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Design and Simulation of a Solar Electricity Based Induction Cooker using Quasi Resonant Topology

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Abstract

Cooking is one of the important human activities. As of 2012, residential energy consumption in Nepal is 80% of the total energy consumption, out of which 60% energy is used for cooking applications. In urban residential sector cooking is dominated by LPG and in rural residential sector cooking is dominated by biomass. Over dependence on LPG and biomass can be reduced by switching to more clean and efficient fuel: electricity. Hydro power development in Nepal is too slow paced and therefore, there is a need to develop solar electricity so as to ensure the energy mix and increase the energy security of the nation.

The efficiency of the AC based existing induction cooker was measured and found to be 85.56%. The functional circuit diagram of the existing induction cooker was simulated in Multisim and efficiency was calculated to be 87%. A solar electricity based DC induction cooker using quasi resonant topology has been designed and simulated. Circuit simulators like Multisim and Proteus were used for the simulation. The simulated system is battery operated with 24 V DC as system voltage and is micro controller based for control operation. It runs on 300 Ah battery with 500 W_P solar photovoltaic panel. The system operates with the input power range from 46.4 W to 1500 W correspondingly drawing input current in the range from 1.93 A to 62.5 A. The output power is in the range from 40.8 W to 1310 W with an average efficiency of 90.10%. The performance parameters of the designed induction cooker shows that the system is technically possible to construct.

Keywords

cooking – solar photovoltaic – DC – induction cooker – microcontroller – quasi resonant topology

1. Introduction

Cooking is an integral part of human life. In Nepal, as of 2012, about 80% of the national energy consumption is used in the residential sector, out of which 60% energy is used for cooking applications[1]. This indicates that cooking is one of the most energy intensive application. In urban residential sector of Nepal cooking is highly dominated by LPG and in rural residential sector of Nepal, cooking is highly dominated by biomass. From time to time, the urban people suffer from LPG shortage. The lack of affordable and systematic supply of LPG is a big problem for urban people. Similarly, rural people have to walk across miles to collect fuel wood for cooking. Besides the cooking process using biomass generates a lot of smokes resulting in the indoor air pollution[2]. Cooking using electricity is one of the most clean and efficient method of cooking as compared to biomass and other method of cooking[3]. But the loadshedding in Nepal prevents people from using electricity for cooking purpose. Developing hydropower plants is the sustainable solution for the technology switching to electricity based cooking. Nevertheless long gestation period, frequent political changes and other issues prevent significant hydropower development in near future.

Clearly, there is a need to switch to cooking using electricity as an ultimate solution for our technology transfer in cooking. While hydropower plants are developed, peoples can use solar PV technology to generate electricity for themselves. Development of solar PV can help in the energy mix and improve our energy security. Besides, rich families in the urban area can use the solar PV technology and at the same time government can subsidised poor families to buy LPGs. This is an extremely important issue and has to be addressed from policy reforms of the nation.

Solar electricity generated can be used for different purpose[4]. Though at present solar electricity is largely used for lighting applications, powering computers, internet etc, solar PV can be used for cooking purposes as well. Experiments done by several researchers and experts in the field of solar sector reveal that solar cooking is possible. At present only few people in the urban area use solar PV technology for cooking purposes. In their system, solar charged battery in used in conjunction with inverter to run induction cooker. The solar powered induction cooking is technically feasible but the use of inverter has reduced efficiency[5]. Therefore, there is a need to explore the possibility of induction cooking using solar powered DC battery. The DC system not only increases efficiency but also eliminates large and costly inverter that is required for cooking purpose using existing AC induction cooker[5].

In this study, the efficiency of the existing AC based induction cooker was measured to be 85.56%. The efficiency from the simulation of the functional circuit of the AC based induction cooker came out to be 87%. Focusing on the cooking applications with an objective to switch the users of LPG towards solar electricity, the design for solar electricity based induction cooker is developed. The designed induction cooker is battery powered. The battery capacity is 300 Ah and the battery voltage is 24 V. The battery gets its power from solar PV panels. Various components of the induction cooker has been designed and simulated. The resonant converter is of quasi resonant type. It uses a single switch implemented by IGBT which is operated in zero voltage switching condition. The output power is the function of the ON time of the IGBT. It can in effect be controlled changing the duty cycle of PWM signal driving the gate of IGBT. The resonant converter is capable of producing output power in the range from 40.8 W to 1320 W by drawing current in the range from 1.93 A to 62.5 A by varying the duty cycle of gate driving PWM signal from 10% to 80%. The efficiency of the resonant converter was found to be 90.10%, in average. The efficiency of induction cooker is very close to the efficiency of the resonant converter because of the fact that other semiconductor devices use very low power. It is therefore reasonable to say that the efficiency of designed induction cooker is 90.10%.

2. Problem Statements

In case of rural area, cooking is heavily dependent on inefficient biomass based cooking. The main problems include the time that is needed to collect the firewood and other biomass by the people, indoor air pollution induced health hazards and various other environmental concerns[1].

