Optimal Design of LLC Resonant Converter with Improved Controllability

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***Abstract*—The aim of this paper is to introduce generalized design and optimization methodology for LLC resonant converters. To investigate operation principles, deriving linear circuit and mathematical models, first harmonic approximation is used which to great extent can simplifies quantitative analysis. For optimal, high efficiency design of LLC converter with controllability feature over wide variation of input voltage, mathematical model of gain function and input impedance are reordered to be used as fitness function and constrain functions and 'Genetic Algorithm' is used to achieve best possible combination of resonant tank elements. Optimized values of Q_e, L_n and n is selected and simulation is carried out using PSIM software to verify the accuracy of the proposed method.**

***Index Terms*—LLC resonant converter, SMPS, ZVS, First harmonic approximation, Wide input voltage range regulator.**

I. Introduction

Power supply design encounters challenges in the fields of high efficiency, high power density and low level of EMI emission. Resonant power converters in general and LLC resonant converter in particular have shown to have the capability of satisfying aforementioned requirement of power supplies. In LLC converters, soft switching can be attained in whole range of output voltage and load variation. Soft switching of power converters not only solves the matter of EMI emission, but also promises higher frequency operation and higher power density by reducing switching losses.

Higher switching frequencies leads to smaller passive elements, but at the same time highly increases switching losses. Among different available topologies, resonant converters has gained much attention due to their low switching losses and higher switching frequency.

Three most popular resonant topologies are: series resonant converter, parallel resonant converter and series parallel converter (in LLC topology) [1]. In resonant converters, input voltage is divided between resonant tank and the load. Varying the frequency of unipolar rectangular input voltage will results in variable impedance of resonant tank which leads to variable voltage gain.

Performance of resonant converters should be investigated in to two extreme conditions: a) maximum input voltage and minimum output current and b) minimum input voltage and maximum output current.

In series resonant converter (SRC) under light load condition, to regulate the output voltage, frequency should be increased. In addition impedance of resonant converter will increase in higher frequencies. This results in more circulating current in resonant tank. Since circulating current is not transferred to the load, this current should be sent back to the power source and as a result conduction loss will increase. Higher input voltage follows by higher circulating current and higher conduction losses. [1].

In parallel resonant converter (PRC) circuit light load regulation problem is not as severe as in SRCs but at the same circulating current plays a more dramatic role.

Among different resonant topologies LLC converter (Fig.1) is proven to be more suitable design for front end DC-DC applications. In light load condition LLC converter requires smaller range of switching frequency variation and is capable of performing in ZVS condition even at no load.

Many studies have conducted to investigate different aspects of resonant converters. Steady state analysis of LLC converter based on actual mathematical model is presented in [2]. Simplified model is introduced in [3]. Design procedure for half bridge LLC converter and different optimization methods has been discussed in different papers. [4]–[8].

Unlike PWM converters, frequency modulation is the preferred control strategy. Different techniques including asymmetric pules width modulation, switching pulse phase shifted control, pulse destiny modulation technique and variation of resonant tank impedance are discussed in different papers as well. [9]–[12]

In [5] it is noted that insufficient information about operation principles and design methodologies are the main drawback over LLC topology developments. Quick review of design procedures proposed by different authors reveals that design methods are based on complex mathematical models. Which makes designing the LLC converter a complicated and time consuming task.

In this paper simplified mathematical model along with revised generic algorithm is suggested for designing optimal LLC converter while satisfying required criteria which would greatly simplifies the designing procedure. In section 2, important characteristics of LLC converter is discussed and required mathematical description is derived. Section 3 discusses about genetic algorithm and how to obtain required mathematical model. In this section fitness function is introduced and constrain functions, based on design criteria, are developed. in section 4, following results of section 3,

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optimal resonant tank parameters are calculated. To certify the results, simulation process was carried out as well.

II. LLC Resonant Converter

In this section brief description of LLC resonant converter based on FHA approximation is provided and main characteristics of this topology is discussed in detail. In Fig.1a typical topology of an LLC converter in half bridge configuration is depicted and in [2] complete and precise analysis is discussed in detail. Simplified circuit which leads to nonlinear, non-sinusoidal model is shown in Fig.1b.

