Output Power-Enhancing Inverter Design for Solar Induction Cooker

R.H.N.S. JAYATHISSA
Department of Computer Engineering, General Sir John Kotelawala Defence Univerity, Ratmalana, Sri Lanka

Abstract- A growing number of people are turning to solar energy to provide power, heat their homes, and desalinate their water. As a result, given that Sri Lanka receives a substantial amount of solar radiation from all directions, solar energy offers an alternate solution to the country's current power crisis. People can use this energy for daily domestic works, particularly for kitchen uses like cooking and water heating. In particular, solar induction cookers are very popular among people around the world. So, this paper proposes heat and energy optimized solar induction cooker. Heat and the energy of induction cooker mainly rely on heating coil and the inverter selected for the cooker. Therefore, this research study proposes a maximum power delivering inverter design with its optimal parameter for utmost efficiency.

Indexed Terms- Inverter, Hysteresis loss, Quality factors, Ripple voltage, Steady-state analysis

I. INTRODUCTION

Induction cooking, a highly efficient technique of cooking, will provide the technology's long-term solution when combined with the solar system. Solar-powered cooking is a long-term, cost-effective solution, despite the fact that it may initially be expensive. Induction heating is a well-known technique for producing extremely high temperatures, such as when melting steel. To generate a high-frequency eddy current that circulates inside the target item, the approach requires a high-frequency current supply.

The basic block diagram of a solar-based induction cooker is shown in Figure.1. The voltage from a solar panel (DC) will charge a battery. The DC from the battery should be converted to a variable AC supply (Inverter). This AC from this inverter will supply a coil on a magnetic core. The resulting alternating flux in the magnetic core will create hysteresis and eddy current losses in the body. The heat generated in the middle will be used to cook food in a pot placed on the magnetic core. The hysteresis and eddy current losses are dependent on the flux and frequency. The heat will be controlled by the frequency and voltage of the inverter. A system is to be built as a prototype to bring one liter of water to boiling temperature in five minutes. It should display the temperature, power level, and duration of how long the system is ON.

Solar Panel

The solar panel converts solar energy into electrical energy by connecting and assembling photovoltaic cells [1]. It can produce and distribute electricity for commercial and residential uses as a component of a larger photovoltaic system.

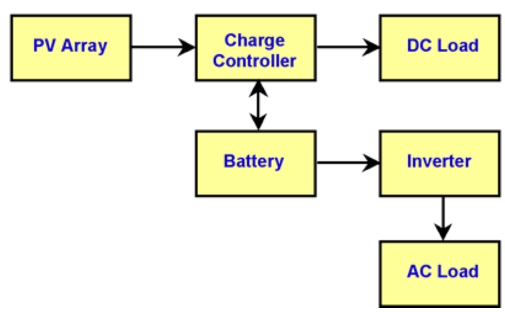

Figure 1. Basic block diagram of a solar based induction

Control Circuit

A system must have a method for determining when a cell is fully charged (changes in terminal voltage, temperature, etc.) and stopping charging before damaging overcharging or overheating takes place[2]. If cooling fans are required to prevent the cells from overheating, we can use them.

Battery
Rechargeable batteries are used in load-leveling applications for grid energy storage, where they store electrical energy. The energy that is saved during the day can be used during the night's peak load for sustainable energy.

Inverter
A power inverter is a converter that transmutes direct current (DC) to alternating current (AC). The converted output can be made to any voltage and frequency according to the applications.

Induction cook top
Induction cooking uses induction heating to heat a metal cooking vessel directly, rather than transferring heat from a flame as with an accustomed cooking stove

Although most used inverter topologies are full-bridge and half-bridge, resonant inverter topologies are generally used for the induction cooker. But most of these strategies result in conducting losses and switching losses. In some techniques, the output power is decreased when the switching frequency is increased, and the highest efficiency range restricts changing frequency. Therefore, the key to a successful induction heater design is to select a well-suited inverter with a suitable selection of semiconductor switches [3].