In case of urban Nepal, heavy dependence on LPG has made peoples insecure especially in the conditions like energy crisis, LPG shortage, etc During the recent energy crisis, urban people wished to use induction cooker as an alternative solution to LPG. But regular power cuts prevented them from doing so. And even when people used induction cookers while grid power was available, excessive loading caused faults in 11 kV distribution transformers causing substantial loss for repair and maintenance. So, lots of peoples were interested in running the induction cooker from a battery which required use of costly and over rated inverters. At that stage, people had increasing interests and confusions regarding the use of induction cooker directly from battery using solar panels. Based on the situation the following research question was raised: Can a DC based induction cooker be simulated and fabricated? In order to answer this question, research objectives were formulated. To make life of people easier in the rural areas, an alternative to biomass based cooking has to be found. Similarly, for the urban area, alternative to LPG has to be found. This study only considers urban areas. From the survey conducted by authors, it has been clear that people are highly willing to use induction cooker and rice cooker if a regular and reliable power supply is provided by the government. In order to fulfill this requirement government needs to construct big hydropower. Frequent political changes and long gestation period of the hydropower projects in the nation implies that the hydropower development in Nepal will not be significant in the near future. Even when hydropower will be available in the future, it could be exploited to reduce trade deficit which is increasing year by year while locally available energy sources like solar energy can be used for cooking purpose. The problem will be solved only if the LPG users in the urban areas are switched by RETs. Clearly there is a need for alternative method of cooking in order to solve the aforementioned problems. Presently using solar electricity, induction cooking can be done by using battery in conjunction with an inverter. Theoritically, use of inverter and battery reduces the system efficiency. And owing to the high cost of inverter, an efficient way of solar electricity based induction cooking can be done.

3. Review of Related Literatures

3.1 Research Gap

Battery powered induction cooking is an emerging topic[5]. Many induction cookers that are available in the market are AC powered. If existing induction cooker is to be run from the battery, it needs to be connected through a DC/AC inverter. Figure 1 shows the block diagram of a conventional approach to power the induction cooker using a battery.

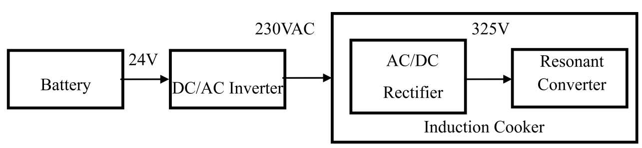

Figure 1: Block Diagram of Conventional Approach for powering an induction cooker from a Battery[5]

As can be seen in the figure 1 , the induction cooker internally converts AC into DC to power the resonant converter. The conversion process involved in DC/AC inverter outside the cooker and AC/DC rectifier inside the cooker is not 100% efficient. Therefore these blocks are redundant and cause reduction in the efficiency of the device.[5]

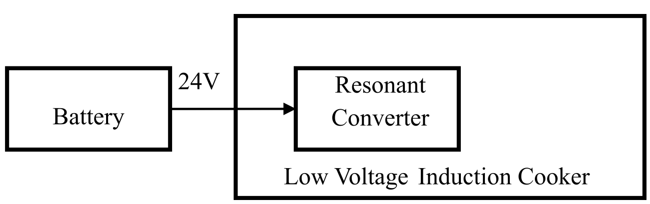

Figure 2: Block Diagram of modern approach to power induction cooker from Battery[5]

Figure 2 shows the block diagram of modern approach for the design of the battery powered induction cooker. At present DC powered induction cooker is not available in the Nepalese market. The area of DC powered induction cooker is still in the emerging phase. This is the main research gap and motivation to this research.

The research gap for this research is justified based on the literature review from following different literature: In a MIT thesis, Weber(2015) has practically implemented a design of 500W to 1kW induction stove[5]. In the study, it is clearly mentioned that the design is first of its kind in the academic world. Author's induction cooker uses 24V DC input from a battery. The limitation of this work includes simple coil design, small operation frequency, simple control system etc. Improvement in these aspects of the design will highly improve the efficiency and operation of the device[5].

The independent experiments conducted by Shrestha(2016) shows the induction cooking using battery is possible[6]. The system used two 12V 150Ah Trojan battery with 75 A discharge capacity for 60 Min. An inverter of rating 3 kVA and a solar panel of 360 W_P was used. The experiment demonstrated the possibility of cooking food for four peoples within 36 minutes using 0.7 kWh of energy. The study mentioned the main limitation of experiment to be the use of 3 kVA inverter and the remedy as use of DC source in induction cooking.

The study by Maharjan (2016) obtained the experimental electrical and thermal performances of cooking appliances available in Kathmandu. The research concluded that the power displayed by the device do not resemble the real power consumed in case of induction and infrared cooker. Furthermore, the thermal performance of induction heater and infrared heater is far more efficient that the coil heater. This study only deals with the AC powered devices.[7]

Thandar et al.(2008) has designed the power system for an induction cooker that is able to operate at 500W output and 24 kHz frequency [8]. The circuit utilizes the series resonant circuit. The study deals the power system only with reference to AC but not on DC.

