A New Approach to the design of DC Powered Induction Cooker

Bikal Adhikari[1*], Jagan Nath Shrestha[2], Shree Raj Shakya[2]

[1]Department of Computer and Electronics & Communication Engineering, Kathford Int'l College of Engineering and Management

[2]Center for Energy Studies, Institute of Engineering, Tribhuvan University

Corresponding Email: [*]bikaladhikari@kathford.edu.np

***Abstract*— About 80 % of total energy consumption in Nepal is being consumed in the residential sector and about 60 % of total residential energy application includes cooking application. At present, in urban area, there is heavy dependence on liquefied petroleum gas for cooking purpose whereas in rural area, there is heavy dependence on biomass. Clearly, there is a need to switch towards clean and efficient fuel: electricity. Load shedding problem has been a reason preventing Nepalese people to switch towards electricity based cooking. Even though at present (2017), Nepal Electricity Authority's has been able to reduce load shedding for residential consumers, there is still a condition of inadequate supply of electricity if all of the consumers will switch towards electricity for cooking purpose. The experimental and simulation efficiency of conventional AC based induction cooker has been found to be 85.56 % and 87 % respectively. DC powered induction cooker has been designed and simulated. The simulation efficiency of which has been measured to be 90.10 %. The hardware realization of the design is malfunctioning in real time testing making a need of power electronic component with the capacity to pass very high current, as high as 80 A at low voltage, as low as 12 V.**

I. Introduction

In case of Nepal, as of 2013, about 80 % of the total energy consumption is being consumed in residential sector and about 60 % of the total residential applications included cooking applications [1]. This makes cooking application one of the most energy intensive application in the nation. A slight change in cooking technology and fuels used might have considerable impact on the national economy.

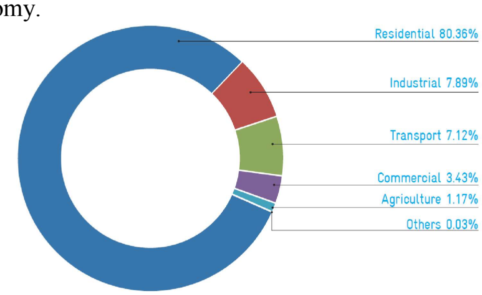

Fig.1. Energy Consumption of Nepal by different Economic Sectors [1]

In the recent energy crisis of Nepal, there was liquefied petroleum (LPG) shortage. To fulfill the daily cooking needs, people switched to Induction Cooker. Faults were seen in the local distribution transformer due to the overloading in the peak hours causing substantial loss of money in repair and maintenance. A lot of people were looking for an alternative way to use induction cooker when there was no grid electricity. The only option available then was to use battery as a source with an expensive inverter. At that stage a lot of people had an interest and confusions in the possibility of using induction cooker directly with battery without the use of higher rated costly inverters. The main objective of this research is motivated by a desire to be able to run an induction cooker directly from DC power supply. [2]

A detail survey in 217 sample households of Lalitpur Sub Metropolitan City Ward Number 2, Nepal was conducted by the authors. From the survey it has been found that the average shade free area per HH is 58.01 m^2 and average solar Photovoltaic(PV) installable area per HH is 22.83 m^2. Installation of solar PV in the area with 4.5 hour peak sun would generate 10.26 kWh per HH per day which is sufficient to cover the energy demand of a house in this ward [2]. The main implication of the result is that people can generate enough energy from their open rooftop so as to cover their daily electrical energy demand for cooking and other applications. This justifies the necessity to consider solar electricity based cooking as a potential technology.

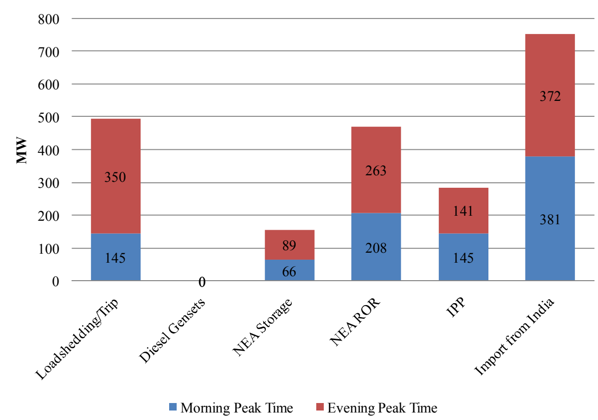

Fig.2. Energy Supply and Demand condition Nepal as of Falgun 2, 2073 [3]

