.68	6.60	180.68
Refrigerator	125	6.92	547.50	6.92	547.50
Dishwasher	500	2.96	100.34	2.96	100.34
Washing machine	500	5.11	173.38	5.11	173.38
Vacuum cleaner (200-700W)	300	0.92	31.20	0.92	31.20
Iron	1000	2.56	156	2.56	156
Window unit AC or electric space heater	900	87.26	3942	87.26	3942
Laptop	50	0.45	127.75	0.45	127.75
Personal computer	270	13.08	492.75	13.08	492.75
External Modem	7.2	0.006	13.14	0.006	13.14
32” LCD television	156	10.92	284.7	10.92	284.7
Total				181	7634.68

2.4 Comparison of the systems

Figure 2.15 presents the losses for the different systems. The power loss of the 24V DC system is higher than for the other systems. In the case with the 48V DC system with the optimized wire area the losses could be reduced by almost 44 % compared with 48 V DC system. Figure 2.16 presents total energy consumption for different system. The 230 V AC system is the highest energy consuming system 48 V DC with optimized cable area is the lowest energy consuming system.

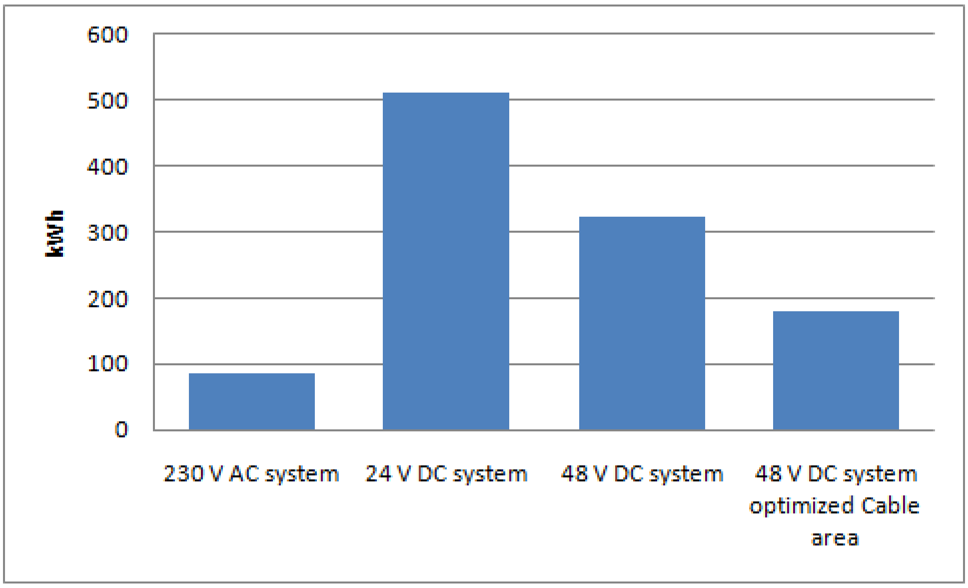

Figure 2.15 Losses for different AC and DC Systems.

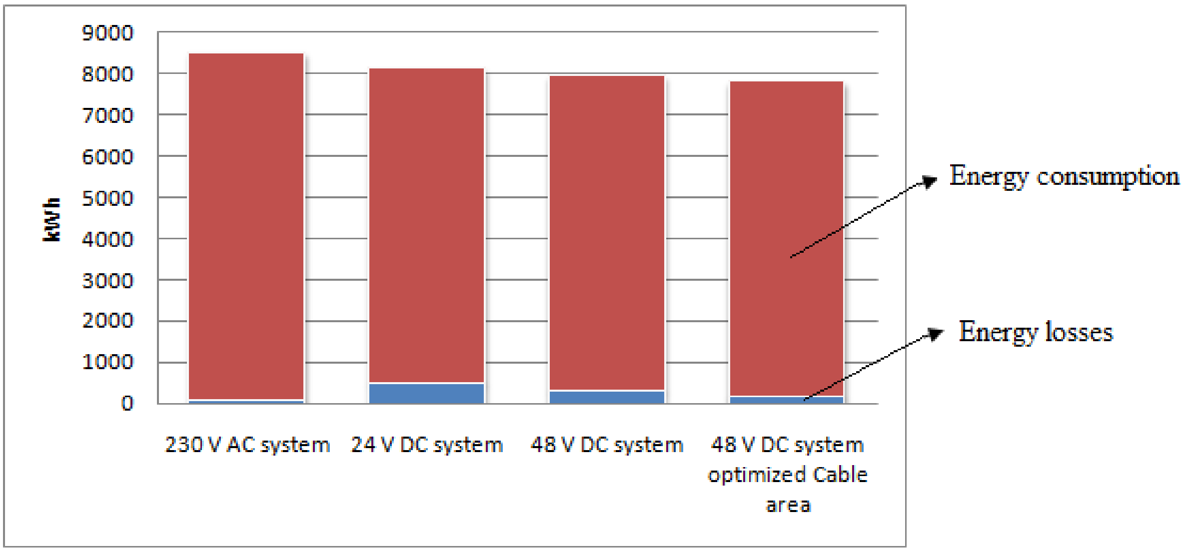

Figure 2.16 Energy consumptions for different systems

Table 2.13 presents the total cable length of the investigated loads for the different systems. For all systems the total cable length for all appliances is 440 m. For the 230V AC system 1.5 mm^2 cable is used for the whole system except for the induction stove where a cable with a cross section of 2.5 mm^2 is used. The total cost of the cable is almost 2525 SEK, see Table 2.13. For the 48 V system most of the appliances can be connected with 1.5 mm^2 cable since they consumes less than 18 A. The total cable cost for this system is almost 3115 SEK. For the 48 V DC systems with optimized cross section it can be noticed from Table 2.13 that thicker cables are used to reduce the losses. The total cable cost of this system is higher almost 3750 SEK. For the 24 V system even less appliances are connected by 1.5 mm^2 cables since the current consumption is higher due to the lower voltage. The total cable cost for the 24 V system is 4755 SEK as can be seen in Table 2.13. The figure 2.17 presents the copper cost of the different systems. In the case of the 48 V DC system with optimized cable area, the cross section of the cable increases the cost of copper 20 % comparing with 48V DC and 48 % increases comparing with 230V DC.

Table 2.13 Investment cost for different systems.

Cable cross section	Length of cable required in 230 AC system	Length of cable required in 24 DC	Length of cable required in 48 DC	Length of cable required in 48 DC optimized cable area
1.5 mm^2	420 m	280 m	340 m	280 m
2.5 mm^2	20 m	-------	60 m	60 m
4 mm^2	---------	60 m	20 m	40 m
6 mm^2	---------	20 m	-----m	40 m
10 mm^2	---------	60 m	20 m	20 m
13.3 mm^2	--------	20 m	-----	----
Total Cost of wire	2525 SEK	4755 SEK	3115 SEK	3750 SEK

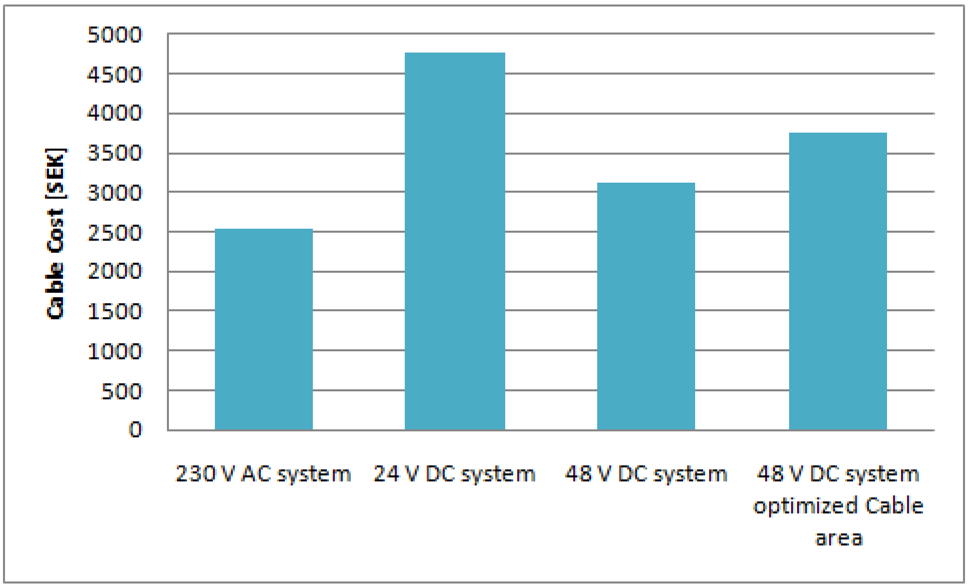

Figure 2.17 Copper cost in Different AC and DC systems.

The total cost of the system, losses and cable cost can be calculated as

$$Total\ Cost = Cable\ Cost + (Energy\ consumption\ per\ year + Energy\ loss\ per\ year).\ Life\ time.\ Energy\ cost \qquad (2.31)$$

In Figure 2.18 the total cost of the system are shown. Here the life time is 20 years and unit price of energy is 1 SEK. From this figure it can be concluded that 48 V DC system with optimized cable area is most economical system compared with the 230 V AC system and within this life time it saves almost 13000 SEK.

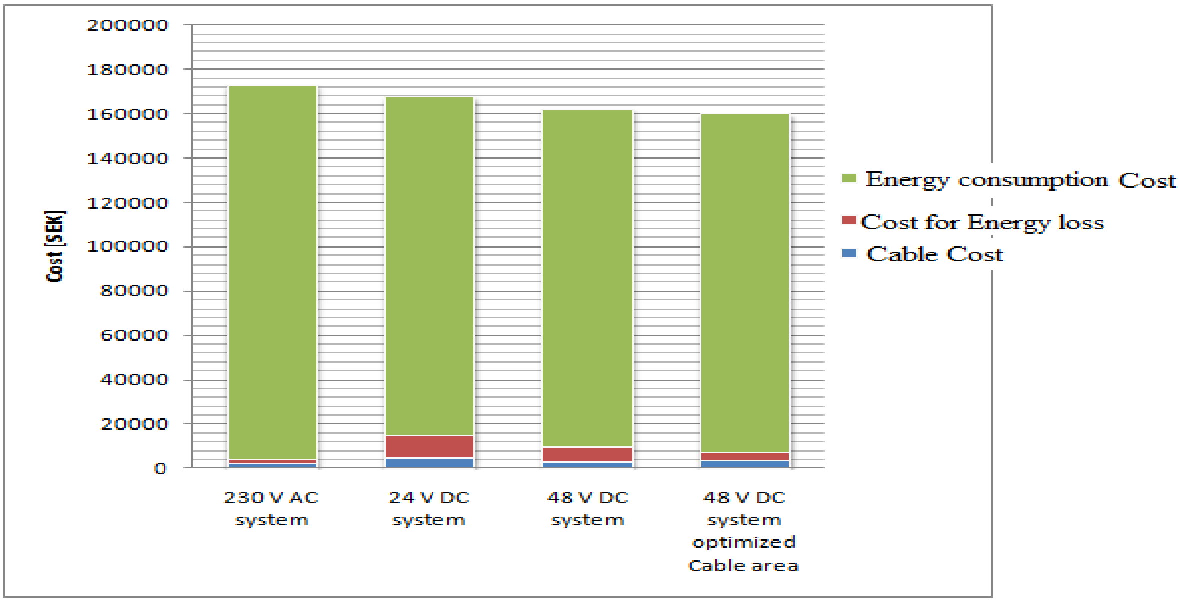

Figure 2.18 Total cost for different system

Figure 2.19 presents the total cost for different systems according to equation (2.31) for different life time and different per unit cost of energy. In the case of the 48 V DC system with optimized cable area, the total cost is 27000 SEK higher compared to 230 V AC system for 20 years life time and per unit energy cost of 2 SEK, and it is 5900 SEK higher for 10 years life time and per unit energy cost of 1 SEK.

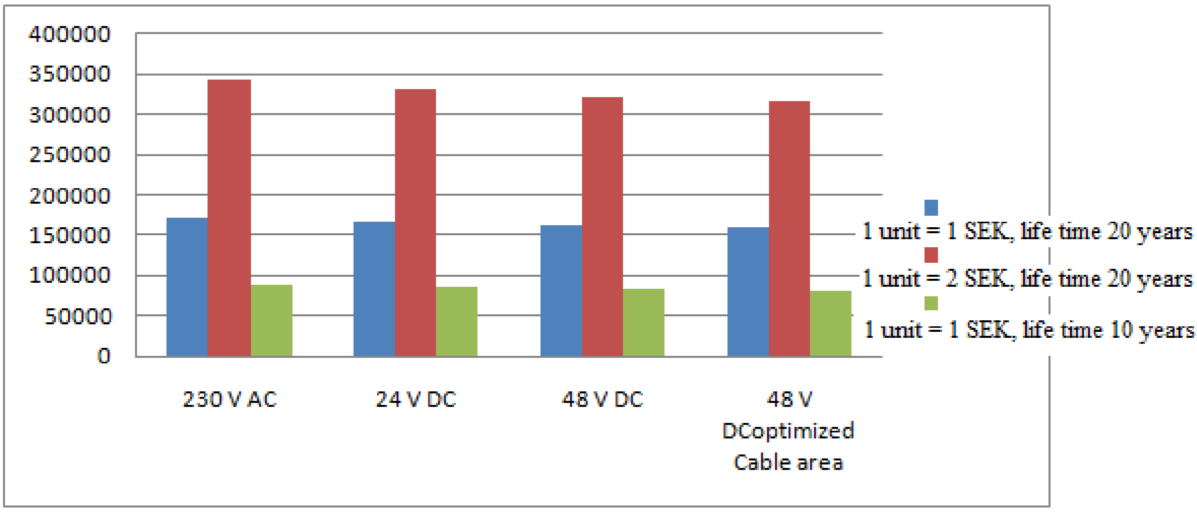

Figure 2.19 Total cost for different system at different price and life time

3. Stove and Refrigerator prototype for low voltage DC supply

Kitchen appliances consume large amount of energy in residential houses. By using efficient kitchen appliances energy losses can be reduced. Most of the kitchen appliances are operate on AC. The stove is one of the high power consuming kitchen appliances and it consumes large amount of energy. This project focuses on an efficient stove design for DC supply. To decrease the energy consumption of the stove, the idea is to combine it with the refrigerator. The heat extracted from the refrigerator is stored in the stove and is used for cooking or other purposes. Thermoelectric module (TEM) is used to extract heat from one side to another side. Two separate TEMs are used for refrigerator and stove. Water is used as a medium to transfer extracted heat of the refrigerator from refrigerator side TEM to stove side TEM. Stove side TEM extracts partial energy from that heat and remaining energy is stored in water tank which raises the temperature the of water. This hot water is used in the dishwasher to reduce energy consumption of the dishwasher. To run the refrigerator on DC, a refrigerator model was investigated by using the peltier effect. The proposed model gives a robust, comparatively silent, harmful CFC (Freon) [36] free refrigerator. The Peltier effect uses electricity to pump heat. But the peltier effect is less energy-efficient than other methods [37]. It is due to the fact that comparatively more energy is required for pumping energy from one side to another side of the peltier module.