In the study by Shakya(2014), all possible scenarios for switching conventional energy resources with RETs and different policy intervention scenarios is explored. The study concluded that total final energy consumption in residential sector can reduce by 14% of the total final energy when policy interventions is done[3].

3.2 Induction Heating

Induction heating is a completely different method to generate heat as compared with conventional electric heaters. In an induction heater, the cooking vessel itself is a part of heat generating device, or the cooking vessel itself generate heats[9]. In traditional resistive coil based heater, heat is transferred to the cooking vessel either through physical contact or by placing it in proximity of the coil. Thus, considerable amount of heat is lost to the nearby air in the heat transfer process. This is the main reason for lower efficiency of the traditional coil heater. Induction heating is a method of heating in which cooking vessel is in itself a part of heat generation process. In an induction heater, a high frequency alternating current is passed through the inductive coil. Due to the phenomenon of electromagnetic induction, an alternating magnetic field is generated within the vicinity of the coil. When a cooking vessel made up of ferromagnetic material is placed nearby, due to the induction, eddy currents are generated in the cooking vessel. The magnitude of eddy current is proportional to the strength of the magnetic field around the coil, the area of the conductor, the rate of change of flux, and inversely proportional to the resistivity of the ferromagnetic material. Since the cooking vessel inevitably has certain resistance, it gets heated because of Joule's heating effect. If R_P is the effective resistance of the cooking vessel and I_{EDDY} is the magnitude of eddy current induced, the heat generated is given by[9]:

$$\dot{Q} = I^2_{EDDY} R_P \tag{1}$$

Where,

I_{EDDY}= Eddy Current and R_P = Resistance of cooking pot

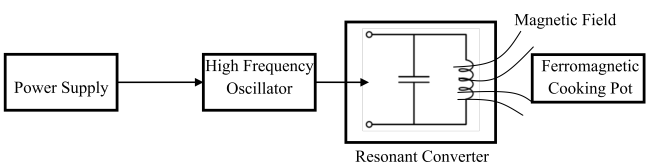

Figure 3: Block Diagram of Induction Heating

Figure 3 shows a general diagram of the induction heater. As can be seen, the power supply supplies DC output to the high frequency oscillator. The high frequency signal is fed to the resonant converter. Because of large alternating current flow in the inductor, a high frequency alternating magnetic field is generated in the vicinity of the inductor coil. If some ferromagnetic material or ferromagnetic cooking pot is brought near the coil, the alternating high frequency magnetic field will induce large amount of eddy current in it. The result is that a large amount of heat is dissipated in the material. Thus, cooking pot is itself a part of heat generation process. The coil just transfers magnetic field, it don't get itself heated. Thus, losses are very small and efficiency is very high in induction cooking.

3.3 Quasi-resonant topology:

Quasi resonant converters are widely used in induction cooker for implementing power converters. Such converters are quite attractive for domestic induction heating because it requires only one switch, usually an IGBT, and only one resonant capacitor. [10]

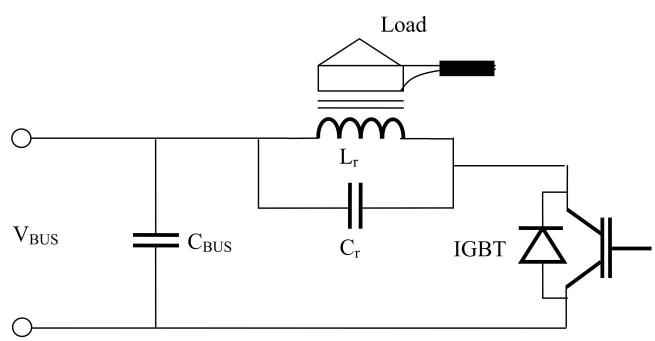

Figure 4: Quasi Resonant Topology for Induction Heating

For a given loading condition, maximum power level, and the maximum voltage, the peak voltage rating for the switch and resonant capacitor can be calculated from the QR theory and can be approximated by following equations[10]:

$$V_{res} = \sqrt{\frac{2E}{C}} \tag{2}$$

Where E is the energy stored into the inductive part of the load during the on phase.

$$E = \frac{1}{2} I_{PK}^2 \tag{3}$$

The peak current is proportional to TON and VDC-Bus

$$I_{PK} = T_{ON} \frac{V_{D-Bus}}{L} \tag{4}$$

The resonant voltage V_{res} can be expressed in terms of T_{ON} and V_{DC-Bus} as:

$$V_{res} = \frac{T_{ON} V_{DC-Bus}}{\sqrt{LC}} \tag{5}$$

Usually T_{ON} is kept constant for particular loading condition. Quasi resonant inverter is T_{ON} controlled. The on-time is fixed for a certain power level and the off-time (T_{OFF}) is determined by the resonant tank circuit. The on-time can be set by PWM driving signal.