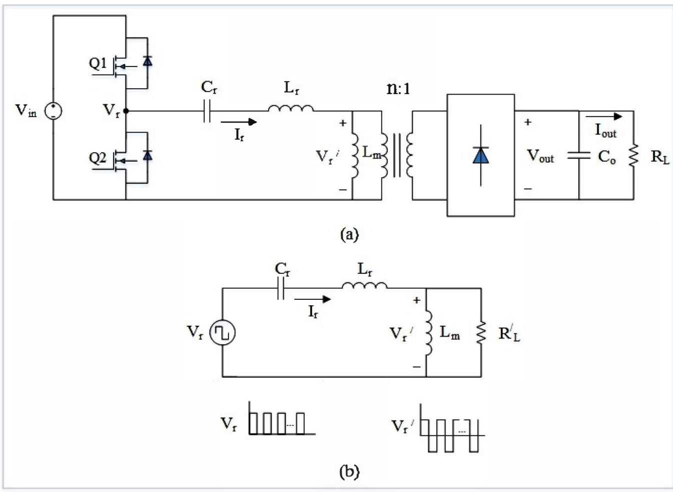

Fig. 1: LLC resonant converter. (a) Complete circuit model in half bridge configuration. (b) AC equivalent circuit

To be able to perform simple circuit analysis linear, sinusoidal equivalent circuit is preferred.

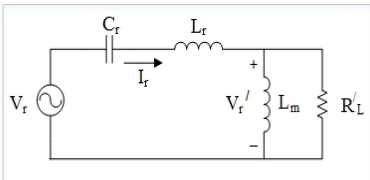

Fig. 2: AC equivalent circuit of LLC converter based on FHA approximation

To achieve this simplified model, first harmonic approximation (FHA method) is developed [3]. Based on this methodology linear and sinusoidal model as in Fig.3 is derived. In order to apply FHA method following steps should be taken [4]:

- Unipolar square wave voltage and current (as in Fig.1b) should be considered purely sinusoidal, with neglected higher harmonic component.
- Bipolar square wave voltage and current in secondary side should be transferred to primary side and only fundamental components should be considered, just as the previous step.
- The effect of output capacitor should be ignored.
- The value of load resistance should be transferred to primary side.

Now that the roles are set and appropriate circuit diagram is derived, important characteristics of LLC converter can be discussed and mathematical model could be developed.

Load resistance transferred to primary side can be expressed as (1) as explained in [6]:

$$R_e = \frac{V_{oe}}{I_{oe}} = \frac{8 \times n^2}{\pi^2} \times \frac{V_o}{I_o} = \frac{8 \times n^2}{\pi^2} \times R_L \qquad (1)$$

Based on Fig.2 and using FHA approach, normalized gain function can be expressed as (2) just as explained in [4]:

$$M_g = \left| \frac{L_n \times f_n^2}{[(L_n + 1) \times f_n^2 - 1] + j\,[(f_n^2 - 1) \times f_n \times Q_e \times L_n]} \right|$$

$$L_n = \frac{L_m}{L_r} \;,\; Q_e = \frac{\sqrt{L_r/C_r}}{R_e} \;,\; f_n = \frac{f_{sw}}{f_o} \qquad (2)$$

And relationship between input and output voltage can be described as [4]:

$$V_o = M_g(f_n, Q_e, L_n) \times \frac{1}{n} \times \frac{V_{in}}{2} \qquad (3)$$

Gain function explains how the converter operates over the frequency variation and paves the groundwork for LLC converter analysis. in this way M_g behavior as a function of f_n, Q_e and L_n were determined. Fig.3 depicts M_g as a function of f_n for different values of L_n and Q_e. Switching frequency is considered as the control variable.