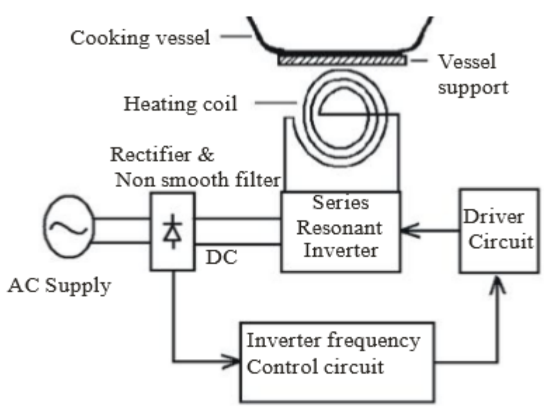

Figure 2. Basic circuit of a domestic purpose induction cooker

Various types of heating coil are used when heating coil design, including foil and tape types of the ring. The main disadvantage of foil coil is that the current distribution is not uniform; the end portion of foil has maximum, and the center has minimum current distribution. The cross-section of the conductor used in the heating coil may be round or square and have single strands or multiple strands. The design of a heating coil with its optimal parameters and the selection of the optimum operating switching frequency of the inverter is necessary to get the maximum efficiency. To avoid unwanted surface heating of the induction coil and to maintain the under-damped condition for the R-L-C load circuit, the value of resistance and inductance of the heating coil should be optimized [4].

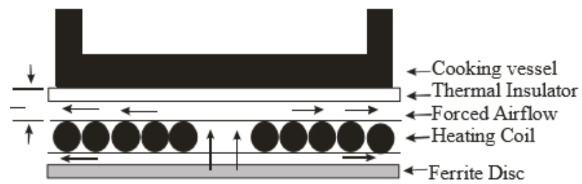

Figure 3. Cross-section of Induction cooker

This paper presents energy efficient solar induction cooker with the optimal inverter design. Key to a successful induction heater design is to select a well-suited inverter with suitable selection of semiconductor switches. A comparative study can be made among the various semiconductor switches in terms of efficiency of the same power rating inverter and selected most energy efficient inverter for the design.

A resonant inverter delivers maximum power to the load only when it works at resonant frequency. On the other hand, material, shape and size of the heater affect the resonant frequency, Q-factor and efficiency of the inverter. Thus, it is necessary to optimize the physical parameters of the cooker so as to get the maximum benefit from it. It is possible only when the circuit is properly analyzed[5].

Heating coil is considered as another main part of the induction cooker. The design of a heating coil with its optimal parameters and the selection of the optimum operating switching frequency of the inverter are necessary to get the maximum efficiency. To avoid unwanted surface heating of induction coil and to maintain the under-damped condition for R-L-

C load circuit, the value of resistance and inductance of the heating coil should be optimized.

II. PROPOSED APPROACH

A. Inverter design

An LLC resonant inverter configuration for solar induction cooker is shown in Figure 4. The inverter consists of four switches with antiparallel diodes, a resonant capacitor (C_p), a series inductor (Ls) in which the leakage reactance of the transformer is included and an induction coil that comprises a series combination of a resistor (R_{eq}) and an induction coil inductor (L_{coil}). A DC blocking capacitor (C_b) is inserted in series with the transformer primary winding. The stray capacitance of MOSFET switching device S_1, S_2, S_3 and S_4 are noted as C_{oss1}, C_{oss2}, C_{oss3} and C_{oss4} respectively.