4. Methodology

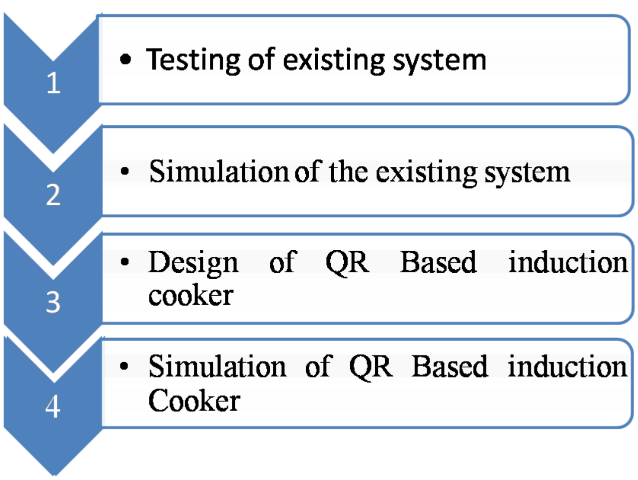

Figure 5: Sequence of tasks carried out

4.1 Testing of Existing System

Testing of the existing induction cooker from market was carried out. The input power was measured by measuring the current and voltage at the input of induction cooker while the output power of the induction cooker was measured by using thermodynamic relations. Followings are the assumptions and measurements of the experiment:

Specific Heat Capacity of Water(C_W) = 4181 J/Kg°C [11]

Specific Heat Capacity of Cast iron(C_P) = 460 J/Kg°C [11]

Density of Water(ρ) = 1000 Kg/m^3 [11]

The data obtained after experiment is as given below:

Input Voltage(V_{in}) = 230 V

Input Current(I_{in}) = 5.28 A

Input Power(P_{in}) = $V_{in} \times I_{in} Cos\varphi$ = 230 × 5.28 Cos 30.6° = 1214.4 × 0.86 = 1044.4 W

Initial Temperature(T_i) = 24 °C

Final Temperature(T_f) = 100 °C

Change in Temperature(d_T) = T_f - T_i = 76 °C

Time taken(t) = 6 Minutes and 26 Seconds = 6 × 60 + 26 = 386 Seconds

Output Power(P_{out})

$$= \frac{(m_W \times C_W + m_P \times C_P) \times dT}{t}$$
$$= \frac{(1 \times 4181 + 0.78 \times 460) \times 76}{386}$$
$$= 893.84W$$

Therefore, the efficiency of the induction cooker is given as:

Efficiency(η) = $\frac{P_{out}}{P_{in}} = \frac{893.84}{1044.4} = 85.56\%$

4.2 Simulation of the functional circuit

The functional circuit diagram of the selected existing induction cooker(AC based) from the market was simulated in Multisim software simulator. The circuit for the simulation was prepared after direct observation of the induction cooker board of the selected induction cooker and literature review from various sources[12] [10].

4.3 Overall System Design

Figure 6 shows the block diagram of the entire system. It consists of solar PV panel, charge controller, battery,