3.1 General Description of the prototype

Three interconnected compartment was made out of styrofoam where one is the refrigerator compartment, the middle one is the compartment for a hot water tank and the last one is the stove compartment as shown in Figure 3.1. The dimensions of each compartment are listed in Table 3.1. The refrigerator side TEM with a air to liquid cooling system is used between the refrigerator and water tank compartment. For the air cooling system, a fan is mounted on the low temperature side of the TEM which is in the refrigerator side. Water is used for the liquid cooling system and it is circulated by a pump. Water pipe goes from the hot side of the low temperature TEM to the cold side of the high temperature TEM via the water tank and pump. The high temperature TEM is connected between the water tank compartment and the stove compartment.

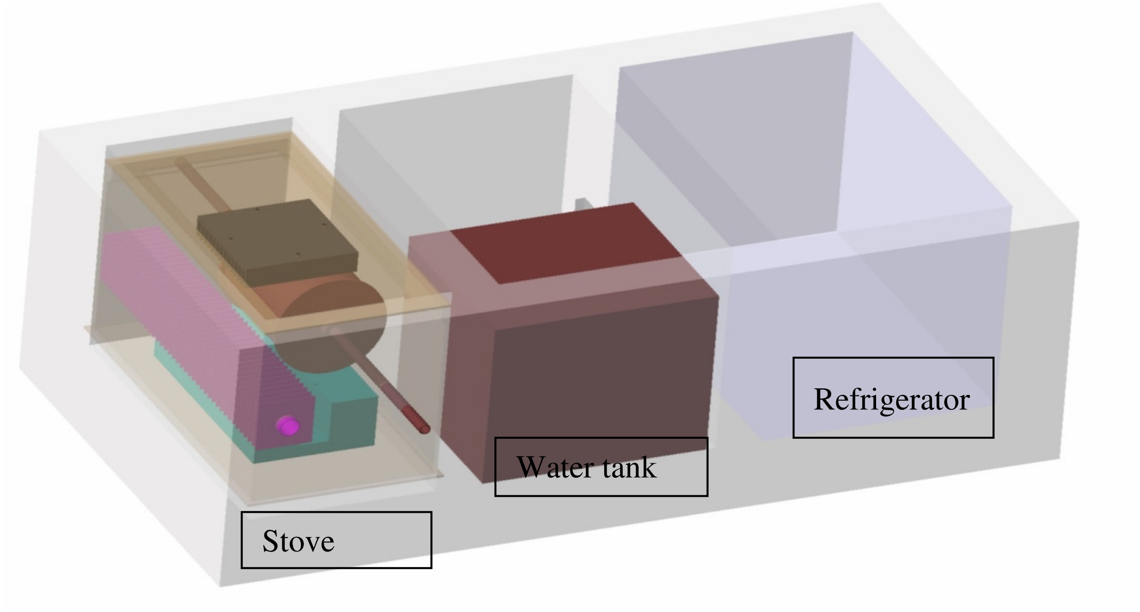

Figure 3.1 Complete model of prototype for refrigerator and stove.

Table 3.1 Dimensions of each part:

Section	Length(cm)	width(cm)	Height(cm)
Refrigerator	48	30	26
Water tank	48	30	26
Stove	48	25	26

An aluminum tank is used inside the stove compartment that contains paraffin for storing the thermal energy, as shown in Figure 3.2. A heat sink is attached with the hot side of the peltier module and it is used to a large surface area to the paraffin for heating it up quickly. A radiator is placed inside the paraffin and it is connected between the water supply tape and the dish washer water compartment via the water tank compartment and takes preheated water from the water tank to supply hot water to the dishwasher by absorbing heat from the paraffin. A small cylindrical water tank is also placed inside the paraffin which will take water from the tap and rises its temperature.

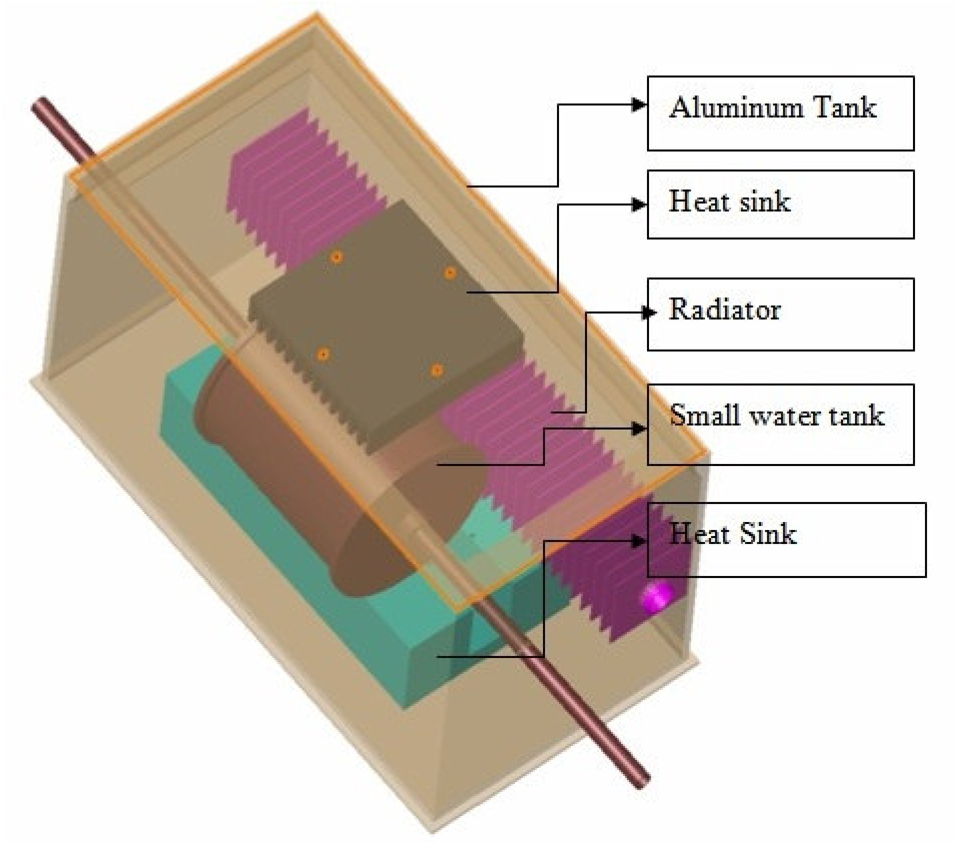

Figure 3.2 Complete diagram of stove side.

The pump and the fan of the low temperature thermoelectric module (TEM) are supplied with 12 volt DC. The low temperature TEM starts to pump the heat from the cold side to the hot side, when it is supplied by the DC voltage. It extracts more heat when the temperature difference between the hot and cold side is low and vice versa. The temperature inside the refrigerator compartment will decrease with time when the module is supplied is supplied with 12V DC. The temperature on the hot side of the module will increase with time. This is due to the fact that the water which is circulating through the hot side of the TEM will absorb thermal energy. The temperature on cold side of the high temperature TEM is increasing due to this water circulation. After passing through the high temperature TEM, the water is entered on the top of the water tank. Water of low temperature is pumped from the bottom of the tank to the hot side of the low temperature TEM, to remove the heat from it. This closed loop process continues until the temperature on the cold side of the high temperature TEM on water tank side becomes 50°C. At that point the high temperature module is supplied with a DC voltage and the module extracts heat from the water and pumps it to the hot side. At this point the hot side temperature of the stove side TEM starts to increase with time. When the temperature reaches above 100°C, the paraffin inside the tank starts to melt and changes its phase from solid to liquid. By changing its phase, the paraffin stores a lot of heat.

3.2 Peltier element

Normally, a conventional cooling system contains three fundamental parts - the evaporator, compressor and condenser as shown in Figure 3.3 [38]. The evaporator is the part where the pressurized refrigerant is allowed to expand, boil and evaporate. Energy is absorbed during the change of state from liquid to gas. The compressor acts as the refrigerant pump and recompresses the gas to change its phase to liquid. The heat absorbed at the evaporator and the heat produced during compression are expelled into the environment or ambient at the condenser.

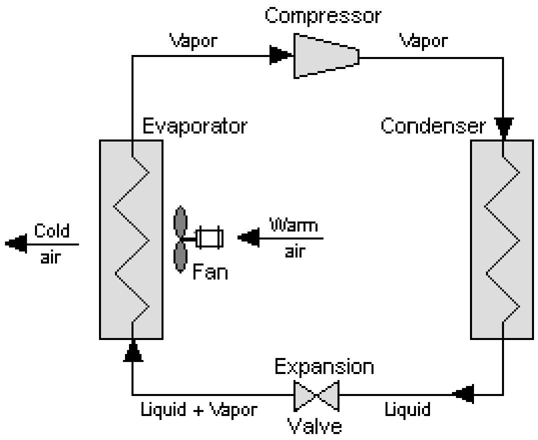

Figure 3.3: Block diagram of conventional cooling system.

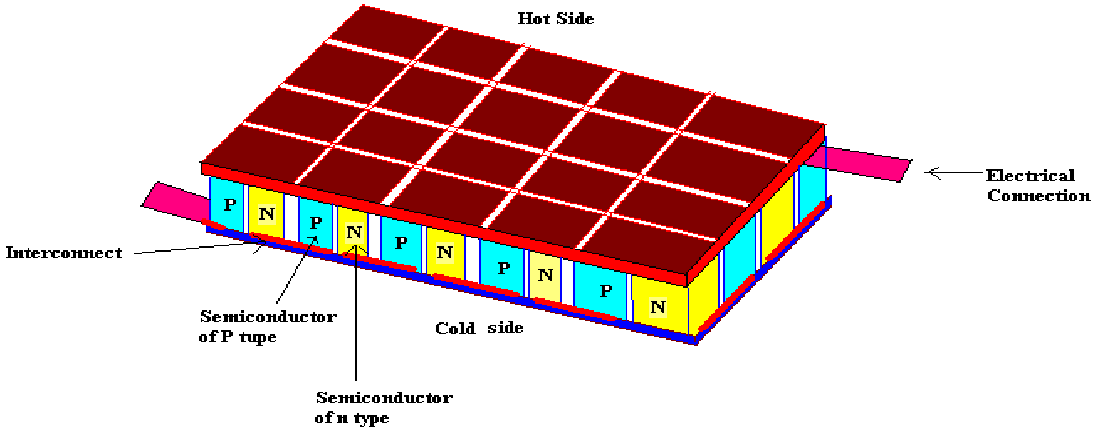

Figure 3.4 Basic structure of a peltier element.

A Peltier element is a device that utilizes the peltier effect to pump heat from one surface to another surface. It consists of two plates, one is the cold plate and the other is the hot plate as shown in Figure 3.4. Two wires come out from the peltier element. If voltage is applied to these wires, heat will be pumped from the cold surface to the hot surface and it will make the cool plate cold and the other plate hot. It does not generate heat or cold by itself rather than just transferring thermal energy from one plate to another. It is called thermo electric cooler

(TEC) or thermo electric module (TEM). It is also important to know that this phenomenon is reversed when the polarity (plus and minus) of the applied DC voltage is changed. It will cause heat to be moved in the opposite direction. A thermoelectric module may be used for both heating and cooling purpose and due to this fact it is suitable for precise temperature control applications. If a temperature difference is applied across the module, a voltage will be generated and thus the module can also be used for power generation.
The advantages of TEM compared to conventional cooling system [39]-[41] can be summarized as:

- It has no moving parts.
- The size of the module is small and the weight is light.
- Possibility of arbitrary modification of the size of the cooling unit.
- It does not require maintenance.
- Its operation is acoustically silent and electrically quiet.
- It is a Freon-free technology.
- Heating and cooling can be done with the same module.
- Operation has wide operating temperature range.
- Precise temperature control can be done.
- Cooling to very low temperatures is possible.
- Environmentally friendly.