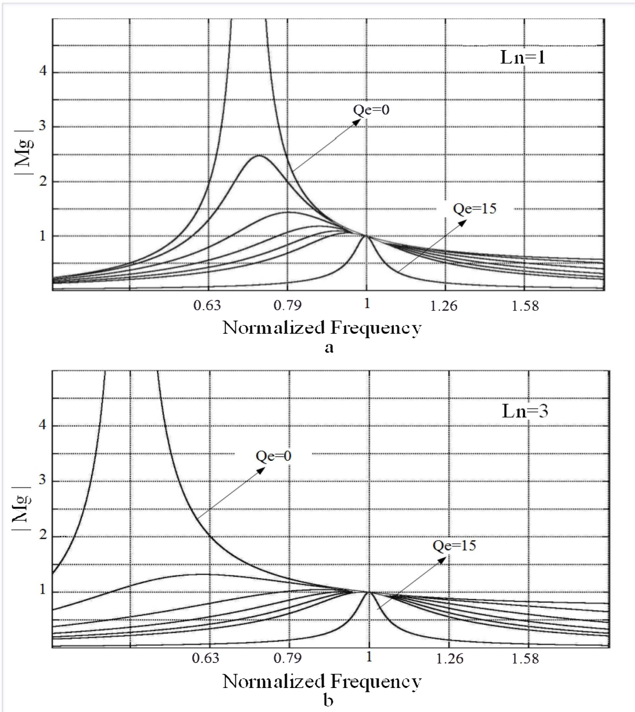

Fig. 3: Voltage gain function with different values of L_n and Q_e

Independent from load condition and different combinations of Q_e and L_n, $(f_n, M_g) = (1, 1)$ is a convex point for all curves [4]. When switching frequency is equal to resonant frequency, impedance of resonant tank is equal to zero so voltage drop across the resonant tank is zero and input voltage is directly applied to the load.

Under no load condition based on equation (2) $Q_e = 0$. In this way peak value of gain function occur at (f_p), in which L_m is in parallel with load impedance, L_m participates in resonant at the whole duration of switching period. (f_p) as described in [4] can be calculated by (4):

$$f_p = \frac{1}{2\pi\sqrt{(L_r + L_m)C_r}} \tag{4}$$

In short circuit condition, considering equation (2) and Fig.2, I_{out} and Q_e are very large ($R_e = 0$), L_m is bypassed and has no effect on gain function and the frequency in which maximum gain value is achieved (f_o) can be calculated by [4]:

$$f_o = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{5}$$

In normal operation mode, range of resonant frequency corresponding to peak gain value is a function of Q_e and it's variation range can be described as [4]:

$$f_p \leq f_{co} \leq f_o \tag{6}$$

For fixed value of L_n, by moving from no load to short circuit condition, R_L would decrease and following (2) it would be clear that Q_e would increase, considering the same equation, maximum peak value of gain function would decrease.

As the Q_e is decreasing while moving from no load to short circuit condition, as described earlier the effect of L_m is decreasing and f_{co} is increasing and moving toward the value of f_o [4].

On the other hand by keeping Q_e constant and moving from no load to short circuit condition, decreasing the value of Ln increases the value of f_{co} which moves it toward f_o. And considering the equation (2) and Fig.2, lower value of L_n will results in higher value of peak gain [5].

In brief, higher value of Q_e and lower value for L_n makes the f_p and f_o closer to each other and the range described by equation (6) is narrower. This results in a better frequency-control band in which gain function becomes more sensitive to frequency variation.

M_g gives a good insight into the operation principle of LLC converter, but input impedance provides mathematical model to study the performance of LLC resonant converter, qualities like conduction loss and soft switching performance can be analyzed by evaluating the input impedance.

Based on FHA method and Fig.2, normalized input impedance of LLC converter can be calculated as [7]:

$$Z_{in} = \frac{x}{Q_e(1+x)} + j\frac{\sqrt{x}}{Q_e}\left[\frac{1}{L_n}(1-\frac{1}{f_n^2}) + \frac{1}{1+x}\right] \tag{7}$$

Where

$$x = (Q_e.f_n.L_n)^2 \tag{8}$$

As mentioned earlier resonant tank acts as voltage divider. Resonant tank exhibit minimum impedance at resonant frequency. By the changing switching frequency, Z_{in} changes as well. Fig.4 depicts how input impedance varies with respect to frequency variation.

In Fig.5 blue and red curves represents no load and short circuit conditions respectively. Crossing frequency in which two curves intercepts can be calculated by using [5]:

$$f_{n \cdot cross} = \sqrt{\frac{2L_n}{L_n(L_n+2)}} \tag{9}$$

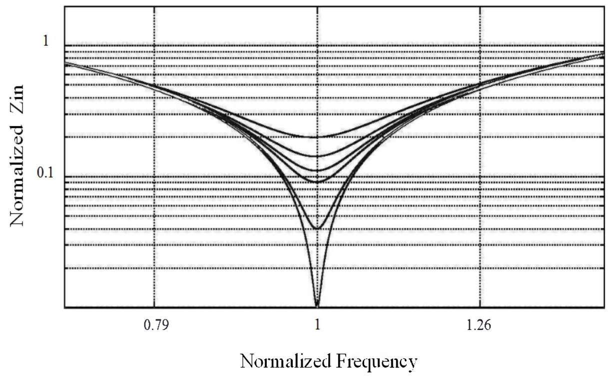

Fig. 4: Normalized Input impedance

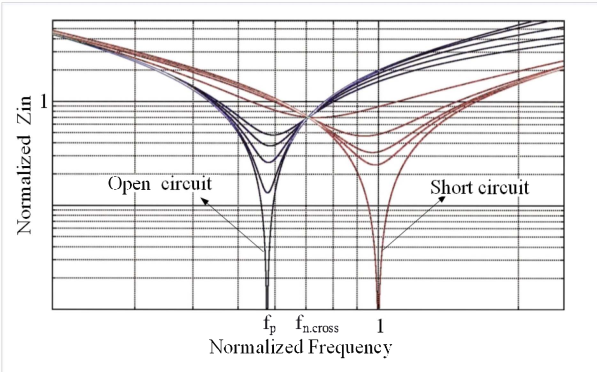

Fig. 5: Normalized Input Impedance in Short Circuit and No Load Condition

$|Z_{in}|$ has a significant effect on converters efficiency, specifically when designing a converter with large input voltage variation. At higher input voltage, switching frequency increases to regulate output voltage. Higher switching frequencies results in higher resonant tank impedance and higher circulating energy in resonant tank. Since circulating energy is the amount of energy sent back to the source in each switching cycle. Higher circulating energy means that two MOSFET's in input stage should process more energy which results in higher conduction loss and hence lower efficiency [1]. Fig.6 shows this phenomenon for two input values.

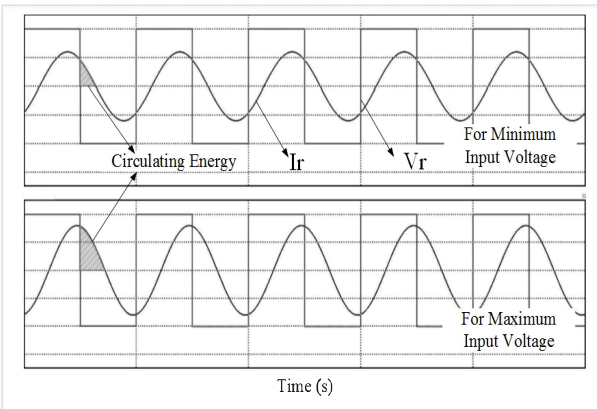

Fig. 6: Circulating Current at Different Input Voltage Condition

Along with $|Z_{in}|$, phase angle of input impedance is of great importance. One advantage of LLC resonant converter topology is the potential of reducing switching losses by inherently achieving ZVS, and phase angle plays an important role. φ_z is the function of switching frequency and varies within $(-\pi/2 < \varphi_z < \pi/2)$ where:

- $\varphi_z > 0$ the impedance is inductive
- $\varphi_z = 0$ the impedance is resistive
- $\varphi_z < 0$ impedance is capacitive

When impedance is inductive, I_r lags behind V_r and the condition for achieving ZVS is prepared, in which MOSFET's voltage should be reduced to zero before applying the gate signal. To achieve ZVS, before applying turn-on signal to the MOSFET, reversal current should discharge the MOSFETs drain-to-source capacitor, C_{ds}, and then forward biasing the body diode [13].

In other words, to achieve ZVS impedance should be in inductive region and enough inductive power should be available during the dead time which is described by following function [4]:

$$\frac{1}{2}(L_m + L_r) \times I_{m.peak}^2 \geq \frac{1}{2}(2C_{ds}) \times V_{in}^2 \tag{10}$$

And a dead time between switching intervals is required which can be calculated by [4]:

$$t_{dead} \geq 16 \times (2C_{ds}) \times f_{sw} \times L_m \tag{11}$$

In this section mathematical model to design LLC resonant converter is derived and important characteristics of this topology is studied. In the next section design criteria are introduced and design methodology based on genetic algorithm is explained in detail.

III. Designing LLC Resonant Converter

In this section design and optimization of LLC converter is discussed. The converter specification is as follows:

- Input voltage: 200 to 400 VDC
- Output voltage: 48 VDC
- Output voltage ripple: 1% at full load
- Output power: 200 W
- Resonant Frequency: 120 KHz

In designing the LLC converter Q_e, L_n and n should be chosen in such way that output voltage regulation is guaranteed in narrow variation of switching frequency and input impedance, and at the same time with same values of main variables, Z_{in} is achieved in such way that by limiting circulating energy in the resonant tank conduction loss is well limited and ZVS is also achieved in the whole range of converter operation so that switching loss is low and hence high efficiency can be achieved.