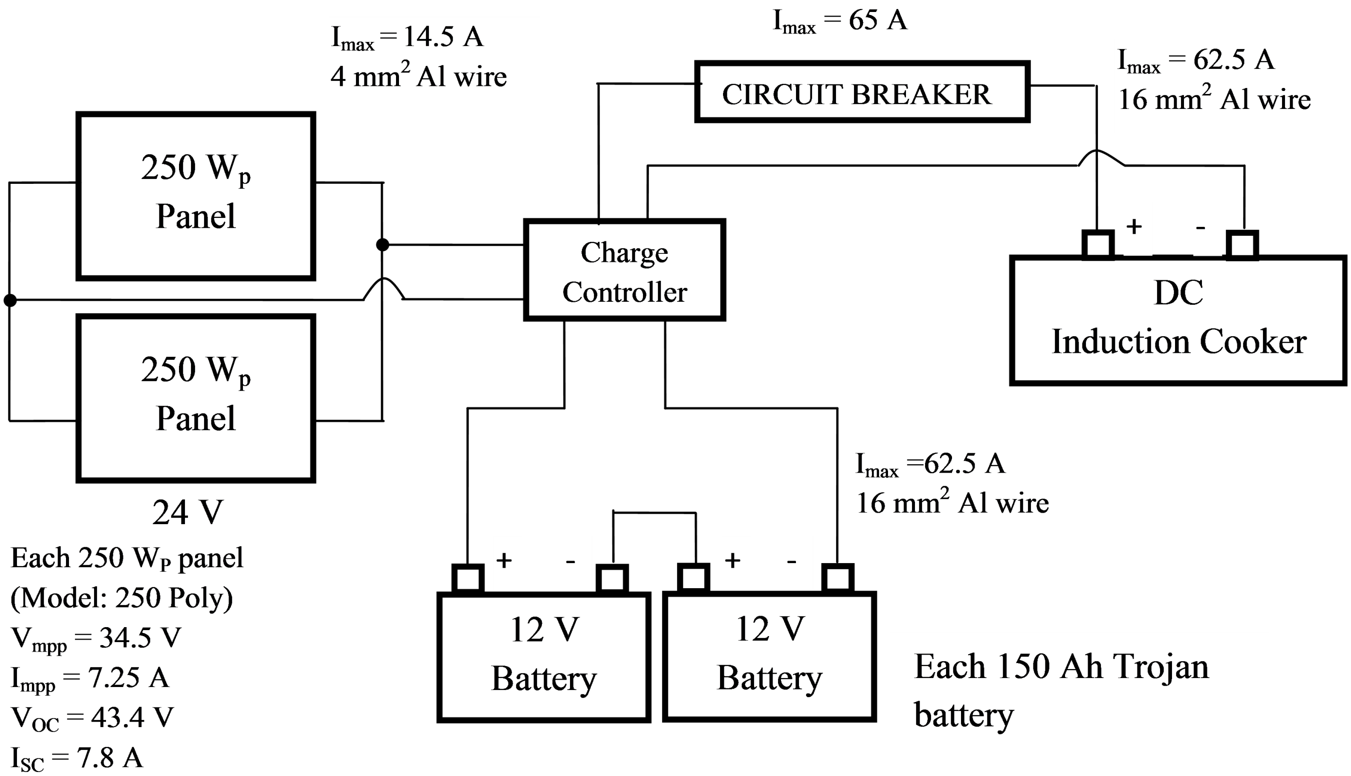

Figure 6: Block Diagram of the entire system

circuit breaker and DC induction cooker. Following are their description:

Solar PV Panel: The solar PV panel is used as the main source of energy. It is used to charge the battery.

Battery: Two 12V, 150 Ah Trojan batteries are connected in series to obtain the 300Ah combination at 24 V. As per the datasheet, each battery can provide maximum 75 Ampere for 70 Minutes at 12 V. For the operation of the designed system the battery must provide 62.5 Ampere at the peak loading of 1.5 kW.

Charge Controller: It is a device whose main purpose is to charge the battery preventing overcharging and deep discharging.

DC Induction Cooker: The DC induction Cooker is an induction cooker that runs off a 24 V DC battery.

Circuit Breaker: Circuit breaker is a protection device that helps to break the circuit when excessive current flows through it. In the context of this system circuit breaker for 75A is used.

Wire Size: The wire from PV panels to charge controller is 4 mm^2 and that from battery to charge controller and charge controller to load is 16 mm^2 [13].

4.4 Design of DC Induction Cooker

Figure 7 shows the block diagram of the DC induction cooker designed. Various components of this system are as follows:

Battery: The battery specification for the DC induction cooker is same as mentioned in earlier section.

Cooking Pan: The base of the cooking pan for the system is made up of ferromagnetic materials. When this ferromagnetic material comes closer to the high frequency alternating magnetic field, large eddy current is induced in it. This eddy current is forced to flow in the ferromagnetic base like a shorted wire. This process generates a lot of heat in very small time period. During the heating of cooking pan, the system draws large amount of current from the power supply. It is the responsibility of a designer to limit this current with reasonable value with appropriate heating level.