Figure 2 shows the stacked bar diagram for energy supply and demand condition as of Falgun 2, 2073 BS. As can be seen from the figure, the total power supply in the country consists of Nepal Electricity Authority's (NEA's) Run of River, NEA Storage Plants, Independent Power Producers (IPPs) and Import from India. In morning peak condition, the total supply is 800 MW and total demand is around 945 MW. Thus, about 145 MW is deficit in morning peak condition. Likewise, in evening peak condition, the total supply is 1215 MW and total demand is around 865 MW. Thus, about 350 MW is deficit in evening peak condition. And worst part is that we are depending on import from India in about 47 % of our power supply [3]. The data shows; despite NEA has not shed any load for Kathmandu valley and other main valleys of the nation, technically there is still the condition for load shedding. It has only been overcome by the good management of NEA and probably by several attempts geared towards reducing distribution losses.

Thus, load shedding has been and is one of the major problems for Nepalese peoples to switch towards electricity as major fuel for cooking purpose in a reliable and economic way. Electricity based cooking is not a new technology. Nepalese peoples in the urban sectors have been cooking using different devices such as Rice Cooker, Induction Heaters, Infrared Heaters, and Microwave etc. If reliable electricity is available to the urban peoples, they are more than willing to switch towards electricity based cooking.

Likewise peoples in rural sector are found to have used biomass like fuel wood, cow dung etc as major fuel. The main problems associated with biomass based cooking are that cooking process generates lot of smoke during cooking and it takes time for people to walk miles across to collect the fuel woods before cooking. In both urban and rural area, there is a need to shift towards electricity based cooking so as to overcome the difficulty encountered. Nepal being located in favorable latitude receives ample solar radiation with more than 300 days in a year [3]. This makes solar PV technology a promising one for generating electricity for cooking applications.

The efficiency of the selected commercially available induction cooker was experimentally measured to be 85.56 %. The efficiency calculated from the simulation of functional circuit diagram of existing induction cooker is 87.00 %. A solar electricity based induction cooker using quasi resonant topology has been designed and simulated using circuit simulators Multisim and Proteus. The designed system is battery operated with 24 V DC as system voltage and is micro controller based for control operation. It runs on 24 V DC, 300Ah battery with 500W_P solar PV 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 show that the simulated system is technically possible to implement. The hardware realization of the design could not be achieved with the use of available components in the Nepalese market due to the component quality issues in low voltage high current condition for a given output power. However, if this design can be realized, solar PV based cooking might be a prominent alternative technology of the nation in future for achieving energy efficiency.

II. RESEARCH GAP

Battery powered or DC powered induction cooking is an interesting research topic. Many induction cookers that are available in the market are ac powered. If one has to run the induction cooker from the battery, he/she needs to connect to it through a DC/AC inverter. Figure 3 shows the block diagram of a conventional approach to power the induction cooker using a battery.

As can be seen in the figure 3, 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].

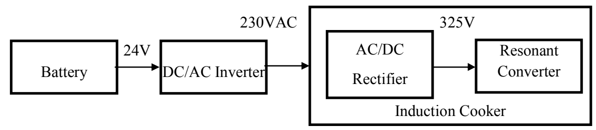

Fig.3. Conventional Approach for powering an induction cooker from a battery. [5]

Figure 4 shows the block diagram of modern approach for the design of the battery powered induction cooker.

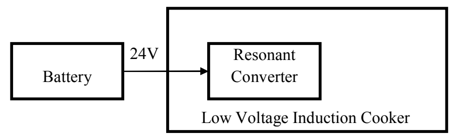

Fig.4. Modern approach for powering induction cooker from Battery [5]

Literature review from following literatures has been used to justify the research gap which forms the ground for this research work:

In the MIT thesis, Weber (2015) has given a design of a 500 W battery powered induction stove and anticipated the possibility to scale up to 1 kW. However, the author has not implemented it practically. The author has clearly mentioned that this is a design of a first kind in the academic world. The author's induction cooker design uses 24 V DC input from a battery. The limitation of this work includes simple coil design, small operation frequency, simple control system etc. As per the author's recommendation improvement in the aforementioned aspects of the design will highly improve the efficiency and operation of the device. [5]