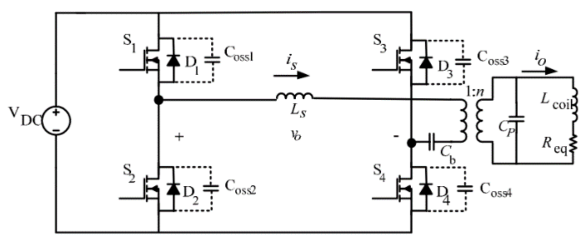

Figure 4. Full-bridge LLC resonant inverter

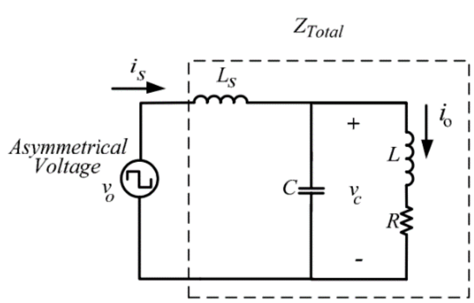

Figure 5. Equivalent circuit

An equivalent circuit of the full-bridge LLC inverter system in Figure 4. is shown in Figure 5. where the input voltage can be viewed as an asymmetrical ac voltage supplied to the system. With a negligible value of C_b, it is noted that the capacitor C, the inductor L, and the resistor R represent the equivalent capacitor C_p, inductor L_{coil}, and the resistor R_{eq} referred to the primary side of the transformer, respectively. The total impedance to the asymmetrical voltage source (vo) is denoted by Z_{Total}. The current is and io are the input and output currents, respectively[6].

B. Circuit Analysis

In order to understand the preliminary characteristics of voltages and currents of the main and load circuits, a mathematical approach is required. The steady-state analysis of the full-bridge LLC inverter is based on the following assumptions.

1) All circuit components are ideal. This is because switching devices, inductors, capacitor and a transformer in the circuit consists of small parasitic and may be negligible compared with the circuit operating characteristics.
2) The dc input voltage, VDC, is constant because the capacitor on the dc bus is assumed to be sufficiently large. This allows the ripple voltage on the dc bus to be neglected which greatly simplifies the analysis of the output voltage of the inverter.
3) The effects of stray capacitance are neglected because their capacitance (in the order of Nano farad) is much less than the resonant capacitor, C_p (in order of microfarad). Therefore, the effects of the stray capacitance on the operating characteristics particularly load current and voltage are essentially negligible.

The relationship between the load voltage (i.e. the capacitor voltage: Vc) and the inverter output voltage (Vo) is derived as below. From Figure 5., voltage across the resonant capacitor can be calculated from voltage divider method [7].

$$\frac{V_c}{V_o} = \frac{\dfrac{1}{\left(j\omega C + \dfrac{1}{(R + j\omega L)}\right)}}{j\omega L_S + \dfrac{1}{\left(j\omega C + \dfrac{1}{(R + j\omega L)}\right)}} \qquad (1)$$

When A= $j\omega C$
B= $j\omega Ls$
C= $R + j\omega L$ substituting above equation,

$$\frac{V_c}{V_o} = \frac{\frac{1}{\left(A+\frac{1}{C}\right)}}{\left(B+\frac{1}{\left(A+\frac{1}{C}\right)}\right)}$$

$$= \left(\frac{C}{AC+1}\right)\left(\frac{AC+1}{BAC+B+C}\right) \quad (2)$$

The ratio of the output voltage (Vo) of inverter and the capacitor voltage (V_C) can be found as,

$$\frac{V_c}{V_o} = \frac{R+j\omega L}{(j\omega L_s \times j\omega C)(R+j\omega L)+j\omega L_s + R + j\omega L)}$$

(3)

Where, L $=n^2L_{coil}$ R= n^2Req and C= C_p/n^2 given that n is the transformation ratio of the transformer.

$$\frac{V_C}{V_O} = \frac{R+j\omega L}{(j\omega L_S \times j\omega C)(R+j\omega L)+j\omega L_S + R + j\omega L}$$
$$= \frac{R+j\omega L}{-\omega^2 L_S CR - j\omega^3 LL_S C + j\omega L_S + R + j\omega L}$$
$$= \frac{R+j\omega L}{-\omega^2 L_S CR - j\omega(LL_S) - j\omega^3 LL_S C + R}$$

(4)