Resonant Converter: The resonant converter is the

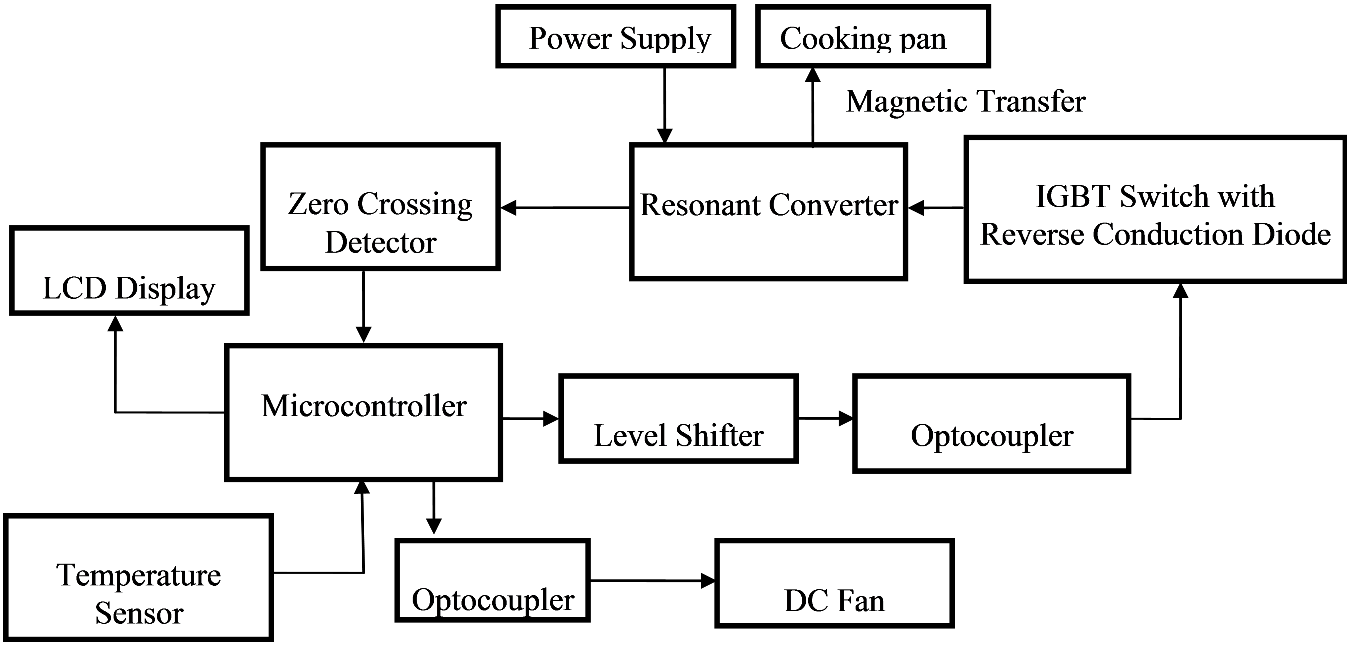

Figure 7: Block Diagram of the DC Induction Cooker Designed

heart of the entire induction cooker. The geometry and inductance of the resonant coil and the value of resonant capacitor has prominent effect on the performance of the entire system operation.

Liquid Crystal Display: It is a display device capable of displaying various information of the system in user friendly form. LCD is driven by the microcontroller. The LCD used is LM 016L with 16 × 2 character display screen.

IGBT: It stands for Insulated Gate Bipolar Transistor. It is the power semiconductor device which is used to implement a switch. The IGBT used is FGA15N120.
Zero Crossing Detector: It is the circuit which helps to detect the zero crossing of the signal at the capacitor terminals.

Microcontroller: It is a digital device which helps to perform control function of the system. It is a central processor for entire control system. It generates appropriate control signal for digital switches, LCD display etc. It receives input from appropriate user interface like keypad, touch pad etc. Arduino microcontroller was chosen for the design.

Level Shifter: The signal output from the Arduino pin is within 5 V. Since the IGBT requires about 15V drive signal for switching, the level shifter circuit is used to shift 5V signal to 15 V signal level.

Optocoupler: It is a device which is capable of coupling two different circuits optical isolation. The Optocoupler used is MCT2E.

4.5 Induction Coil

Though the design for an inductive coil can be designed by using analytical equations given by Sinha et al.(2010), the standard coil manufactured by some third party company has been used for the design[14]. The inductance of which is around is 95µH (as measured by RLC meter in the lab). The coil taken is compatible to work in 500 W to 1500 W output power range.

4.6 Calculation of PV Size and Battery Size:

The designed system takes the input of 1500 Watts from the battery. The battery voltage is 24 Volts . Assuming the 1.5 hours daily operation, the energy in watt hours is given by:

$$E = P \times H = 1500 \times 1.5 = 2250Wh$$

Battery is required to deliver 2250 Wh of energy daily. This much of energy has to be supplied from the Solar PV panel. Regarding this system, $500W_P$ of solar panel will be used. The battery capacity in the Ampere Hour is given by the following equation[4]:

$$C = \frac{E}{B_V \times DOD \times \eta_B} \times n_A \tag{6}$$

Where,

B_V = Battery Voltage

E = Energy in Wh

DOD = Depth of Discharge

η_B = Battery Efficiency

n_A = Autonomy days

We have, BV =24V, E= 2250 Wh, DOD = 0.8, η_B = 0.8, n_A =2 days

The battery capacity C comes out to be 292.96 Ah. The nearest value is 300 Ah. If 24V, 300 Ah batteries are not available, we can use two 12V, 150 Ah batteries in series to make a 300Ah battery system with 24 V system voltage.

4.7 Simulation of the System in Proteus

The simulation of the system circuit in Proteus ISIS software simulator is as shown in figure 8. As can be seen in the figure 8, the circuit diagram consists of different blocks such as Microcontroller, LCD, Battery, Temperature Sensor, Level Shifter, Gate Driver, Zero Crossing Detector, IGBT etc.

4.8 Simulation of the Resonant Converter

The resonant converter for the induction cooker is based on the Quasi resonant topology. This circuit is the heart of the induction cooker designed. The simulation of the resonant converter in Multisim circuit simulator is shown in the figure 9.

It consist of 24 V DC voltage source. Capacitor C_1 is resonant capacitor whose value is taken to be 296 μ F. T_1 is a multisim model for coupled inductors. The left side of the T_1 is the spiral coil of the induction cooker, whose value is 95μH. The value was measured using RLC meter. The right side of the T_1 is the equivalent R-L model for cooking pot. For modeling the cooking pot R-L series circuit was used. The value of resistance was kept at 3.2 Ω and the value of inductance was kept at 80 μ H. These values are based on the applicaiton note published by ON Semiconductors company[15]. The switching device used was IGBT (Insulated Gate Bipolar Transistor). The model number is IRG7PH46UDPBF. It is a 1200V Ultra Fast Low $V_{CE(ON)}$ trench IGBT in a TO-247AC package manufactured by International Rectifiers. The drive signal for the IGBT was generated by using standard Multisim PWM generator model using 30 kHz, 12 V signal source as reference. Various power and current probes shows the readings taken. The symbol labeled XSC1 is the Virtual Oscilloscope of Multisim. The power of the induction cooker is controlled by the on time of the IGBT. This can be achieved by varying the duty cycle of gate driving PWM signal generated from the microcontroller. Multisim was particularly chosen for this simulation because of its good user interface and accuracy in the simulation of analog and power circuits.