The experiments independently conducted by Shrestha (2016) shows that the induction cooking is possible. The system used two 12 V, 150 Ah Trojan battery with 75 A discharge capacity for 60 Min. An inverter of 3 kVA rating and a solar panel of 360 W_P were used. The experiment demonstrated the possibility of cooking food for four people within 36 minutes using 0.7 kWh of energy. The researcher has mentioned that the main limitation of the system is related to the use of expensive and higher rated 220 V AC 3 kVA inverter. The remedy for this problem is to use dc source along with solar electricity. [6]

The study by Maharjan (2016) has 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. This study only deals with the AC powered devices. [7]

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

III. INDUCTION HEATING AND QUASI RESONANT TOPOLOGY

A. 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 [10]:

$$Q = I_{EDDY}^2 R_P \quad (1)$$

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

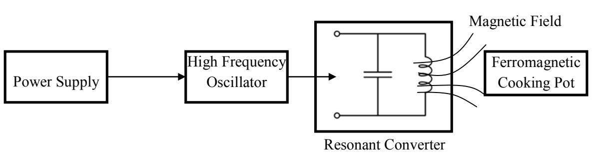

Fig. 5. Block Diagram of a typical induction cooker [11]

Figure 5 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 induction coil. If some ferromagnetic material or ferromagnetic cooking pot is brought near the coil, the alternating high frequency magnetic field induces 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.

B. 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].

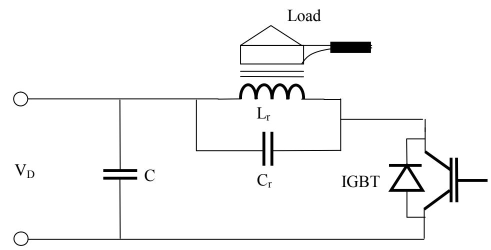

Fig.6. Operating circuit topology for quasi resonant topology

Figure 6 shows the circuit diagram for quasi resonant topology used in induction heaters. The V_D is a dc voltage obtained after rectification (in context of ac powered device) whereas battery voltage in case of dc system. L_r is the induction heater coil and C_r is the capacitor. The combination of L_r and C_r set up the frequency of the oscillation and time period of resonance. The IGBT is used as switching device to facilitate the power conversion to the load. This combination is allowed to resonate for a fraction of the time period of the gate control signal of IGBT. That is why the circuit is called **quasi-resonant topology**. 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]:

$$V_{res} = \sqrt{\frac{2.E}{C}} \quad (2)$$

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

$$E = \frac{1}{2} L\, I_{PK}^2 \quad (3)$$

The peak current is proportional to $T_{ON,}$ V_D

$$I_{PK} = T_{ON}.\ \frac{V_D}{L} \quad (4)$$

The resonant voltage Vres can be expressed in terms of T_{ON} and V_D as:

$$V_{res} = \frac{T_{ON}.\ V_D}{\sqrt{LC}} \quad (5)$$

Equations 1 through 4 are the direct results of energy conservation principle between capacitor and inductor using well known formula $E_L = \frac{1}{2} LI^2 = E_C = \frac{1}{2} CV^2$

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 load i.e.

cooking pot can be modeled as the series combination of the resistor and inductor. The coupling between the induction coil and the load is determined by the magnetic coupling between the induction coil and the equivalent inductance of the cooking pot.

By using a simple transformer analogy, the cooking pot's equivalent resistance and inductance can be reflected back in the circuit. And hence induction coil, cooking pot, as well as their coupling can be represented simply by an equivalent series combination of resistor and capacitor. The power dissipated in the resistor R_0 denotes the actual power transferred to the load.

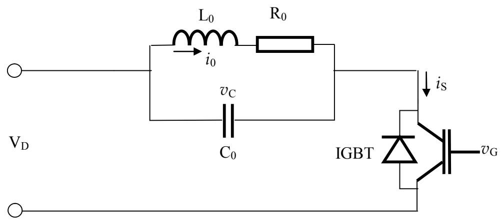

Fig.7. Quasi-resonant circuit with RL model of coil-pot coupling [11]

Figure 8 shows various current and voltage waveforms during the Quasi-resonant circuit operation. The entire circuit operation can be described in terms of two modes and four different time intervals as following:

Mode 1: The circuit enters this mode of operation when the gate voltage is high. During this mode the IGBT is turned on. During mode 1, the supply voltage V_D essentially charges the induction coil and circuit behaves as a first order series R-L circuit.