3.2.1 Basic structure of the Peltier element

The thermoelectric module operates in an analogous way as the conventional cooling systems. Thermal energy is absorbed at the cold junction by electrons as they pass from a low energy level in the p-type semiconductor element, to a higher energy level in the n-type semiconductor element acting as the evaporator. Thermal energy is expelled to the hot junction when the electrons are moving from a high energy level of n-type element to a lower energy level p-type element acting as the condenser [42]. Thermoelectric Coolers acts as a heat pump and a solid state device without moving parts, fluids or gasses. The electrical power that is supplied to the module provides the energy to move the electrons through the system as the compressor. Peltier elements are mainly made of semi conductive materials. It has a lot of PN junctions that are connected in series electrically and thermally in parallel as shown in Figure 3.4. They are heavily doped which indicates special additives that will increase the excess or lack of electrons. The thermoelectric elements and electrical interconnects are mounted between two ceramic substrates. The substrates are used to hold the overall structure together mechanically and also to insulate the individual elements electrically from one another and from external mounting surfaces. Instead of using two highly doped semi conductors, two different metals can be used as is done in thermo couples. Typically copper or constantan is used.

The specification of a thermoelectric module usually shows the achieved temperature difference in the conjunction to the transferred power in watts as shown in Figure 3.5.

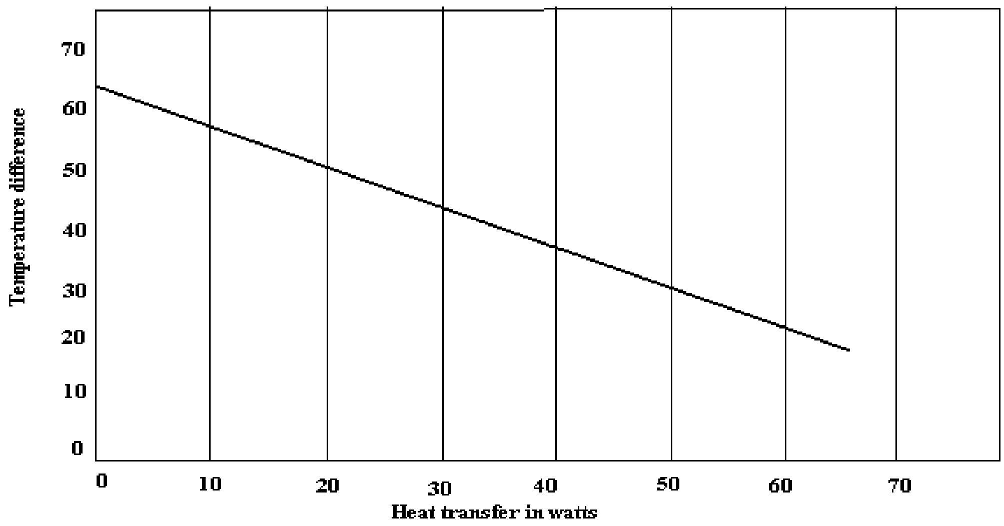

Figure 3.5 Heat transfer capacity of peltier module with temperature difference.

From Figure 3.5, the temperature difference can be calculated that will be obtained according to the power that the thermoelectric module will have to move across the plates. The power is measured in watts, which is comparable with thermal power.

3.2.2 Cooling system of Peltier Element

The Peltiers normally generate a lot of heat on the hot surface, which is more than the heat they dissipate. It is due to the fact that the TEC itself draws a lot of current which generates heat itself due to losses. The most commonly used cooling method for peltier modules is the air cooling. A heat-sink that carries a cooling fan is mounted on the hot side of the peltier module to transport the heat away from the body. Heat transfer paste is used to transfer the heat efficiently. The heat sink should be chosen in a way so that it would be able to draw all the heat power that comes from the hot side of the peltier module.

Different types of cooling systems are used for peltier modules such as air to air, air to liquid and liquid-liquid cooling system. Air to air cooling system has mounted fan on both sides of the module. Both fan spreads the air to the surroundings. The fan that is attached on the cold side, spreads cold air and the fan that is connected to the hot side, spreads hot air. A air to liquid cooling system is used between the refrigerator compartment and the water tank compartment for the prototype. The fan of the air cooling system is supplied by low DC voltage. The water circulated by a pump serves to take away the heat from the hot side of the peltier module to the tank water.

3.3 Thermal insulating material for the refrigerator

There are a lot of thermal insulation material available, but only a few of them is suitable for using in refrigerator applications due to initial cost, the value of thermal conductivity, availability, durability, adaption of its shape, etc. In this application, it is better to use low thermal conductive material instead of higher thickness. Expanded polystyrene or Styrofoam, expanded perlite, fiberglass, cork etc. can be used as thermal insulating material [47],[48]. In the design of the prototype, Styrofoam is chosen as thermal insulation material as it is a low cost and low thermal conductive material [48]. Thermal insulating materials are used to reduce the heat transfer through the wall of an insulated enclosure. Heat always transfer from a high temperature to a low temperature region. Heat energy can be transferred by conduction or radiation. In a refrigerator, heat is transferred from external surrounding into the refrigerator. Heat transfer through the walls of insulated enclosure can be expressed by the following equation (4).

$$Q=\frac{A.\Delta T}{\frac{x}{k}+\frac{1}{h}} \tag{3.1}$$

Where,

Q= heat conducted through the enclosure (watts)

ΔT= temperature difference between the inside and outside of the enclosure(Degrees C)

x= thickness of insulation (meter)

k= thermal conductivity of insulation material (watts/meter-^{o}C)

A= area of enclosure (square meter)

h= heat transfer coefficient (watts/meter^2)

The Figure 3.6 shows the heat conduction through the enclosure with respect to the thickness of the insulation and temperature difference. Here the insulating material is Styrofoam with thermal conductivity of 0.033 watts/meter-^{o}C. The area of the enclosure is the outer surface(0.48x0.30x0.36) of the prototype refrigerator (0.42m^2). From the curve of Figure 3.6, it is clear that as the thickness of the insulation increases, the heat conduction decreases. For the selected insulation with thickness of 5cm and a 20 ^{o}C temperature difference, the heat conduction of the refrigerator is 11.14 watt.

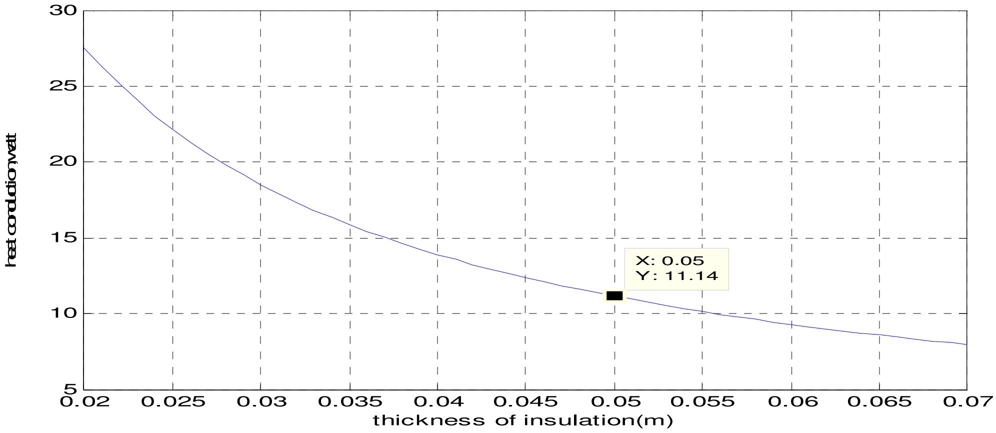

Fig: 3.6 Heat conduction vs. thickness of insulation.

3.4 Energy storage system

Normally energy is stored from some primary source in a convenient form that is easy to use at later time when a specific energy demand is to be met. There are different methods [43] available for energy storage such as electrochemical, electrical, mechanical, potential and thermal. Batteries and Fuel cells uses the technique of electrochemical energy storage systems where Capacitors, Super conducting energy storage systems stores energy in the form of electricity. Several energy storage systems such as Compressed air system, Flywheel, Hydraulic accumulator, Hydroelectric and spring system stores mechanical energy. Potential energy due to gravity can also be saved in hydro-electric system. Thermal energy storage system stores the heat and is known as latent heat storage. The extracted heat from the refrigerator that is coming out on the hot side of the peltier module can be stored in a thermal energy storage system that can be used at a later time.

3.4.1 Thermal energy storage system

Thermal energy storage system refers to different technologies that are used to store energy in a thermal reservoir, which gives the opportunity to use the stored energy later. It can be maintained at high or low temperature compared to the ambient temperature. There are various types of available stores for thermal energy such as in Phase Change materials, Underground, Hot bricks & Water.

Latent heat refers to the amount of energy released or absorbed by a chemical substance during its state change which occurs without changing its temperature. This implies a phase transition such as the melting of ice or the boiling of water [43] [44].Latent heat storage device contains phase change materials. Normally solid-liquid phase change materials are used as these stages are manageable compared to gas. Different types of phase change materials [45] are used to store the heat energy such as Organic Phase Change material for example Paraffin (C_nH_{2n+2}) and Fatty acids ($CH_3(CH_2)_{2n}COOH$), Inorganic Phase Change material for example Salt hydrates (M_nH_2O). Paraffin is good for storing thermal energy as it has a high specific heat capacity and it is relatively cheap.

Solid liquid phase change materials such as paraffin, changes their state at a certain temperature without increasing its own temperature significantly at that point. It absorbs huge amount of thermal energy during this change of state from solid to liquid. The amount of the stored thermal energy depends on the volume and heat storage capacity of the phase change material. The stored thermal energy is released when the ambient temperature around the liquid decreases and the phase is changed to its previous stage. Paraffin shows crystalline characteristics due to higher purity and special composition and it gives high heat storage capacity. It is non toxic, ecologically harmless, easy to handle, has large melting temperature range and its performance is stable during phase change cycle. The paraffin that is used in this thesis work is RT 100 [46]. It has melting temperature range of (90-112) °C, typically 100 °C and flash point is 312°C . The heat storage capacity is 124kJ/Kg. Density of solid paraffin at 15°C is 0.88 kg/l while density of liquid at 115°C: 0.77 kg/l. Heat conductivity is 0.2 W/(m*k) and volume expansion in phase change range is 14%.

3.5 Design of the prototype

The operation of peltier element depends on the input current (I) and voltage (V_{in}), the hot side temperature (T_h) and cold side temperature (T_c); and the heat input or heat pumped, (Q_c). In order to investigate the module performance it is necessary to set at least three of these variables. Two common methods involve either fixing the value of T_h, I and Q_c or fixing the values of T_h, I and T_c. Figure 3.7 shows the function of a peltier element [40].

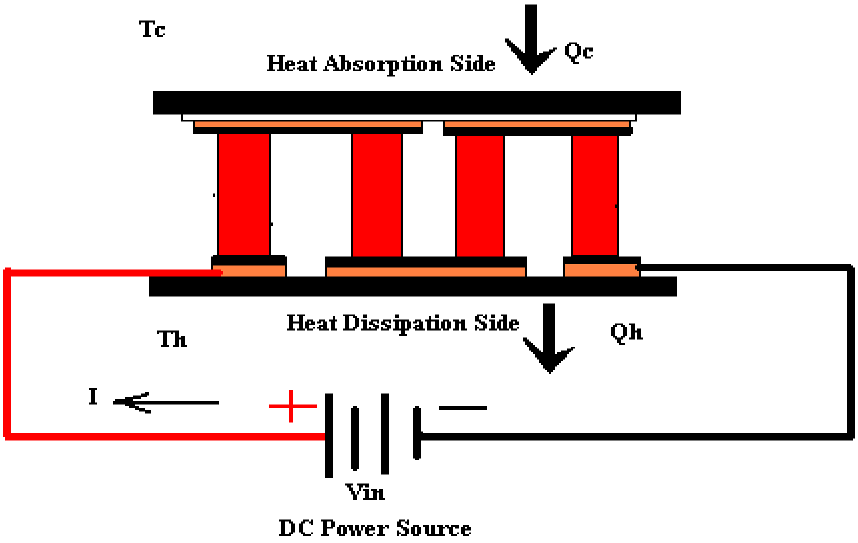

Figure 3.7 Single stage peltiel element.

The temperature difference (°C or °K) across the module is

$$DT = T_h - T_c \tag{3.2}$$

And the seebeck coefficient is

$$S_M = \frac{S_{MTh} - S_{MTc}}{DT} \tag{3.3}$$

Where, S_{MTh} is the module's Seebeck coefficient at the hot side temperature T_h and S_{MTc} is the module's Seebeck coefficient at the cold side temperature T_c.

The module resistance as a function of temperature difference can be written as

$$R_M = \frac{R_{MTh} - R_{MTc}}{DT} \tag{3.4}$$

Where, R_{MTh} is the module's resistance at the hot side temperature T_h and R_{MTc} is the module's resistance at the cold side temperature T_c.

The thermal conductance of the module, as a function of temperature can be expressed

$$K_M = \frac{K_{MTh} - K_{MTc}}{DT} \tag{3.5}$$

Where, K_{MTh} is the thermal conductance at the hot side temperature T_h and K_{MTc} is the thermal conductance at the cold side temperature T_c.