The resonant frequency of the system in Figure 5 is given as,

$$\omega_o = \sqrt{\frac{L+L_s}{L \cdot L_s \cdot C}} \quad (5)$$

Instead, the ω is ω0 apply on above equation,

$$\frac{V_C}{V_O} = \frac{R+Lj\sqrt{\frac{L+L_S}{LL_SC}}}{R-R\left(\frac{L_S+L}{L}\right)}$$

$$= \frac{R+Lj\sqrt{\frac{L+L_S}{LL_SC}}}{R\left(\frac{L-L_S-L}{L}\right)}$$
$$= \left(\frac{RL+L^2 j}{-RL_S}\right)\sqrt{\frac{L+L_S}{LL_SC}}$$
$$= \left(-\frac{L}{L_S}-\frac{L^2 j}{RL_S}\right)\sqrt{\frac{L+L_S}{LL_SC}} \quad (6)$$

So, we calculate the capacitor voltage as a function of Vo,

$$V_c = V_o\left(-\frac{L}{L_S}-\frac{L^2 j}{RL_S}\right)\sqrt{\frac{L+L_S}{LL_SC}} \quad (7)$$

This inverter is designed to operate such that the switching frequency (ω) is slightly higher than the resonant frequency (ω0) for ZVS operation. This enables to take only the fundamental component (V_1) of the inverter output voltage (vo) in Figure5. into account. The load voltage is given as,

$$V_C = \left(-\frac{L}{L_s} - j\frac{L^2}{RL_s}\sqrt{\frac{L+L_s}{L \cdot L_s \cdot C}}\right)\cdot V_1 \quad (8)$$

The fundamental component V_1, of the capacitor voltage V_C in (8) can be obtained from the following coefficients of Fourier series of the inverter output voltage Vo,

$$\hat{V}_n = \frac{V_m}{\pi}\sqrt{a_n^2 + b_n^2}$$
$$\phi_{vn} = \tan^{-1}\frac{a_n}{b_n} \quad (9)$$

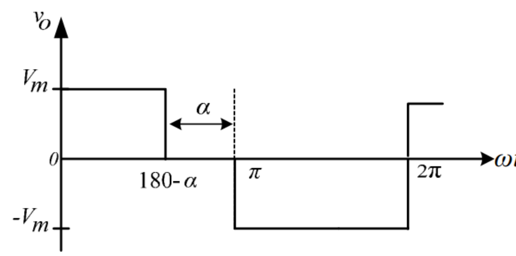

Figure 6. Asymmetrical voltage waveform

From Figure 6. the time variation in steady state of the voltage may be represented by the following Fourier series. We can define even function and odd function equations in (10) and (11)

$$b_n = \frac{1}{\pi}\left[\int_0^{180-\alpha^0} V_m sin(n\omega t) d(\omega t) + \int_0^{2\pi} (-V_m) sin(n\omega t) d(\omega t)\right]$$
$$= \frac{V_m}{\pi}\left\{\left[\frac{-cos(n\omega t)}{n}\right]_0^{180-\alpha^0} + \left[\frac{cos(n\omega t)}{n}\right]_\pi^{2\pi}\right\}$$
$$= \frac{V_m}{n\pi}\left[-cos\left(180-\alpha^0\right) + cos(0) + cos(2n\pi) - cos(n\pi)\right]$$
$$= \frac{V_m}{n\pi}\left[2-(-1)^n - cos\, n\left(180-\alpha^0\right)\right] \quad (10)$$

Where Vm is the amplitude of the asymmetrical voltage waveform.

$$a_n = \frac{1}{\pi}\left[\int_0^{180-\alpha^0} V_m \cdot cos(n\omega t) d(\omega t)\right]$$
$$= \frac{V_m}{n\pi}\left[sin(0) - sin\left(180-\alpha^0\right)\right]$$
$$= \frac{V_m}{n\pi} sin\left(180-\alpha^0\right) \quad (11)$$

Where Vm is the dc input voltage assuming the same value as VDC, φvn is the phase of the nth harmonics of vo and α is the shifted angle of the switch S4. Using (9), the amplitude of the fundamental voltage v1 can be calculated as,

$$\hat{V}_1 = \frac{V_m}{\pi} \times \sqrt{\sin^2(180-\alpha) + (3-\cos(180-\alpha))^2} \quad (12)$$

and the average output power (Po) at the load can be obtained as,

$$P_o = V_1^2 \operatorname{Re}\left\{Z_{total}(j\omega_0)^{-1}\right\}$$

Which is expanded to

$$P_o = \frac{V_m^2}{2R\pi^2}(\sin^2(180-\alpha) + (3-\cos(180-\alpha))^2)\left(\frac{L}{L_s}\right)^2 \quad (13)$$

For the zero power angle φ, the output power Po in (13) depends on the shifted angle α. Figure 7 shows the relationship of the output power and α, obtained using (13).