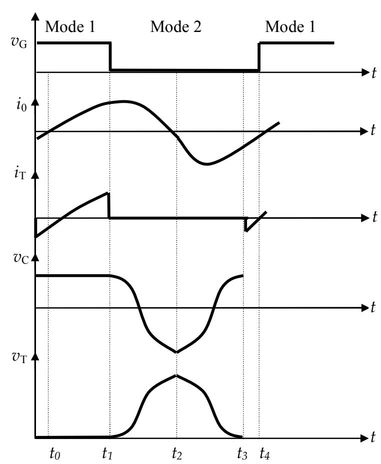

Fig.8. Various waveforms in the quasi-resonant circuit

Time interval [0, t_0]: Reverse Current Conduction by Diode:

Until the time t_0, the reverse conduction diode in the IGBT conducts current through the inductor so as to ensure smooth turn on of the transistor. This is mainly needed to achieve Zero Voltage Switching. In order to keep the current in the inductor flowing, reverse conduction diode conducts current from earlier cycle.

Time interval [t_0, t_1]: Induction Coil Charging Phase:

After time t_0, at the first instant, capacitor acts as an open circuit. The inductor gets charging current though the supply voltage V_D. The current i_0 rises exponentially. The voltage v_C across the capacitor remains constant and equal to V_D and the voltage v_T across the transistor's collector emitter terminals is equal to zero. This condition remains until time t_1. At time t_1, the transistor is turned off. The voltage v_G becomes low. This marks the end of mode 1 and start of mode 2.

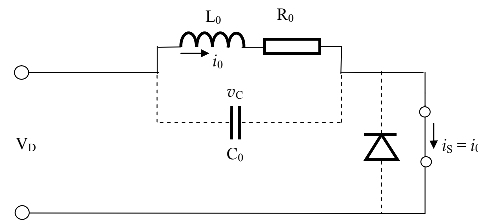

Fig.9. [t_0, t_1] inductor charging period

Mode 2:

The circuit enters this mode of operation when the gate voltage is low and the IGBT is turned off. During this mode the circuit behaves as a second order R-L-C series circuit. While the transistor is turned off, the R-L-C series circuit is left to resonate. This mode last as long as the time period of resonance of the circuit. Thus off time of the IGBT is determined by the resonance time of the series R-L-C circuit. This mode can be broken down in two time intervals i.e. [t_1, t_2] and [t_2, t_3].

Time Interval [t_1, t_2]: Capacitor Charging Period of Resonant Stage

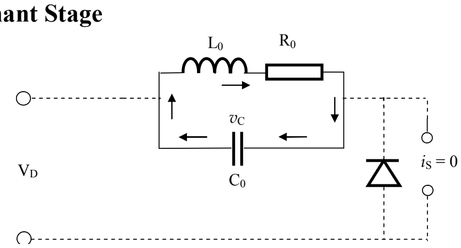

Fig.10. [t_1, t_2] LC Resonant stage: capacitor charging period

As soon as the switch is turned off at t_1, inductor and capacitor start to resonate. The inductor supplies current to the capacitor. The resistor R_0 dissipates power and capacitor keeps on discharging. The voltage across the capacitor drops from V_D. This situation continues until the voltage v_C is zero. The energy stored in the capacitor is completely released when $v_C = 0$. The inductor L_o continues to release energy at the same time and part of the energy is dissipated in resistor R_0 as the output power. The rest of energy in L_0 charges capacitor in sinusoidal fashion. At time t_2, $i_0 = 0$ and the energy stored in the inductor is completely released. The capacitor voltage v_C reaches its maximum value. The voltage across the transistor at this condition is given by equation 6:

$$v_T = V_D + v_{Cmax} \qquad (6)$$

Time Interval [t_2, t_3]: Capacitor Discharging Period of Resonant Stage:

After time t_2, the capacitor begins to release energy and inductor current i_0 begins to flow in the reverse direction. A part of this energy is dissipated in R_0 and rest of the energy is stored in the form of magnetic field of inductor L_0. Before v_C reach zero, the inductor current i_0 attains its negative peak. As soon as $v_C = 0$, the energy stored in the capacitor is released completely. Now inductor releases its energy by supplying current. Some of the energy is dissipated in R_0. Remaining energy is used to charge capacitor with reverse polarity. This will continue until voltage across the capacitor reach V_D i.e. at time t_3. The voltage across transistor at this condition is given by equation 7:

$$v_T = V_D + v_C = V_D + (-V_D) = 0 \qquad (7)$$

Thus, capacitor is fully charged. The charging stops. But inductor still has some energy and there is a tendency for inductor current i_0 to flow. The reverse conduction diode turns on at this point.

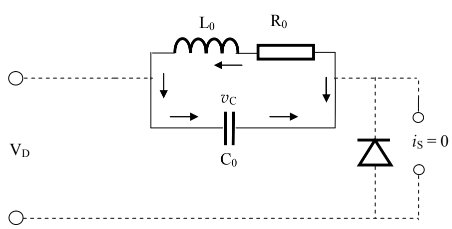

Fig.11. [t_2, t_3] LC Resonant stage: capacitor discharging period

Time Interval (t_3, t_4): Inductor Discharging Period of Resonant Stage:

During this time interval, to keep the current in the inductor flowing and to turn on the transistor at Zero Voltage Switching Condition, the reverse conduction diode conducts the current from the induction coil. The energy stored inside the induction coil is released completely. With capacitor voltage v_C equal to supply voltage V_D, the voltage across the transistor is zero. At this condition, the transistor is turned on by making gate signal high. And the cycle repeats.

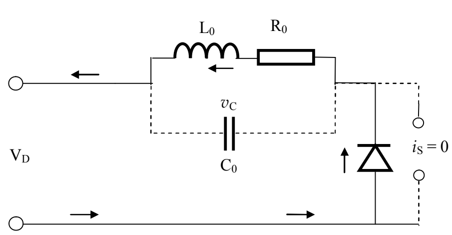

Fig.12. [t_3, t_4] Inductor discharging period

IV. METHODOLOGY

Figure 13 shows the basic methodology adopted in carrying out this research work. Problem formulation was the first task done. The problem formulation identified the problems associated with conventional approach to power induction cooker using battery as a source. In literature review, different articles, books, dissertations etc were studied.

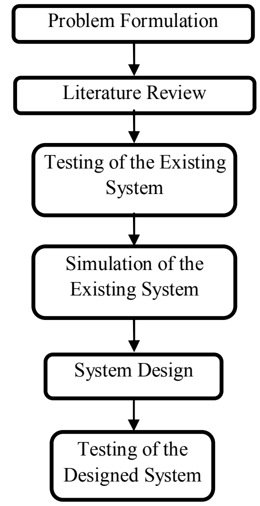

Fig.13. Block diagram of Methodology adopted

Following literature review, testing of existing induction cooker in the market was done which was followed by the simulation of its functional circuit. The design of the DC induction cooker was simulated by the circuit simulators: Multisim and Proteus. The real time testing of the designed system was carried out. The key motivation of the authors in this research work has been to use the DC source as the power source instead of conventional AC source to power the induction cooker so as to increase the efficiency of the system.

A. Overall System Design

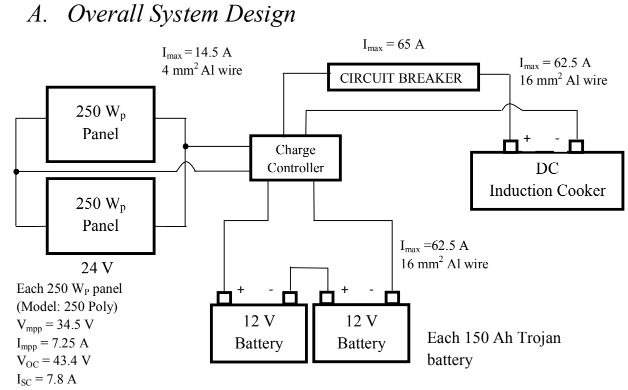

Fig.14. Block Diagram of the System

Figure 14 shows the block diagram of the entire system. It consists of Solar PV panel, charge controller, Battery, Circuit Breaker and DC induction cooker.