Heat pumped by the module in W is

$Q_c = S_M \times T_c \times I - 0.5 \times I^2 \times R_M - K_M \times DT.$ (3.6)

Q_c can be differentiated with respect to input current to maximize the pumped heat

$\frac{Qc}{dI} = S_M\ T_c - I\ R_M = 0$ (3.7)

$I = \frac{S_M T_C}{R_M}$ (3.8)

$Q_{c,max} = \frac{1}{2}\frac{S_M{}^2 T_C{}^2}{R_M} - K_M \times DT$ (3.9)

The input voltage to the module in volts is

$V_{in} = S_M \times DT + I \times R_M.$ (3.10)

At the optimal current for maximal pumped heat (3.8)

$$\begin{aligned} V_{in} &= S_M \times DT + \frac{S_M T_C}{R_M} \times R_M \\ &= S_M\, DT + S_M\ T_c \\ &= S_M\,(T_h - T_c) + S_M\ T_c \\ &= S_M\ T_h \end{aligned} \quad (3.11)$$

The electrical power to the module in W is

$P_{in} = V_{in} \times I.$ (3.12)

At the optimal voltage and current for maximal pumped heat it is

$$\begin{aligned} P_{in} &= S_M\ T_h \times \frac{S_M T_C}{R_M} \\ &= S_M{}^2 \frac{T_h T_C}{R_M} \end{aligned} \quad (3.13)$$

The coefficient of performance as a refrigerator is:

$COP = \frac{Q_c}{P_{in}}$ (3.14)

The heat rejected by the module in W is

$Q_h = P_{in} + Q_C.$ (3.15)

It also can be expressed as

$Q_h = S_M \times T_h \times I - 0.5 \times I^2 \times R_M - K_M \times DT.$ (3.16)

The coefficient of performance as heater (COPH) is

$COPH = \frac{Q_h}{P_{in}}$ (3.17)

3.5.1 Refrigerator side Thermoelectric module

In this combined refrigerator-stove system, the refrigerator side thermoelectric module is used both as a refrigerator and as a heater. It pumps heat from the refrigerator, to cool it, to the hot side where it heats the water simultaneously for later use. In the thermoelectric module 4 peltier elements are used. The 4 elements are connected in parallel. Figure 3.8 shows the performance curves of one peltier element at ambient temperature 20^{o}C. The input voltage to the peltier element is 12 volt DC. At this voltage it is taking a current of almost 5 A when the temperature difference is 20 ^{o}C. The input power of this module is 4*12*5 W= 240 W. From heat Pumped vs. Current curve, the amount heat pumped by the module is (4*32.5)W= 130W. The efficiency of the refrigerator at 20 ^{o}C temperature is 130/240 = 54%. From the performance vs. current curve, coefficient of Power is 0.54. Total rejected heat by the system is 4*(12*5+32.5) W = 370W. The efficiency of heating water is 370/240 = 154%.

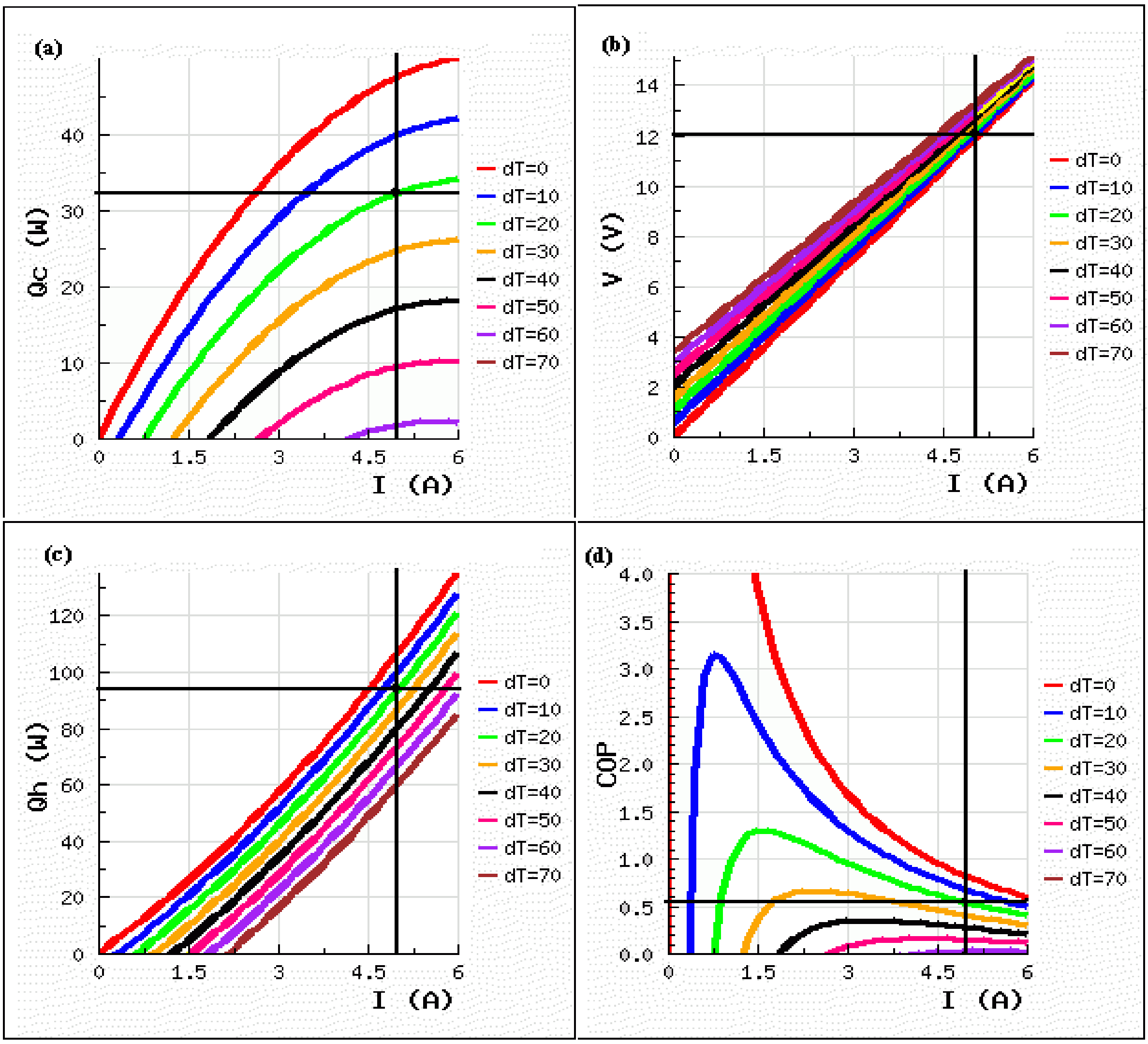

Figure 3.8 Performance curve for single module (a) Heat Pumped Vs. Current, (b) Voltage Vs. Current, (c) Heat Rejected Vs. Current and (d) Performance Vs. Current at 20 ^{o}C hot side temperature.

The Figure 3.9 shows the performance curve of the peltier element when the hot side temperature is 50 °C. In this case the input current reduces to 3.8 A and the input voltage is still 12 volt DC. The input power to the system is (4*45.6) W= 182.4W and (4*12)W= 48W of heat is removed. The efficiency of the refrigerator system is (48/182.4)=26% and the coefficient of power is 0.26. The total rejected heat is (4*58) W= 232W. The efficiency of heating water is almost 232/182.4 = 127%.

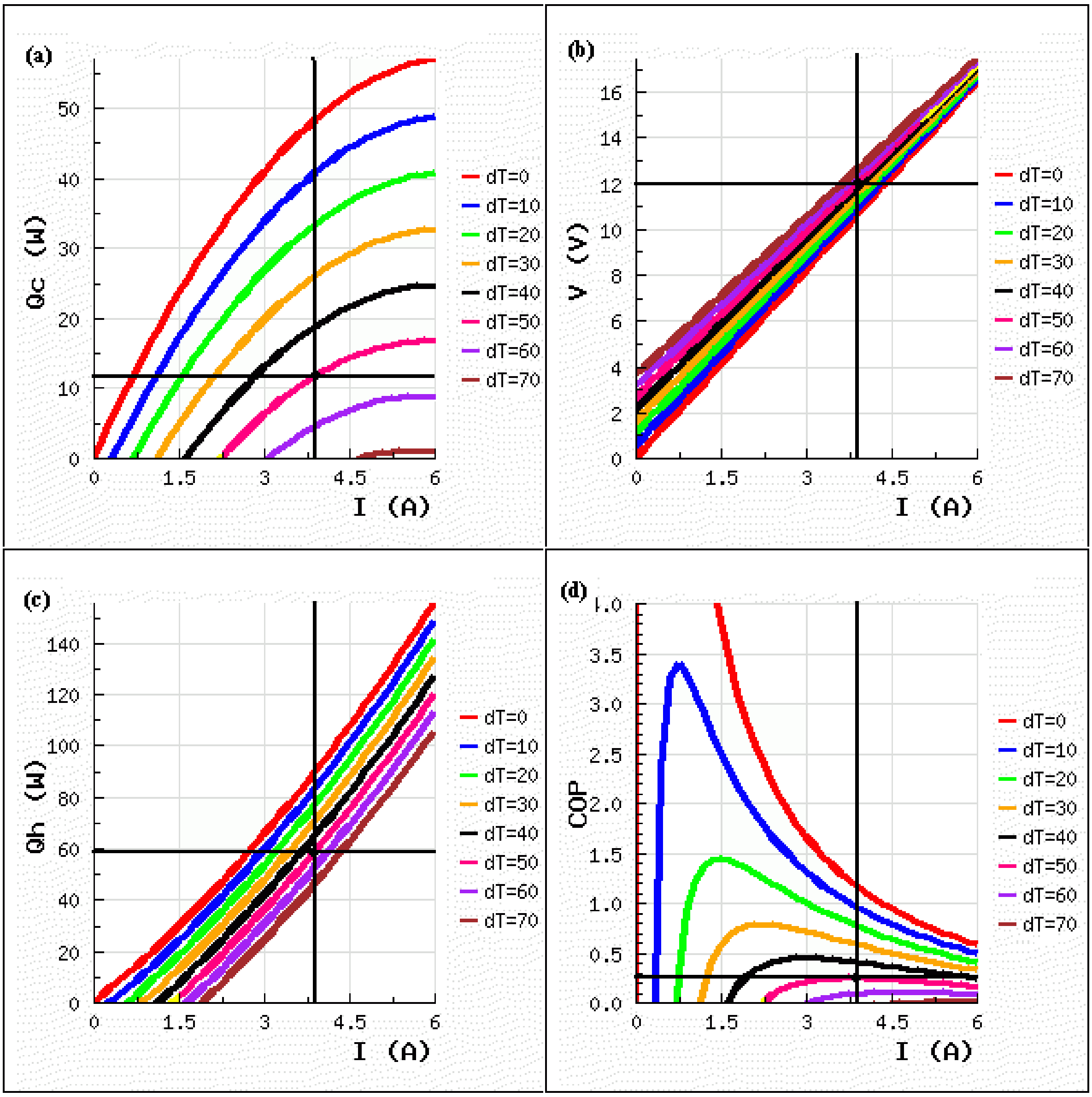

Figure 3.9 Performance curve for single module(a) Heat Pumped Vs. Current, (b) Voltage Vs. Current, (c) Heat Rejected Vs. Current and (d) Performance Vs. Current at 50 °C hot side temperature.

As mentioned above, the power coefficient of a thermoelectric module depends on the temperature difference between the hot side and the cold side. For low temperature difference, the maximum amount of pumped energy is high. The curve 3.8 shows the performance curve of the thermoelectric module that used in refrigerator side. Four series connected peltier elements are used in refrigerator side TEM. The input voltage of this module is 12x4=48 volt. The performance curve of this module is shown in Figure 3.10. Figure 3.10 shows that the amount of pumped heat reduces when the temperature difference increases.

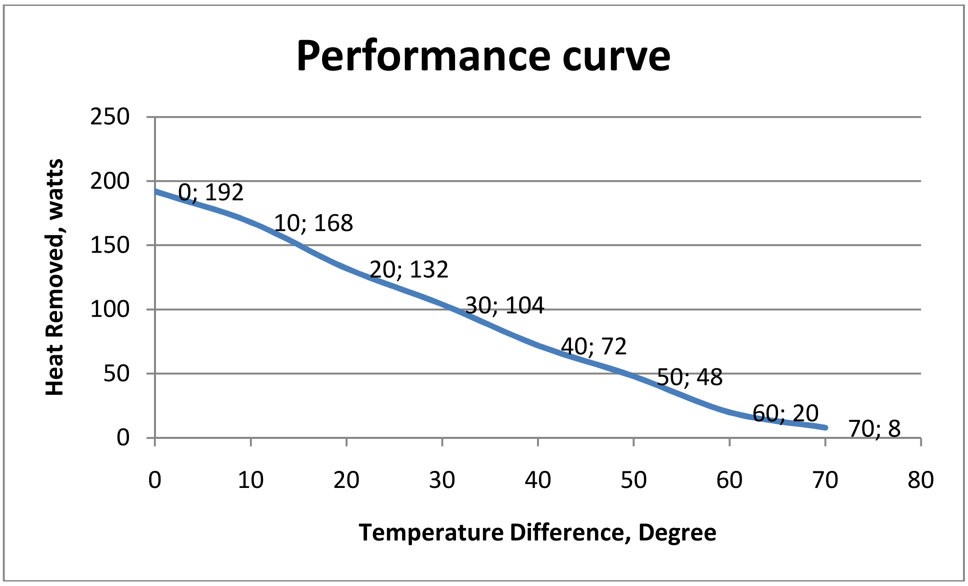

Figure 3.10 performance curve for a thermoelectric module.

3.5.2 Stove side Thermoelectric module

High temperature is necessary for the stove. It is not possible to get high temperature (>100 °C) using one single thermoelectric module when the refrigerator temperature is 0-4 °C. Two stage operation is required to get this high temperature difference. The purpose of the stove side module is to get high temperature and the energy from this module is stored in the paraffin. Figure 3.11 shows the performance curve of the hot side module. The amount of current taken by this module is 3.1A. Four peltier elements are connected in series while of power consumed by this module is 148.8W. The heat transferred by this module is (4*8)W =32W. The total rejected heat is (4x50)W= 200W. Rejected heat efficiency by this module is (200/148.8)=134%. There will be some losses due to heat leakage of the system during storing the energy. If we assume the amount of loss as 30 %, then the efficiency will be (200x0.7/148.8)= 94 %.