5. Results and Discussion

5.1 Simulation of the Functional Circuit

The average efficiency of the existing AC based induction cooker from the simulation has been found to be 87%. It is in close agreement with the experimentally measured efficiency(85.56%). Table 1 shows the variation of efficiency with control voltage. Corresponding input current, input power and output power are also indicated in the table.

Table 1: Variation of efficiency with control voltage

Voltage, V	Input Current, A	Input Power, W	Output Power, W	Efficiency
0.36	0.87	200	176	0.87
0.91	2.17	500	440	0.87
1.36	3.26	750	652	0.86
1.82	4.35	1000	880	0.87
2.91	6.96	1600	1424	0.87
4.00	9.57	2200	1936	0.87
Average Efficiency η				0.87

5.2 Simulation of Resonant Converter

Table 2 shows the variation of output power with duty cycle of the gate driving PWM signal. The duty cycle of a 30 kHz control signal is varied from 10% to 80% and different parameters like input power, input current, output power and efficiency was measured. From the observation of Table 2 it can be concluded that the designed induction cooker has an average efficiency of

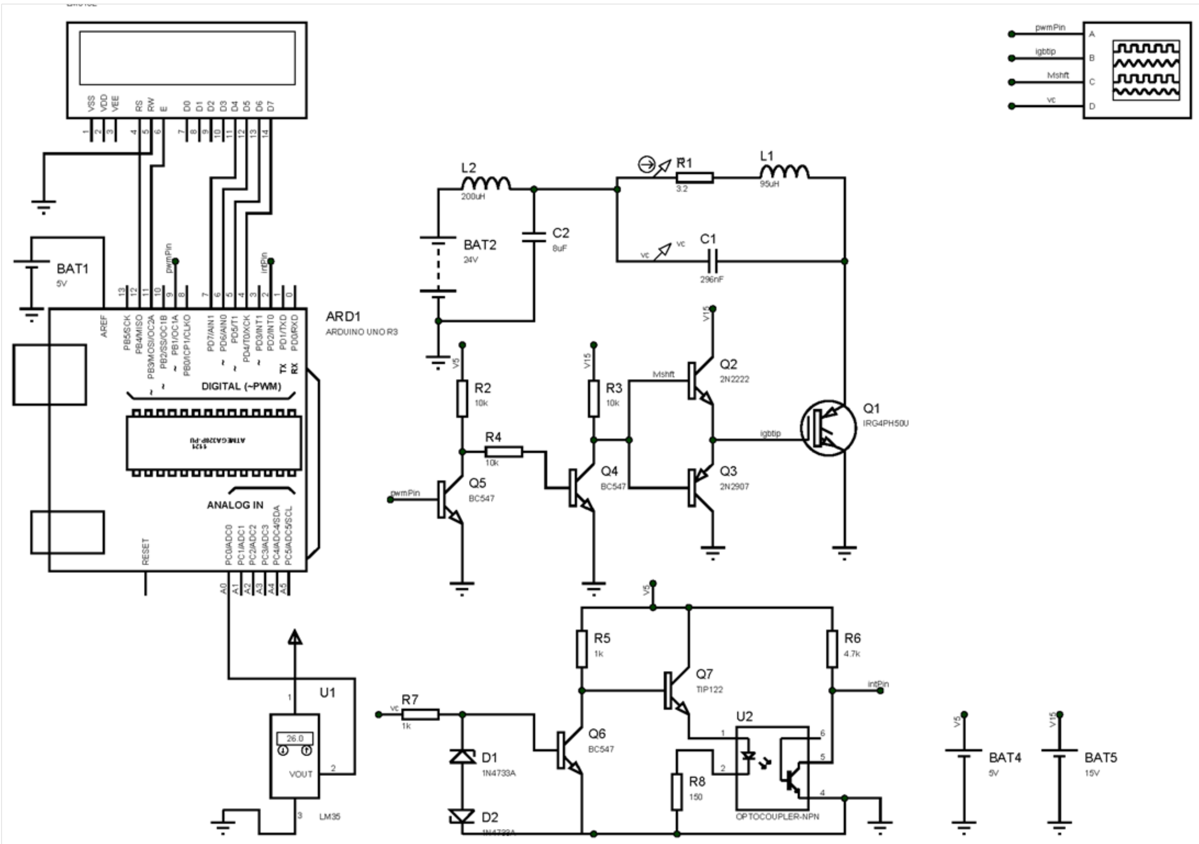

Figure 8: Simlation of system designed in Proteus

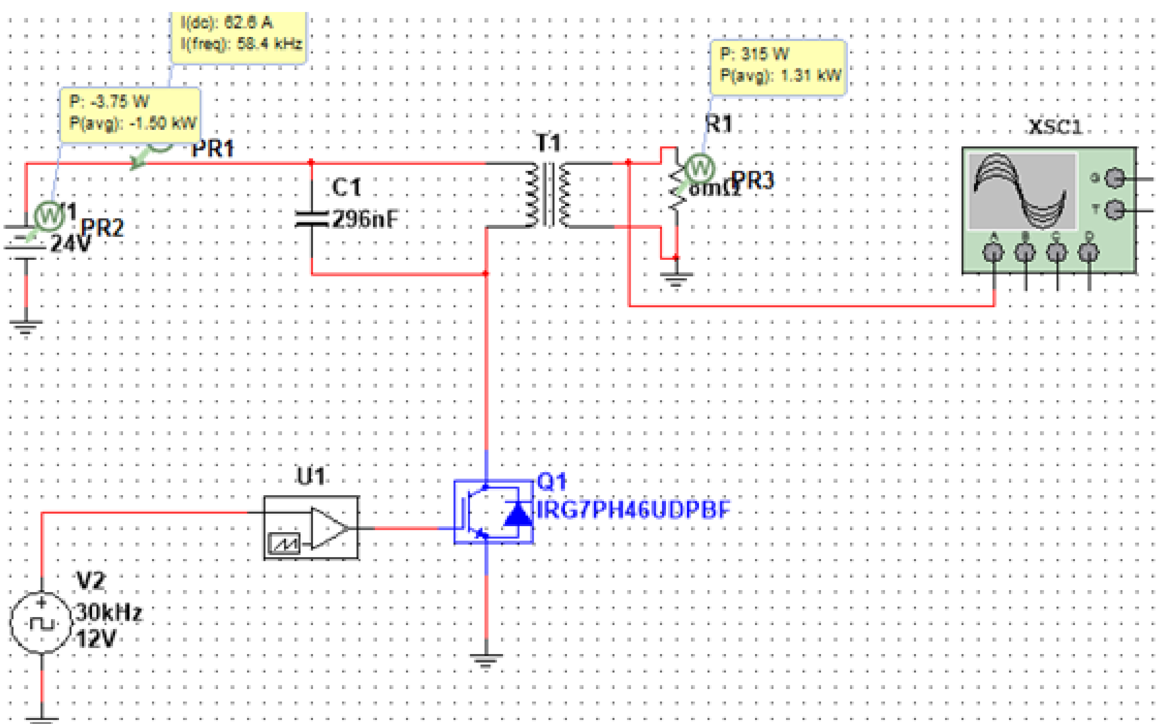

Figure 9: Circuit for the simulation of Quasi resonant topology

90.10%. It runs on input power in the range 46.4 W to 1500 W drawing current in the range 1.93 A to 62.5 A. The output power is in the range 40.8 W to 1310 W.

Table 2: Variation of power, current and efficiency

Duty Cycle(%)	Input Power	Input Current	Output Power	Efficiency
10	46.4	1.93	40.8	87.93
20	97.5	4.06	88.3	90.56
30	163	6.79	149	91.41
40	250	10.42	230	92.00
50	375	15.63	342	91.20
60	560	23.33	508	90.71
70	870	36.25	780	89.66
80	1500	62.5	1310	87.33