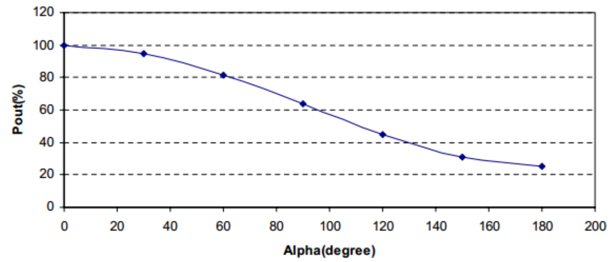

Figure 7. Output power versus α

CONCLUSION

It is seen that an increase of α results in reduction of the output power. Meaning that the output power can be controlled through an adjustment of α .The greater the angle α less power delivered to the load. By substituting α with 0° and 180° in (13), the output power $P_o$results in 100% and 24.97%, respectively. Notice that the output power $P_o$does not reach zero through the setting of α because the voltage reduction in the asymmetrical control is through the positive cycle. The negative cycle of the output voltage remain unaffected. The equivalent circuit in Figure 6 receives only negative cycle of the asymmetrical input voltage. Based on the superposition principle, there always exists a small amount of output current flowing through the load.

From (13) we can define the output power as a function of Q that is shown in (14). The output power $P_o$is essentially directly proportional to the quality factors (Q), providing that the angle is kept constant.

$$P_o = \frac{V_1^2\sqrt{CL_s}Q\tan\phi}{\tan\phi\sqrt{Q\tan\phi - 1}} \quad (14)$$

The frequency response of the output power (P_o) under different quality factors (Q) is shown in Figure 8 with the angle α set to zero. At higher Q factor, the inverter operates close to the resonant frequency, ω_0, (i.e. the normalized frequency $f_s/f_b$is close to 1). Unlike the induction coil current (i_o) shown in Figure .9, the Q factor has negligible effect on the resonant frequency. That is the peak value of i_o occurs at the same frequency regardless of the Q factors.

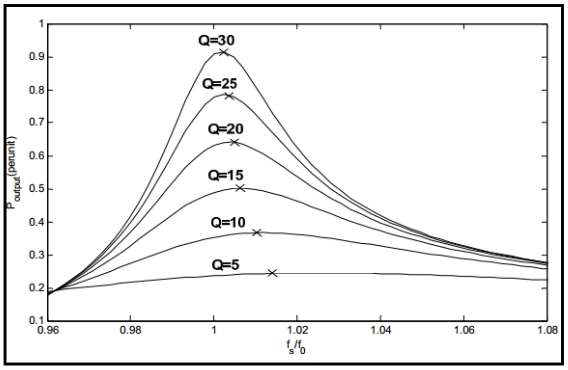

Figure 8. Frequency response: output power (Po) at various Q factors

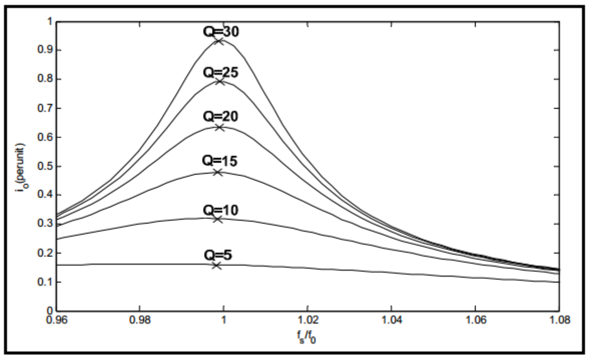

Figure 9. Frequency response: output current (io) at various Q factors

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