Considering (2), (3) which describes gain function and input impedance, different combinations of L_n, Q_e and n could provide the same result. In order to achieve best possible solution, using genetic algorithms (GA) is suggested in this paper. Main variables Q_e, L_n and n and their variation range are introduced to the algorithm, GA randomly generates initial population which typically contain several hundreds or thousands of solutions and covers entire range of possible solutions. Then the fitness of this primitive population is evaluated and more fit individuals are selected and they will evolve to form the next generation of population and this process will continue until termination condition being reached. As a result large number of possible solution are evaluated and the combinations of Q_e, L_n and n who achieves satisfactory fitness level will be the output of the algorithm.

In the rest of this section fitness and constrain functions based on mathematical model developed in section 2 will be introduced and the output of GA is then evaluated to choose the best combination of Q_e, L_n and n.

A. Fitness Function

Power density is one of the major challenges in designing a power supply. Input stage capacitor which supplies energy during a holdup time can be reduced in size by designing converter with wide rang of operation, as a result power density of converter would increase [5]. In LLC converter wide range of input voltage variation may lead to very high or very low switching frequencies which increases the power loss and destroy the uniformity of converter efficiency profile.

To achieve acceptable efficiency profile the design will be done such that for switching frequencies higher than f_p (in inductive region), slop of gain function is maximized. So the fitness function is defined as:

$$\frac{-d}{df_n} M_g(f_n, Q_e, L_n) \tag{12}$$

This results in high sensitivity of gain function to variation of switching frequency and as discussed in section 2, better frequency control band could be achieved.

Although doing so may leads to very low value for L_m which increases conduction loss or low gain value but as will be discussed later, constrain functions will be defined so that main design criteria are guaranteed.

B. Constrain Functions

In defining fitness function the only consideration is to calculate the values of Q_e, L_n and n so that highest M_g sensitivity with respect to frequency variation could be achieved, on the other hand in defining constrain functions, quality aspects of converter operation is considered.

1) Minimum and maximum gain: This function is defined to make sure that the gain function can meet the criteria set by converter specifications introduced earlier in this section. In inductive region gain function should satisfy the following range:

$$M_{min} \leq M_g \leq M_{max} \tag{13}$$

Considering (3), minimum and maximum of gain can be calculated as:

$$M_{min} = \frac{n \times V_{out}}{V_{in \cdot max}/2} \quad , \quad M_{max} = \frac{n \times V_{out}}{V_{in \cdot min}/2} \tag{14}$$

2) ZVS and efficiency : As described in section 2, impedance should be in inductive region to ensure the ZVS operation with satisfying (15):

$$\varphi_z = (|Z_{in}| e^{j\varphi_z}) > 0 \tag{15}$$

In order to decrees conduction loss by reducing the circulating energy, phase angle between resonant tank current and voltage should be as low as possible. Equation (16) is defined to warrant this criteria:

$$\varphi_z = (|Z_{in}|e^{j\varphi_z}) < 60^\circ \tag{16}$$

φ_z is calculated based on equation 7.

Important advantage of using genetic algorithm is the capability of defining different constrain functions. For example one could develop the mathematical model to define RMS value of magnetizing current such that appropriate selection of L_m could lead to high efficiency by decreasing switching and conduction loss. Alternatively, dead time optimization [8] could be one of the constrain functions. Using genetic algorithm gives designers the tool to fulfill different criteria by applying appropriate constrain function.

Now that the fitness and constrain functions are defined, genetic algorithm is executed using MATLAB software and the output results are discussed in the section 4.

C. Evaluating results of GA

Results provided by genetic algorithm are categorized in Table I . Design 2 is chosen due to lower conduction loss and narrow frequency range. For calculation of resonant tank elements following equation can be used:

$$C_r = \frac{1}{2\pi \times Q_e \times f_o \times R_e} \tag{17}$$

$$L_r = \frac{1}{(2\pi \times f_o)^2 \times C_r} \tag{18}$$

$$L_m = L_n \times L_r \tag{19}$$

IV. Simulation Results:

The value for resonant tank elements have been calculated in previous section and presented in Table I. Based on design 2 in Table I ,M_g and φ_z can be drawn as depicted in Fig.7.