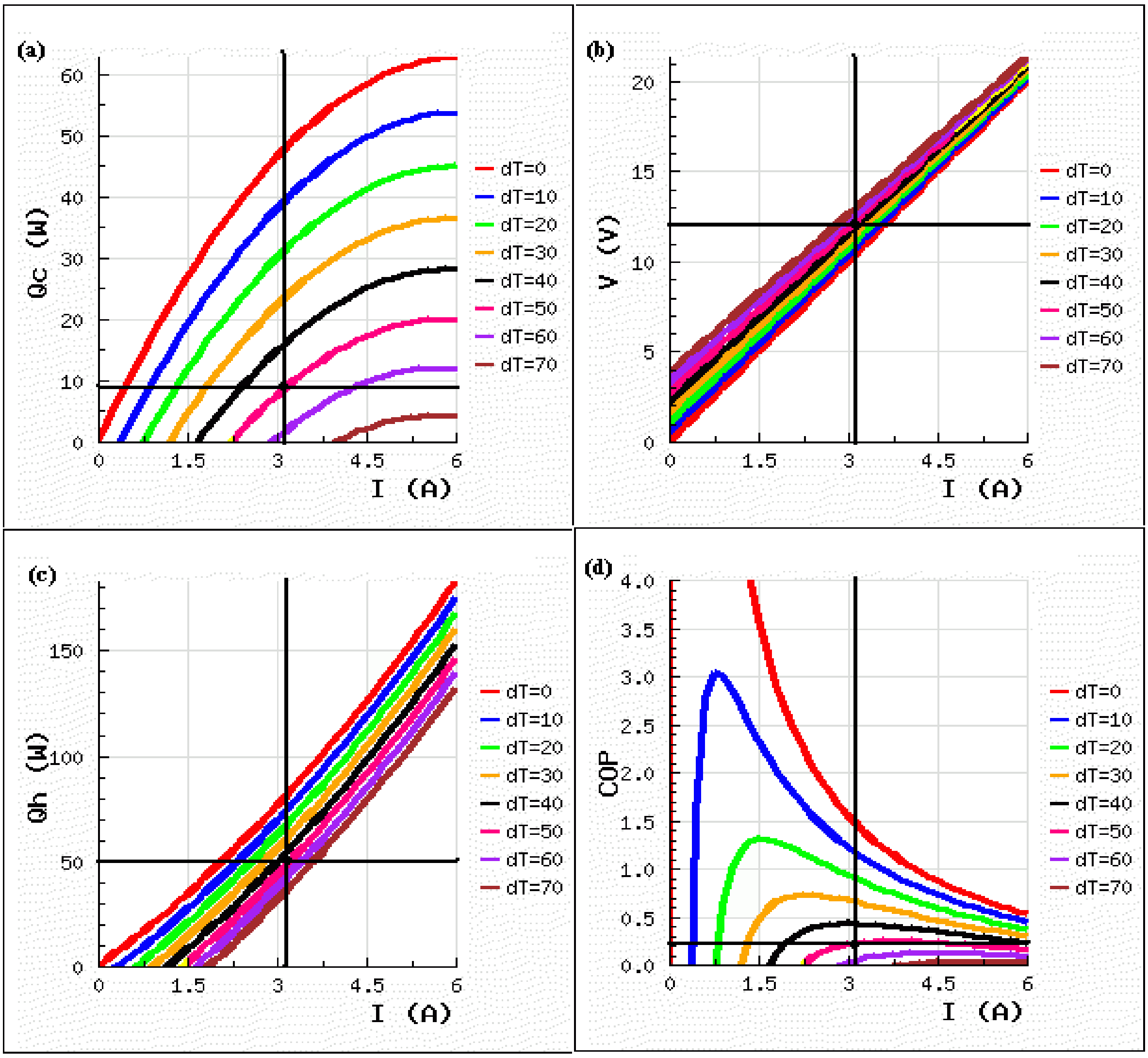

Figure 3.11 Performance curve for a single module(a) Heat Pumped Vs. Current, (b) Voltage Vs. Current, (c) Heat Rejected Vs. Current and (d) Performance Vs. Current at 100 °C hot side temperature.

3.6 Working principle

The working principle of a peltier element is described in Section 3.2. A combined unit of refrigerator and stove is designed using Peltier elements. The idea is that the peltier element will pump out heat energy from the refrigerator and the energy will be stored in a latent heat storage element e.g., paraffin. The electric energy required to pump the heat from the refrigerator is also transformed to heat and it will increase the amount of stored thermal energy. Due to the fact that the thermal energy from the refrigerator is stored and later used for heating the stove, the overall efficiency of the system is increased compared to a standard stove and refrigerator. Figure 3.12 shows a drawing of the system. The left side is the refrigerator unit, the right side is the stove unit and the two rectangular units between the refrigerator and stove are thermoelectric modules. Between these two modules there is a 9L water tank. Water is used for transferring heat as well as getting hot water for using in other purposes.

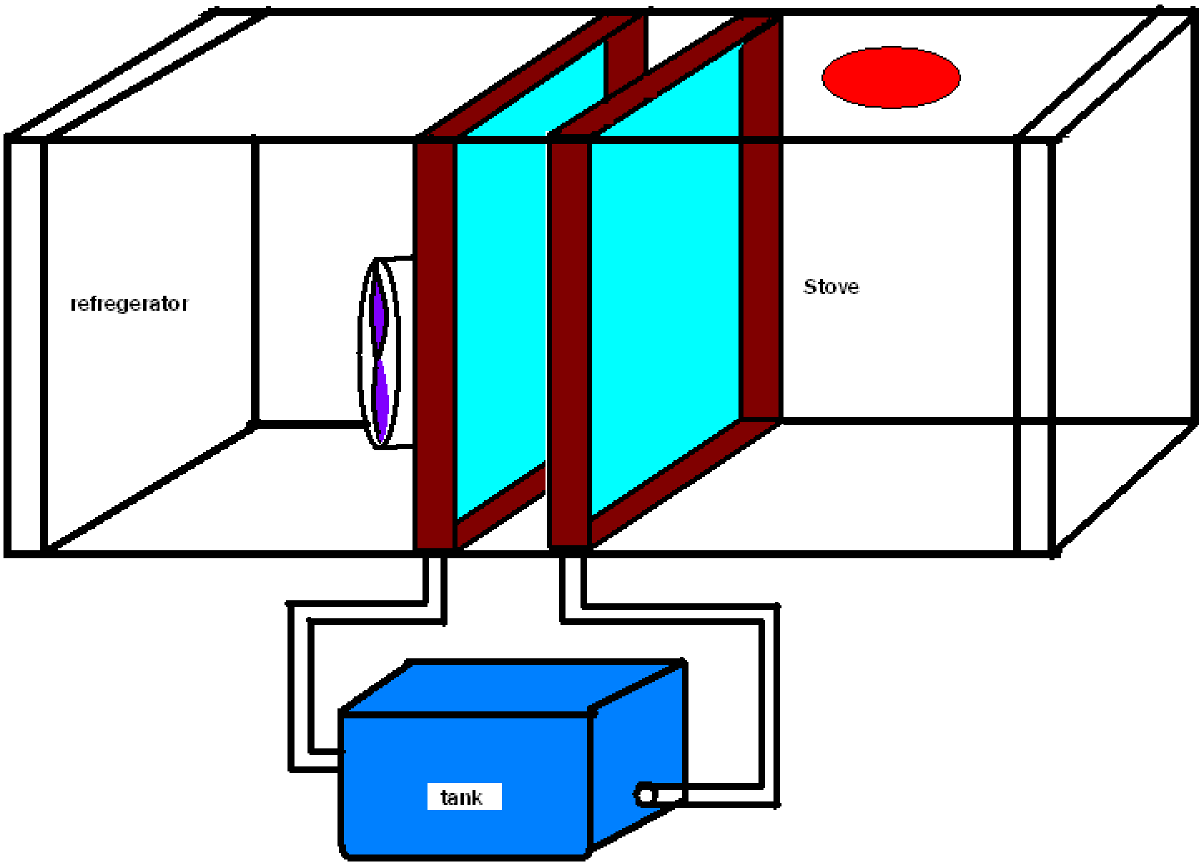

Figure 3.12 Block diagram of combined refrigerator and stove.

Each thermoelectric module consists of 4 peltier element with a rated input voltage of 12 volt DC. The 4 peltier elements are series connected to obtain a total input voltage of 48V DC for the system. The electrical connection diagram is shown in Figure 3.13. The cooling system of the refrigerator side thermoelectric module is air-to-liquid. Inside the refrigerator it is air cooling and a fan is used to reduce thermal resistance of the heat sink inside the refrigerator. Liquid cooling system is used at the hot side of the refrigerator. The temperature inside the refrigerator is maintained between 0 to 4°C and the hot side temperature of the module is maintained at almost 60 to 65°C as the maximum temperature difference of the module is 63°C. In the stove side the temperature must be greater than 100°C. To increase the temperature on the stove side thermoelectric module is used, that rises the temperature of the paraffin up to 120 °C. The second module also has four series connected peltier elements and the input voltage of the module is 48 V DC. The cooling system used for this system is liquid-to-direct. Liquid cooling system is used on the cold side of the module and the other side is just a metal plate attached to the hot side of the peltier elements.

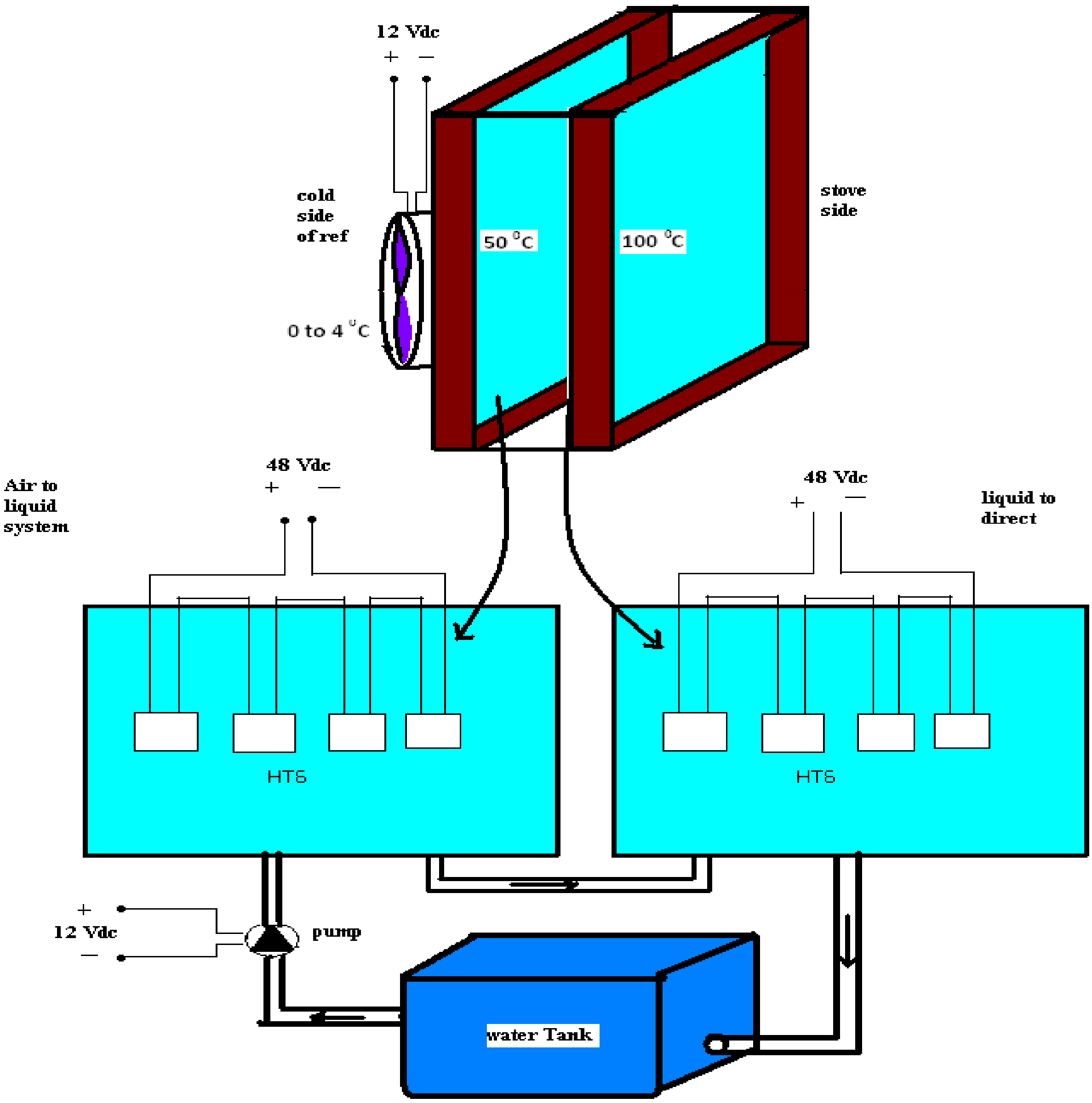

Figure 3.13 working principle for the system.