B. Block Diagram of DC induction cooker subsystem

Figure 15 shows the block diagram of the designed DC induction cooker subsystem used in this research work. It consists of several components out of which Resonant Converter, Zero crossing detector and IGBT along with microcontroller are used to implement the power converter. The level shifter has been used to shift the 5 V logic level signal to 15 V logic level signal so as to turn on and off the IGBT. Optocoupler together with DC fan is used for cooling mechanism inside the induction cooker.

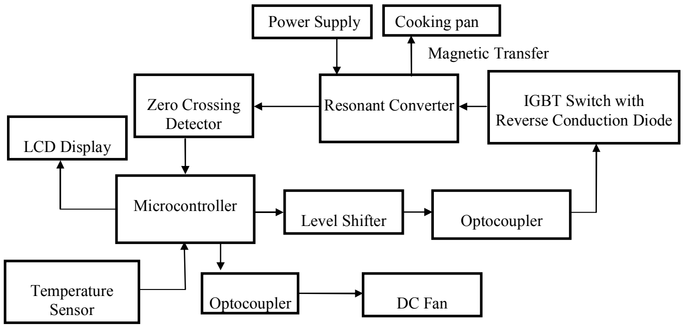

Fig.15. Block Diagram of the DC Induction Cooker Sub-system

C. Flowchart of the System Operation

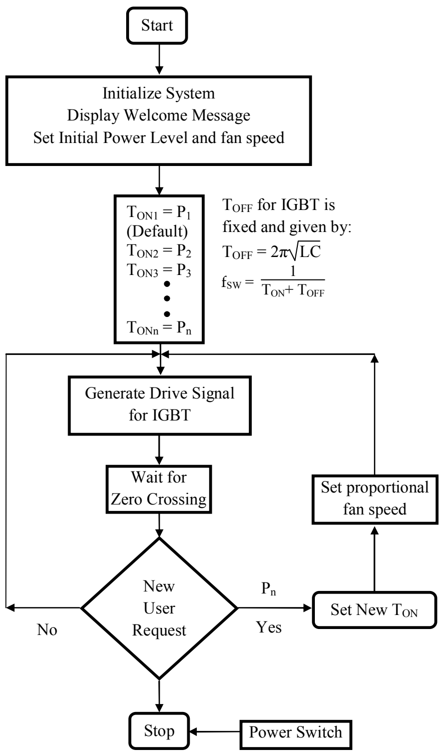

Fig.16. Flowchart of the system operation

Figure 16 shows the flowchart for the operation of the DC induction cooker. After start the system initializes its ports to required logic level. The system reads the value of temperature sensor. Initially system is configured to low power level. Based on T_{ON} corresponding to required power level, the drive signal for IGBT is generated. During T_{ON} the induction coil charge. And the IGBT is turned off after time T_{ON}. The circuit resonates when the IGBT is turned off and the end of the cycle is determined by the zero crossing detection circuit. When the zero crossing is identified, the IGBT is again turned on and the cycle continues. The system can be shut down by the hardware switch.

V. RESULTS AND DISCUSSIONS

A. Testing of existing AC based induction Cooker

A DC powered induction cooker from the market was taken. The experimental efficiency of the induction cooker measured in the lab was found to be 85.56%. From the simulation the efficiency, output power, input power and input current at different control voltage is as shown in the table 1.

TABLE 1

Efficiency, Output Power, Input Power and Input Current at Different Control Voltage

Voltage(V)	Input Current(A)	Input Power(W)	Output Power(W)	Efficiency
0.36	0.87	200	176.00	0.87
0.91	2.17	500	440.00	0.87
1.36	3.26	750	652.50	0.86
1.82	4.35	1000	880.00	0.87
2.91	6.96	1600	1424.00	0.87
4.00	9.57	2200	1936.00	0.87
			Average η	0.87

Thus, the average efficiency of the existing induction cooker from the simulation has been found to be 87%.

B. Simulation of the designed induction cooker

From the simulation of the designed circuit in Multisim and Proteus, it has been found that 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. After the simulation following data has been obtained:

TABLE 2

Variation of power, current and efficiency with duty cycle

Duty Cycle (%)	Input Power(W)	Input Current(A)	Output Power(W)	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	62.50	1310	87.33

As can be seen from table, the usable output power of 508 W, 780 W and 1310 W can be obtained with the duty cycle of 60, 70 and 80 respectively. Only these powers are practically usable.