As can be seen from the Table 2, the usable output power is available when the duty cycle is either 60, 70 or 80. This is because at 60% duty cycle output power is 508 W, at 70% duty cycle output power is 780W and at 80% duty cycle output power is 1310 W. Furthermore, the control signal can always be adjusted to provide more flexible power outputs such as 500 W, 700 W, 1000 W, 1200 W, 1300 W, and 1500 W.

6. Conclusions

This paper presented the design and simulation of a solar electricity based induction cooker using quasi-resonant topology. The conclusions are:

i. The testing of the selected AC based induction cooker from the market has been done and its efficiency was experimentally measured to be 85.56%.

ii. The simulation of the functional circuit of the selected AC based induction cooker has come out to be 87%.

iii. The design and simulation of microcontroller based DC induction cooker operating in the output power range from 500 W to 1500 W has been completed. It has an average simulation efficiency of 90.10%.

7. Futureworks and Recommendation

7.1 Futurework

The design presented the use of quasi-resonant topology as the power converter while the use of full-bridge and half-bridge resonant converter topologies would have resulted in more efficient system. So, the future research can be carried out by using the aforementioned topologies. Furthermore, the efficiency of selected induction cooker from the market is found to be 85.56%. The simulation of the design shows the possibility of the efficiency improvement upto 90.10%. Thus, a detail fabrication of the simulated system can be done to obtain the better comparison between the existing induction cooker and the designed system.

7.2 Recommendation

This research shows that the solar PV based induction cooking is technically possible to implement. Further research with hardware testing is needed to construct and manufacture solar electricity based DC induction cooker.

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