4 Experimental Results

In order to analyze the performance of the designed combined stove refrigerator unit, some experiment was performed. The experiment was done for different purpose such as controlling the temperature (0-4 ^{o}C) of the refrigerator unit, checking the performance of the stove unit by melting phase change material paraffin (by storing the heat energy into the paraffin). The input voltage was 48 volt for both thermoelectric module. The total input power of the two module was always less than 500W. For the first two experiments, 3.5 l of water was used and later it was increased to 9 l of water as the prototype was tested together with a dish washer which requires 9 l of water. In this chapter, the results of this experiment are discussed. Finally, the prototype was tested together with the dishwasher from the other group working in the same project, that runs on a low DC voltage. The peak power consumption of the dishwasher was reduced from 2000 W to 50 W by supplying hot water from the water tank [51]. In the end of this chapter the experiments are compared with the measurements.

4.1 Experiment

4.1.1Experiment 1

This experiment was performed to evaluate the performance of refrigerator side TEM. The experiment started with the initial sink temperature of refrigerator side TEM at 16 ^{0}C, while initial temperature of the 3.5 L water in the water tank was 13 ^{0}C. Figure 4.1 shows the temperature of the heat sink of the refrigerator side TEM and the temperature at the hot side of the same TEM. The sink temperature of the refrigerator side TEM took 4 minutes to go down from 16 ^{0}C to 0 ^{0}C as shown in Figure 4.1. After that 18 minutes passed to reach at -13 ^{0}C and maintained same temperature for 12 minutes. The sink temperature started to increase after 30 minutes and it took 54 minutes to reach 0 ^{0}C from -13 ^{0}C. At the 100th minute of the experiment, the sink temperature was at 1 ^{0}C. After reaching to a certain temperature, the sink temperature increased with the increment of the hot side temperature of TEM. It happened to maintain an almost constant temperature difference between the two plates of TEM. Because at 50 ^{0}C temperature difference, the module can only move almost 10 W of thermal power and this is the same amount that is leaking into the refrigerator compartment at steady state operation. The temperature of water increased almost linearly from 13 ^{0}C to 62 ^{0}C within 100 minutes of the experiment. Figure 4.2 presents the input current, voltage and power of the thermoelectric module at the refrigerator. Initially TEM took 225 W as it has removed more energy. The energy removed by the TEM decreased with the increment of the temperature difference. As a consequence, the power taken by the TEM was reduced e.g., the TEM took 168 W at the instant of the 70th minute of the experiment.

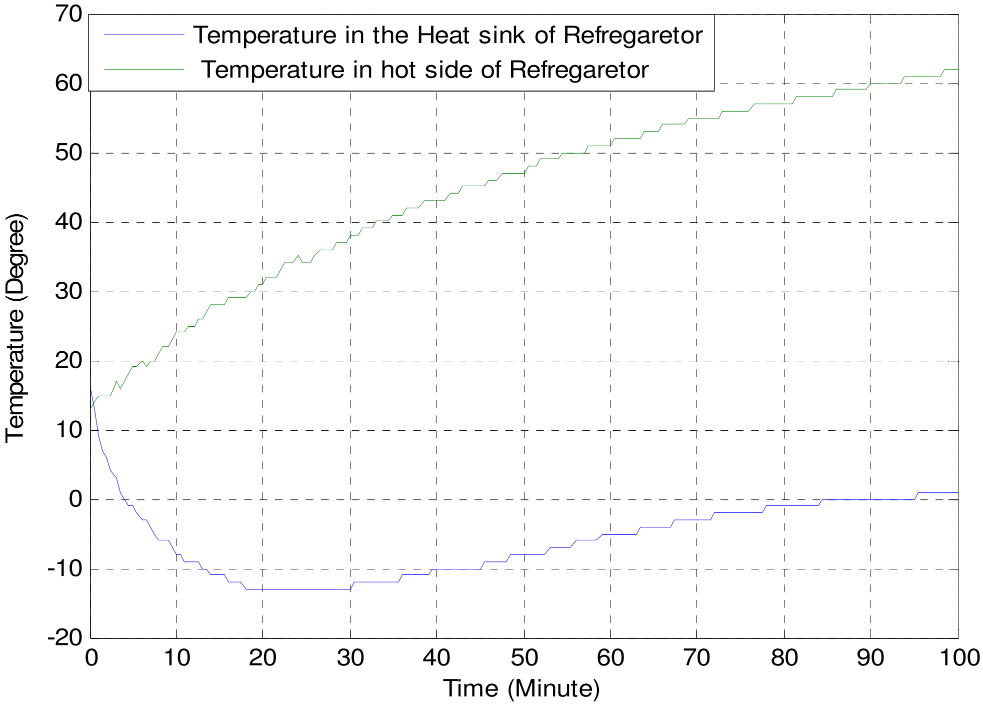

Figure 4.1 Temperature variation in both side of the refrigerator with time.

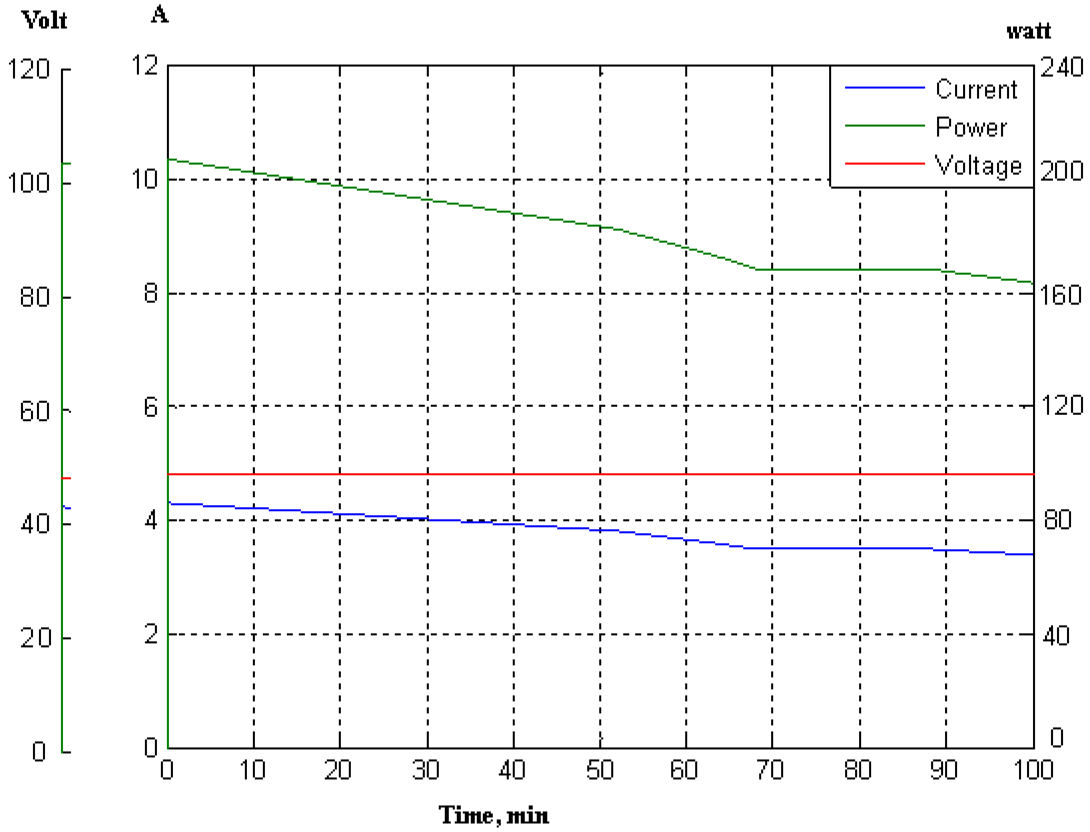

Figure 4.2 The input current, Voltage and Power of experiment 1.

4.1.2 Experiment 2

This experiment was performed to control the temperature of the refrigerator by changing the water in the tank. In this experiment, A bottle with 1 liter of water was kept inside the refrigerator while the initial temperature was 15 ^{o}C, there was 3.5 L of water in the water tank which temperature was 18 ^{o}C, the temperature inside the refrigerator was 17 ^{0}C and the input voltage to the TEM was 48 volt. Figure 4.3 shows the temperature on the heat sink of the refrigerator side TEM and temperature at the hot side of the same TEM and Figure 4.4 presents the input current, voltage and power of thermoelectric modules. The temperature of the air inside the refrigerator decreased from 18 ^{o}C to 0 ^{o}C within 12 minutes and it remained between 0 ^{o}C to -1 ^{o}C for 23 minutes. The module consumed 192 W at the instant of 12 minutes. In the mean time, water temperature in the water increased from 19^{o}C to 50 ^{o}C. The Stove side TEM was supplied by 48 V DC at the instant of the 35th minute of the experiment when the temperature of tank water reached to 50 ^{0}C. At the 61st minute, the hot water of 68 ^{0}C temperature in the tank was replaced by cold water. The hot water was taken to be used in other purposes such as in the dishwasher.

After the high temperature thermoelectric module was supplied with DC power, the air temperature inside the refrigerator remained within 0 ^{o}C to 4 ^{o}C for almost 30 minutes. The temperature of the circulating water increased from 50 ^{o}C to 69 ^{o}C at the same time. The water temperature was reduced to 46 ^{o}C by pouring cold water from the tap and taking same amount of water out of the tank. The breaking point in the curve is showing the time instant of replacing the tank water. The air temperature inside the refrigerator again started to decrease and maintained its temperature between 0 ^{o}C to 4 ^{o}C for 35 minutes more. Initial power taken by the refrigerator side TEM was 225 W at 0 ^{o}C temperature difference and decreased to 190 W while the temperature difference reached to almost 50 ^{o}C. After the stove side TEM was supplied by 48 V DC, the total power taken by the both TEM was 384 W and it reduced to almost 300 W at 100th minute with the increment of the temperature difference and the temperature of the stove module was 131 ^{o}C.

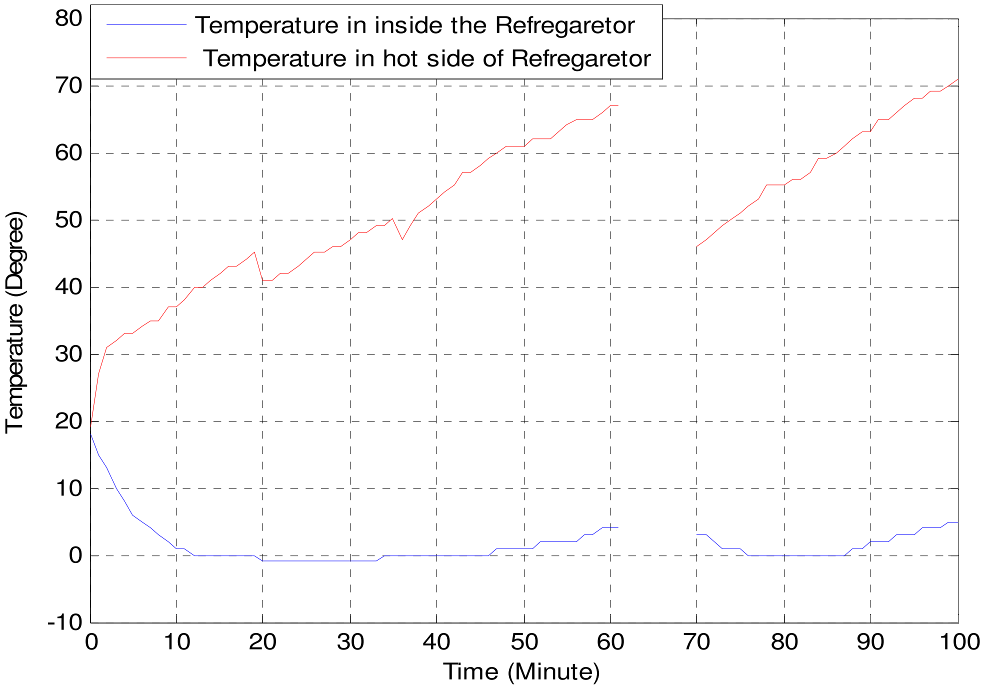

Figure 4.3 Temperature variation in both the cold side and hot side of the low temperature thermoelectric module.

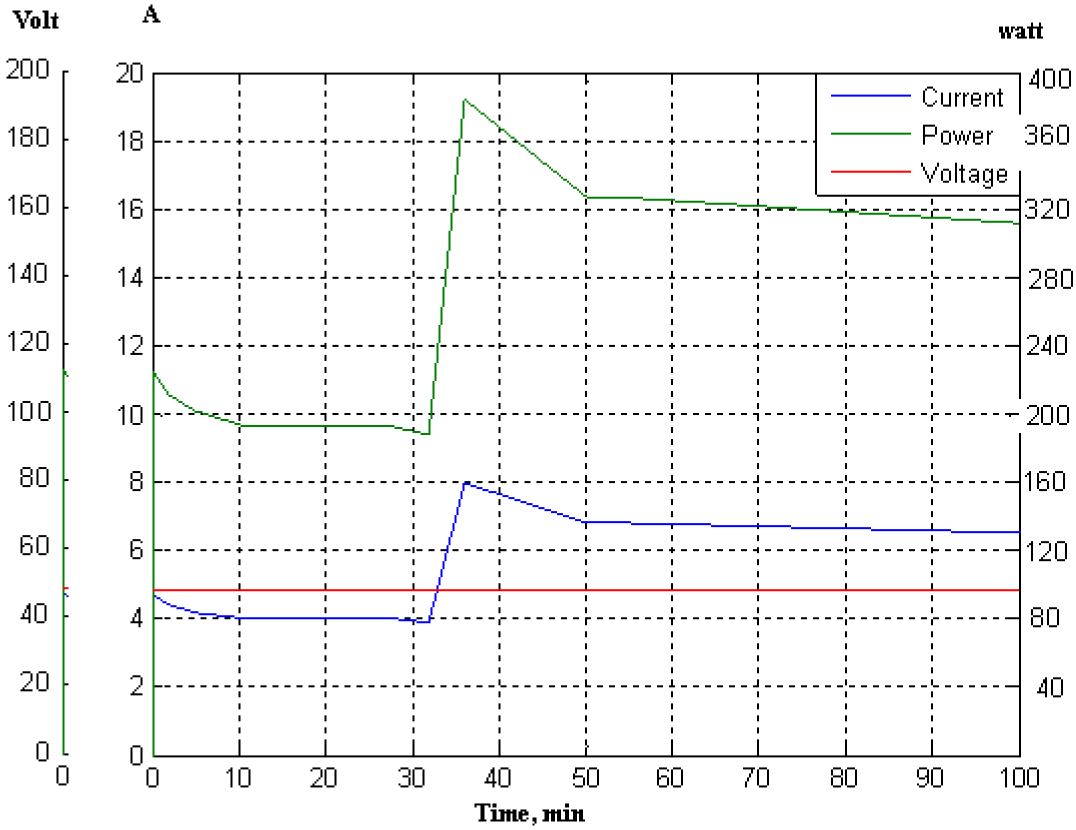

Figure 4.4 The input current, Voltage and Power of experiment 2.