C. Testing on the hardware of the final design

The prototype of the designed system is not working satisfactorily in the real time environment. The main reasons are:

i. The IGBT which should be able to handle around 30-40 Amperes of current easily has malfunctioned at 10 A current.
ii. PCB tract is not able to handle large current.
iii. The capacitor of 296 nF is not available in the market, so the required value was realized by the combination of available polyester capacitance.
iv. The circuit assembly and soldering is not perfect as it is not done by using professional equipment.

v. The circuit uses simple drive circuit (by simple it means drive circuit is designed using available discrete components). It lacks professional driver IC specially fabricated for induction cooker design, which is usually expensive.
vi. Though the system is not stable, the cooking pot was heated slightly during testing, which confirmed induction heating.

VI. Conclusions and Recommendations

A. Conclusions

i. The testing of the selected induction cooker from the market has been done and its efficiency was experimentally measured to be 85.56 %.
ii. The simulation efficiency of the functional circuit of the selected 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%.
iv. The hardware realization of the design has been completed which upon the real time testing is malfunctioning due to component failures.
v. In order to realize the design in real time power electronic components with high current rating at low voltage like 12 V level is required.

B. Recommendations

This research just touches the surface of induction heating using dc power source. Followings are the recommendations of this research work:

i. Further research is needed in the design of power converter stage. The research on full-bridge topology and half bridge topology is needed to explore the possibility of high power (more than 1kW and below 2 kW) systems at 24 V.
ii. Further research must be conducted in pan-coil modeling. This provides accurate models so that it can help in improving induction cooker design.
iii. Specially prepared driver ICs for IGBT like IR2110 should be used in the design of drive circuitry instead of simple drive circuitry.
iv. Because of high current and high frequency of the circuit, the PCB should be designed with enough trace width. The PCB should have enough clearance between the components to reduce the parasitic capacitance and inductance.
v. Future research is needed in the DC infrared cooker apart from DC induction cooker.

VII. References

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IX. Biographies

Bikal Adhikari is an interdisciplinary engineer. He received his M.Sc. Engineering degree in Energy Systems Planning and Management and his Bachelor's of Engineering degree in Electronics and Communication Engineering from Tribhuvan University, Nepal. At present, he is working as a full time lecturer in the Department of Computer and Electronics & Communication Engineering at Kathford Int'l College of Engineering and Management. His research interests lie in the area of Energy Engineering, Power Electronics, Solar PV technology, Systems Programming etc.

Jagan Nath Shrestha is a visiting professor and researcher at Center for Energy Studies, Institute of Engineering, Tribhuvan University. He is a retired professor at the Department of Electronics and Computer Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University. He received his M.E. degree in Radio Communication Engineering from Moscow Electro Technical Institute of Telecommunication (former USSR) in 1972. He received his Ph.D. degree in Physics (Solar Photovoltaic) from L. N. Mithila University, India in 2005. He is a founder director of Center for Energy Studies at Institute of Engineering, Tribhuvan University.

He is a pioneer and leading expert in the area of Solar PV technology in Nepal. He has worked as consultant to many national and international organizations in the area of Renewable Energy Technology. His research interests lies in the application of Renewable Energy Technologies: especially Solar PV technology in developing countries.

Shree Raj Shakya is a senior Mechanical Engineer and Energy Engineer. He received his B.Sc. in Physics degree and B.E. in Mechanical Engineering degree from Tribhuvan University in 1993 and 1999 respectively. He went on to receive his M.Sc. Renewable Energy Engineering degree from Tribhuvan University in 2004 and his Ph.D. in Energy Engineering degree from Asian Institute of Technology, Thailand in 2012. At present he is working as an Assistant Professor and Program Coordinator of M.Sc. Engineering in Energy Systems Planning and Management program at the Department of Mechanical Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University. He is also an acting director at Center for Energy Studies, Institute of Engineering, Tribhuvan University. He has worked as a research consultant to many organizations. His research interests lie in the area of Energy Systems Modeling and Analysis, Energy Systems Planning, etc.