4.1.3 Experiment 3

This experiment was performed to evaluate the performance of both modules when supplied with 52V DC. In this experiment, two bottles with total 1.5 l of water was kept inside the refrigerator at an initial temperature of 20^{0}C, the initial temperature inside the refrigerator was 18 ^{0}C and the temperature of the tank water was 18 ^{0}C. Figure 4.5 shows the temperature of the heat sink in the refrigerator and the temperature at the hot side of the refrigerator side TEM. Figure 4.6 presents the input current, voltage and power of thermoelectric modules. The temperature of the air inside the refrigerator felt down from 17 ^{o}C to 0 ^{o}C within 13 minutes and it remained at 0 ^{o}C for 20 minutes from the instant of the 13th minute to 33rd minute. In the mean time, the water temperature increased from 25^{o}C to 50 ^{o}C. The stove side TEM was supplied by 52 V DC supply at the instant of the 33th minute of the experiment, when the temperature at cold side of that module reached to almost 50 ^{0}C. After the high temperature TEM was supplied with DC power, the air temperature inside the refrigerator started to increase and reached to 4 ^{o}C within almost 19 minutes. It happened due to the fact that the amount of extracted heat was less than the amount of leakage heat entered into the refrigerator. In the mean time, the water temperature increased from 50 ^{o}C to 63 ^{o}C. The hot water of 62 ^{0}C temperature in the tank was replaced by cold water at the instant of 49th minute and the water temperature inside the tank was reduced to 45 ^{o}C. The discontinuous line on the graph of Figure 4.5 shows the time instant of the water replacement which is from the 49th minute to the 62nd minute. The air temperature inside the refrigerator again started to decrease and maintained its temperature between 0 ^{o}C to 4 ^{o}C for more 40 minutes. The initial power taken by the refrigerator side TEM was 260W at 0 ^{o}C temperature difference and it decreased to almost 215W when the temperature difference reached almost 50 ^{o}C. The temperature at the stove side module was 141 ^{o}C in steady state. The total power taken by the both TEMs was 429W initially at 33rd minute and it reduced to almost 360W at the 100th minute due to the increment of the temperature difference.

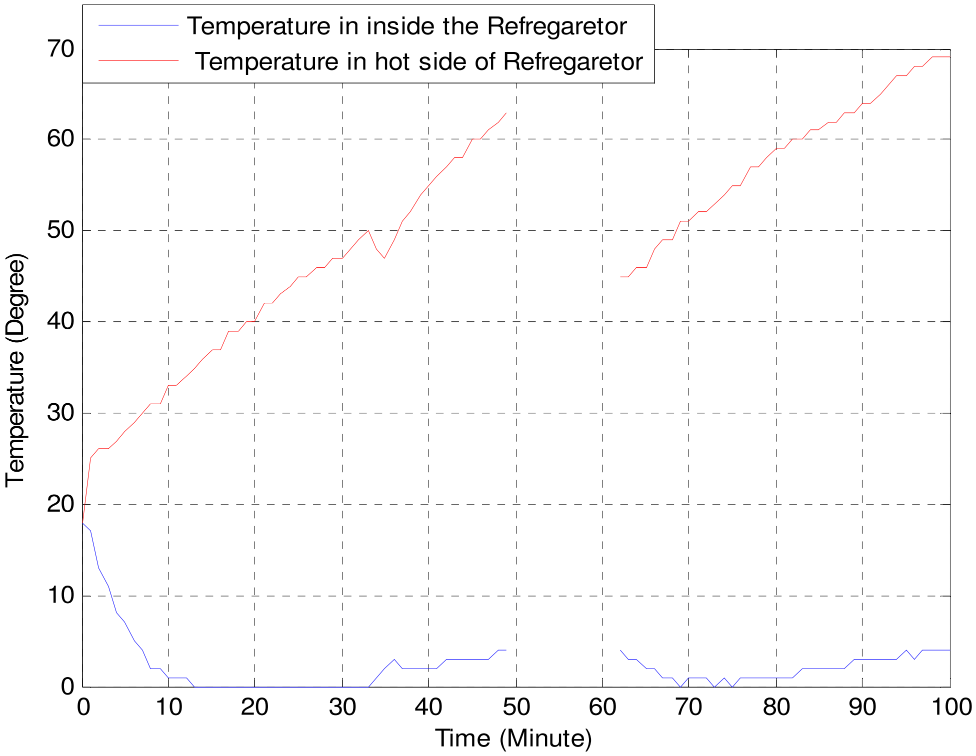

Figure 4.5 Temperature variation in both the cold side and hot side of the low temperature thermoelectric module for 52 V supply.

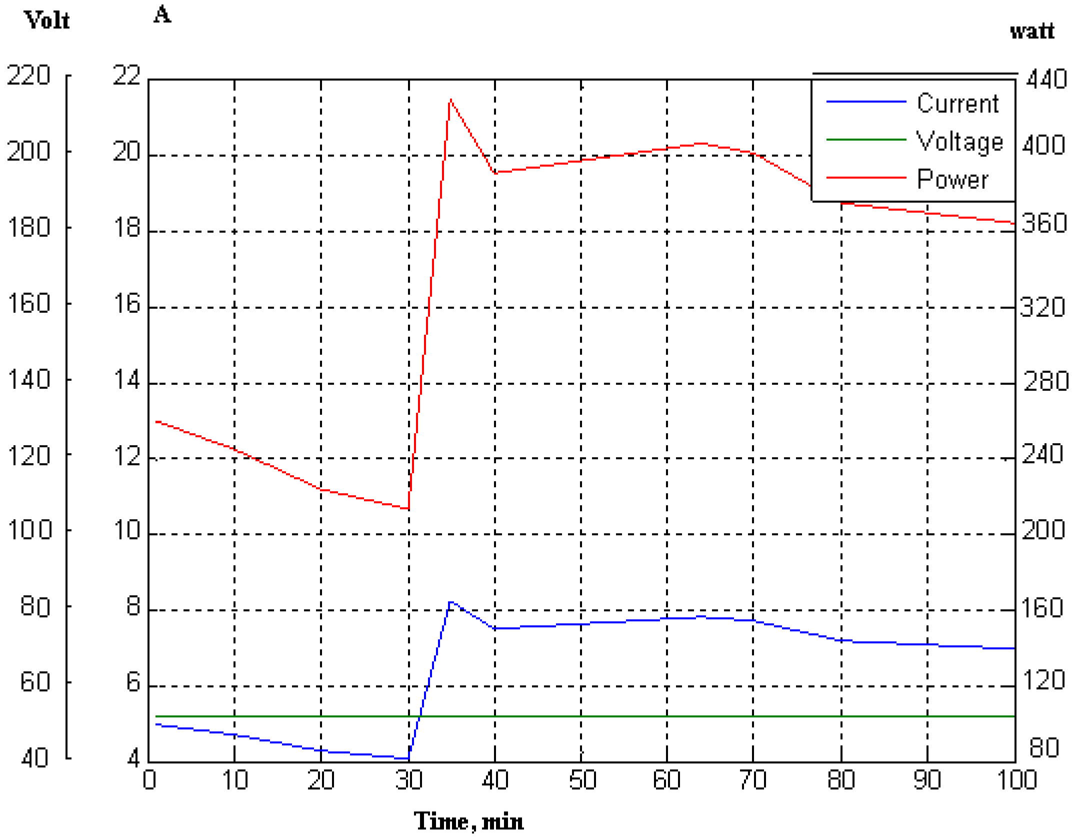

Figure 4.6 The input current, Voltage and Power of experiment 3.

4.1.4 Experiment 4

This experiment was performed to evaluate the performance of the stove side TEM. In this experiment, there was no water inside the refrigerator. Initially the refrigerator side TEM was supplied by 48 V DC, stove tank was filled with 7 kg of paraffin, the temperature of the air inside the refrigerator was 17 ^{0}C, the temperature of the heat sink of the refrigerator side TEM was 15 ^{0}C and the temperature of the 9 l tank of water was 7 ^{0}C. Figure 4.7 shows the temperatures of the refrigerator, water tank and paraffin for this experiment. The temperature of the air inside the refrigerator decreased from 17 °C to 0 °C within 6 minutes and it was further reduced to -18 °C at the 32nd minute of the experiment when the temperature of the water in the water tank was at 31 °C. This means that the hot side temperature of the TEM is almost 32 °C. After this point, the refrigerator temperature started to increase with the increment of hot side temperature in order to maintain a constant temperature difference of 50 °C between both side of the TEM as it is designed. The refrigerator air temperature reached to 0 °C from -18 °C after 60 minutes and in the mean time, the water tank temperature was increased to 41 °C. The refrigerator temperature increased faster than the increment of the water tank temperature. This because of the high temperature difference between the refrigerator temperature and the surrounding room temperature, the leakage of thermal energy from the surroundings to the refrigerator was larger. The stove side TEM was supplied by 48 V DC at the 116th minute of the experiment when the temperature of the water tank reached to 50 °C. As mentioned before, the aluminum stove tank was filled up with 7 kg paraffin for this experiment. The hot side temperature of the stove TEM took 254 minutes to increase the temperature from 30 °C to 100 °C and in the mean time the temperature of the water tank increases from 48 °C to 72 °C. The temperature gradient inside the paraffin is clear from the two curves of top paraffin temperature and bottom paraffin temperature as shown in Figure 4.7. The curve is showing larger temperature gradient and it is due to the fact that the paraffin has low heat conductivity of 0.2$Wm^{-1}k^{-1}$.

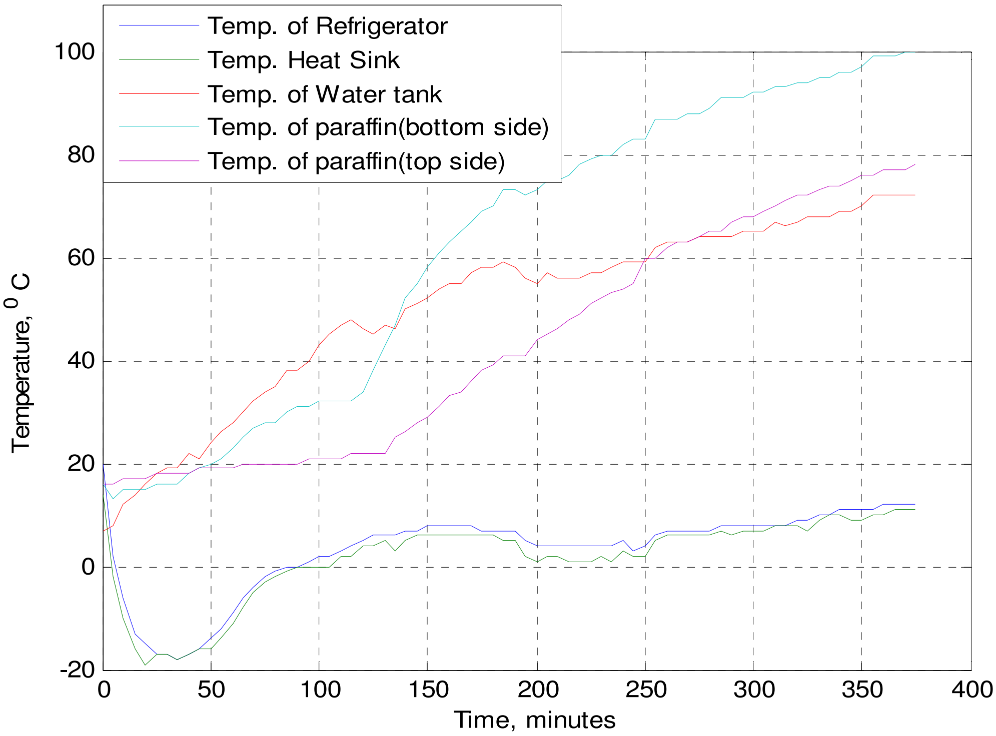

Figure 4.7 Temperature variation in refrigerator, water tank and paraffin without water inside the refrigerator.

4.1.5 Experiment 5

This experiment was performed to see the overall performance of the system. In this experiment, initially two bottles with total 1.5 l of water was kept inside the refrigerator, the temperature of the air inside the refrigerator was 18 ^{0}C, the temperature of the heat sink of the refrigerator side TEM was 16 ^{0}C, the temperature of the 9 l tank water was 16 ^{0}C, the refrigerator side TEM was supplied by 48 V DC and the stove tank was filled up with 8 kg of paraffin. The stove side TEM was supplied by 48 V DC at the instant of 80th minute of the experiment, when the temperature at the cold side of that module reached to almost 32 ^{0}C. In this experiment the stove side module was supplied earlier compared with the other experiments, to heat up the paraffin quickly. Figure 4.8 is showing the temperatures of the refrigerator, water tank and paraffin for this experiment. The temperature of the air inside the refrigerator decreased from 18 ^{o}C to 0 ^{o}C within 10 minutes and stayed between 0 ^{o}C to 4 ^{o}C for 220 minutes. In the mean time the hot side temperature of the refrigerator side TEM increased from 16 ^{o}C to 58 ^{o}C. After that point the refrigerator temperature started to increase with the increment of the water tank temperature by keeping almost 50 ^{o}C temperature difference between both sides of TEM. The temperature of the paraffin at the bottom side of the tank increased from 19 ^{o}C to 112 ^{o}C after 470 minutes while at the top side of the tank the temperature of the paraffin was only 80 ^{o}C. The temperature of the water tank was reduced to 57 ^{o}C at 490th minutes as shown in Figure 4.8 by replacing 3.5L of hot water with cold water from the water tap. The water tank temperature was further reduced to almost 50 ^{o}C by circulating water through the dish washer. The temperature gradient inside the paraffin is clear from the two curves for temperature of paraffin at top side of the tank and the temperature of paraffin at the bottom side as shown in Figure 4.8.

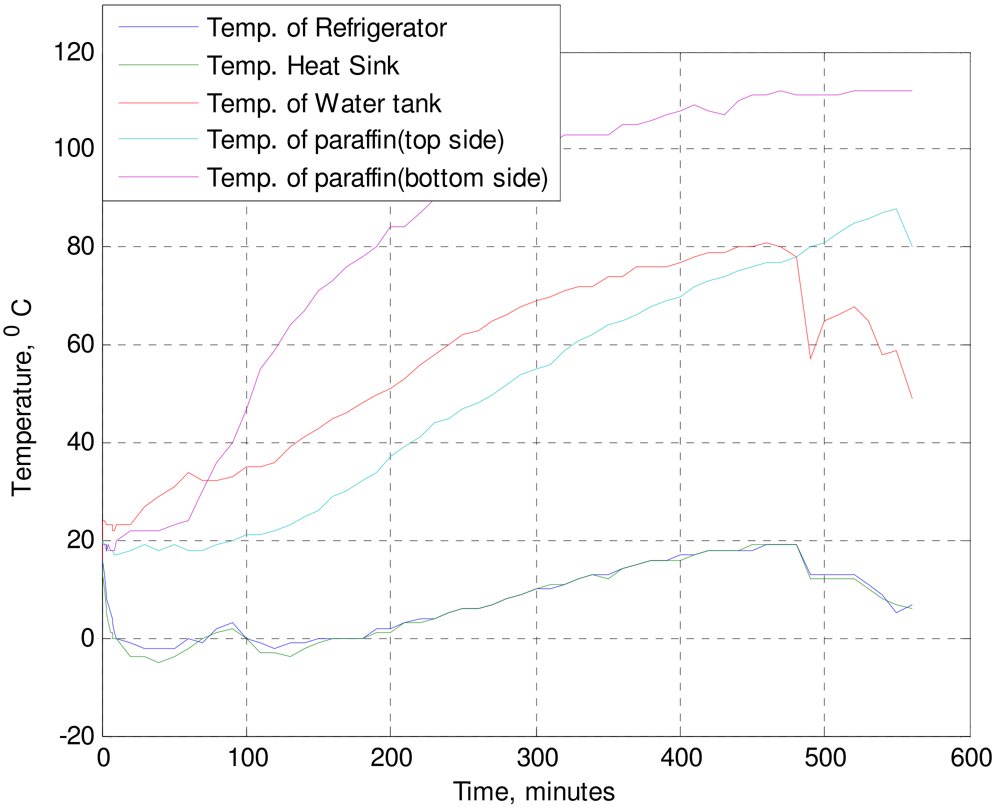

Figure 4.8 Temperature variation in refrigerator, water tank and paraffin with water inside the refrigerator.

4.2 Comparison between theoretical and experimental result

In this section the theoretical calculations for the TEMs, presented in section 3.5 are compared with the measurements presented in section 4.1. For the refrigerator side TEM experiment 2 is used and the measured values for this experiment are shown in Figure 4.3 and Figure 4.4.

The inner volume of the refrigerator is 0.26x0.38x0.20=0.01976 m^3. From experiment 2, the temperature of the refrigerator reduces from 18 °C to 0 °C within 12 minutes. And the temperature of the 1 liter water decreases from 18 °C to 6 °C, see Figure 4.3. At 20 °C and 101.325 kPa, dry air density is 1.2041 kg/m^3 [49]. The Specific heat of dry air is 1.012 $J \cdot g^{-1} \cdot K^{-1}$ [50]. The amount of air inside the refrigerator is 0.01976 m^3 x 1.2041 kg/m^3 = 0.023793 Kg = 23.793 g and the removed energy from this air is 23.793 g x 1.012 $J \cdot g^{-1} \cdot K^{-1}$ x (18-0) K = 433.41 J. The specific heat of the water is 4.186 kJ. $kg^{-1} \cdot K^{-1}$[50]. The amount of energy removed from the water is 1kg x 4.186 kJ. $kg^{-1} \cdot K^{-1}$ x (18-6) K = 50.232 kJ= 50232 J. The specific heat of the aluminum is 0.91 kJ. $kg^{-1} \cdot K^{-1}$[50]. The weight of the heat sink used with the refrigerator side TEM is 0.5 kg. The temperature of the heat sink decreases from 18 °C to -2 °C during the same interval of 12 minutes. The amount of energy removed from the heat sink is 0.5kg x 0.91 kJ. $kg^{-1} \cdot K^{-1}$ x (18-(-2)) K = 9.1 kJ = 9100 J. Total amount of heat removed from the heat sink, air and the water is 9100 J + 433.41 J + 50232 J=59765.41J.

The average input power to the refrigerator TEM is 208W for the first 12 minutes. The input energy during this period of 12 minutes is 208 $J.s^{-1}$ x (12 x 60)s = 149760 J.

The efficiency of the refrigerator side TEM as a refrigerator is 59765.41/149460=**39.9%.**

This module rises the temperature of the tank water from 19°C to 35°C within 12 minutes. The amount of energy absorbed by the water is 3.5 kg x 4.186 kJ. $kg^{-1} \cdot K^{-1}$ x (35-19) K = 234.416 kJ= 234,416 J. This energy higher than the sum of electrical energy and the extracted energy from the heat sink, air and the water. It is due to the fact that the energy extracted from the aluminum body of the TEM and the metal part of the mounted fan are not considered.

The efficiency of this module in heating mode is 234,416J/149,760J = **162%**.

For the stove side TEM experiment, experiment 5 is used for the comparison with the theory.

The amount of paraffin used in experiment 5 is 7 kg. The temperature rises from 22 °C to 43 °C within 30 minutes as can be seen in Figure 4.8. During this period between 65th minute and 95th minute, the average input power was 233 W. The specific heat of the paraffin is 2.5 $kJ \cdot kg^{-1} \cdot K^{-1}$ [50]. The amount of energy stored in the paraffin is 7 x 2.5 $kJ \cdot kg^{-1} \cdot K^{-1}$ x(43-22) = 367 kJ. The amount of energy taken by the stove side TEM within this period is 233 $J.s^{-1}$ x (30 x 60) s =419,400 J =419 kJ.

The efficiency of the stove side TEM is 367kJ/419kJ = **87.6%.**

Table 4.1 presents the theoretical and measurement efficiency of the refrigerator side and stove side TEMs. Theoretical calculations for the efficiency of the module are shown in Section 3.5. The refrigerator side module's cold side theoretical efficiency is higher than the measurement efficiency and it is due to the fact that the refrigerator was not well insulated which reduces the efficiency. The hot side's theoretical efficiency is less than measurement efficiency. The reason could be that, energy extracted energy from the heat sink were not taken into account for the theoretical calculation of efficiency. Energy is stored in the paraffin at higher temperature compared to room temperature and there will be continuous heat leakage through the thermal insulating material. Moreover, the amount of heat used to heat up the aluminum tank of the paraffin was not considered in theoretical calculation. As the prototype was not properly insulated, the loss due to heat leakage is considered as 30%. The stove side module's theoretical and measurement efficiencies are almost equal if we compare it with the theoretical value in which 30% heat loss has been taken into account.

Table 4.1 Theoretical and measured efficiency of the module.

	Refrigerator side Thermoelectric Module efficiency		Stove side TEM efficiency	Stove side TEM efficiency
	Cold side	Hot side	Without considering heat loss	considering 30% heat loss
Theoretical	54%	154%	134%	94 %
Measurement	39.9%.	162%		87.6%

The amount of energy required to increase the temperature of half liter water from 20 °C to 100 °C = 0.5kg x 4.186 J $kg^{-1}K^{-1}$x (100-20)K = 167.44 kJ. The heat of vaporization for water is 2261 J/g. Total amount of energy required to boil half liter of water is 500g x 2261 J/g + 167.44 kJ = 1.3 MJ. The heat storage capacity of the paraffin is 124kJ/Kg. The weight of the paraffin used in the stove for boiling water practically is 9 kg. The amount of heat stored in the paraffin is 9kg x 124 kJ/kg = 1.12 MJ.

By using the stove of the prototype, 700 ml of water was boiled in the pot and it took almost 25 minutes to boil the water.

4.3 Theoretical Calculation for large scale model of refrigerator

For the calculation large scale model, a standard size of refrigerator with 167.6cm height, 83.82cm width and 81.28cm length has been taken into consideration. The inner volume of the refrigerator = 1.15 m^3. The weight of the air inside the refrigerator is 1.15 m^3 * 1.2Kg/m^3 = 1.38Kg = 1380g. To cool down the refrigerator from 18°C to 0°C, the amount of energy that needs to be removed from the air is 1380g * 1.012 $J\cdot g^{-1}\cdot K^{-1}$ * (18-0) K = 25.1 kJ

If we consider that one water bottle of 1 liter is kept inside the refrigerator, then the amount of energy required to be removed to cool down it from 18°C to 0°C is 1kgx4.186 kJ. $kg^{-1}\cdot K^{-1}$ x(18-0) K = 75.6 kJ. A heat sink is attached with the refrigerator side TEM. The TEM will extract heat from the heat sink and the heat sink will cool down from 18°C to -2°C. The amount of energy removed from the heat sink is 0.5kg x 0.91 kJ. $kg^{-1}\cdot K^{-1}$ x (18-(-2)) K = 9.1 kJ. The total energy that needs to be removed in this case is (25.1+75.6+9.1) kJ =109.8kJ From the calculation of Section 4.2, we found that the refrigerator side TEM took 12 minutes to remove 59.8 kJ of energy from the refrigerator. Therefore, the time required to remove 109.8 kJ energy by the same TEM will be = 22 minutes.

The average power taken by the module is 208W in this case and the total energy taken by the refrigerator side TEM during this 24 minutes is 208J/s * 22 * 60 s = 275kJ

The efficiency of the TEM to work as refrigerator = 109.8kJ/275kJ = 39.9 %.

5 Conclusion

This report investigates the alternative for household appliances of using a 48 V DC supply, instead of the normal 230 V AC voltage. The losses for AC to DC and DC to AC conversion inside the home appliances can be reduced by using a DC distribution system in the house. For the wiring of the 48 V DC distribution system with optimized cable area, the cable cost will increase by 48% compared to the cable cost for 230 V AC distribution system. But the savings for the 48 V DC system will be higher in the long run due to reduced energy consumption per year. This work considered a 20 years life span for the calculation of the total cost for the different distribution systems. The savings in the total cost for the 48 V DC distribution system with optimized cable area compared to the 230 V AC distribution system, will be almost 13000 SEK within the 20 years life time.

In case of a low voltage DC distribution system, there is a problem of high power loss in the cable for the high power consuming loads. The stove is one of the high power consuming kitchen appliances and it consumes large amount of energy. This project focuses on an efficient stove design for DC supply. To decrease the energy consumption of the stove, the idea is to combine it with the refrigerator. The heat extracted from the refrigerator is stored in the stove and is used for cooking or other purposes. Some portion of the extracted heat is stored in the water tank which can be used for different purposes such as for a dishwasher. This technique of storing the extracted heat, increased the overall efficiency of the system. The practical efficiency of storing the extracted heat in the water is 162 %, where the theoretical efficiency is 154% and theoretical efficiency was calculated without considering the heat extracted from the heat sink. The efficiency of storing heat in the paraffin of the stove is 87.6%, where the theoretical efficiency is 94% after considering a 30% loss in the system due to weak thermal insulation. The practical efficiency of the refrigerator using TEM is 39.9%, where the theoretical efficiency is 54%. The average power taken by the refrigerator side TEM is 208 W. The maximum power taken by the both TEM of the prototype unit is 384 W. It can be concluded that the practical results from the experiments are reasonable compared to theoretical results if the losses in the system are taken into account.

The prototype was tested together with a dishwasher of the other group in the same project and it runs on 48V DC supply as well. The hot water from the water tank was supplied to the dishwasher and the energy consumption of the dishwasher was reduced to less than one tenth of normal power consumption.

Due to the fact that the thermal energy from the refrigerator is stored and later used for heating the stove, the overall efficiency of the system is increased compared to a standard stove and refrigerator. To implement the proposed design practically, more research is recommended for improvement of the insulation system, to improve the efficiency of the whole system. More analysis is required to make the TEM more efficient for extracting energy and to make the unit cheaper. Design of automatic control system is also recommended for the proposed system.

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