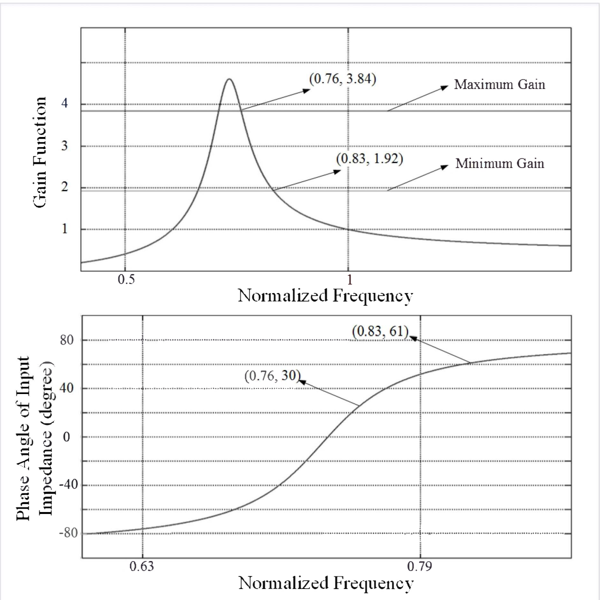

Fig. 7: Main Converter Characteristics

Based on Fig.7a gain function can satisfies M_{min} and M_{max} at $f_{sw} = (0.76 \times 130KHz = 98.8KHz)$ and $f_{sw} = 0.83 \times 130KHz = 107.9KHz$ respectively. In Fig.7b φ_z for aforementioned frequencies are 30° and 61° respectively. Final circuit is simulated using PSIM software. $T_{dead-time}$ is calculated based on equation 11. Simulation is done for $V_{in} = 400$ volt and full load condition. Fig.8 depicts important wave forms of the circuit. During the transition time (dead-time) resonant tank current is equal to magnetizing current and Q_1 current is circulating through Q_2s capacitance and discharge C_{ds} and then forward bias body diode Q_2 such that that ZVS can be achieved.

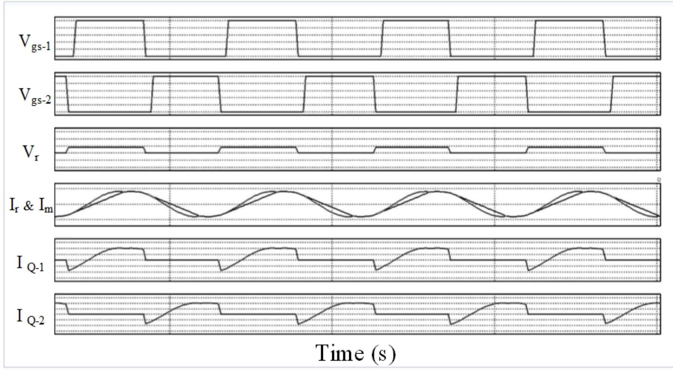

Fig. 8: Main Circuit Wave-Forms (from top, gate signal of MOSFET 1 and 2, input voltage of resonant tank, resonant tank and magnetizing currents, MOSFET 1 and 2 currents)

V. Conclusions

The LLC resonant converter due to it's innate characteristics is suitable topology for front end dc-dc converters. Operation principles and characteristics of this topology are investigated in the second section of this paper. First harmonic approximation provides a valuable method to study the LLC resonant converter circuit, by using this method simplified linear and sinusoidal circuit model can be achieved which simplifies mathematical model of the circuit.

Lack of straight forward design methodology has been one of important drawbacks of this topology which makes it difficult for engineers to fully take advantage of this type of converters. Beside that low controllability and high circulating current in high switching frequencies are major problems of LLC resonant converter. In section 3, LLC converter is investigated from quality and performance point of views. ZVS condition is investigated and the effects of Z_{in} on achieving ZVS is studied. Z_{in} plays an important role in this regard. $|Z_{in}|$ and φ_z is investigated in this section and the effect of L_m in efficiency of converter has been studied. Fitness function is introduced and for optimization, genetic algorithm is employed to calculate best possible combination of resonant tank elements, which proves to be able to greatly simplify mathematical calculation. Beside that by using GA, designers can set different design goals by appropriate introduction of constrain functions which will make the design procedure easier and more precise.

In section 4, simulation is done and proved the feasibility of this design methodology. ZVS condition is guaranteed throughout the operation rang, the converter can produce regulated output voltage considering the wide range of input voltage variation and high controllability is achieved. Z_{in} is designed is such way that φ_z is well limited, considering that

TABLE I: Results of Genetic Algorithm

	L_n, Q_e and n	C_r	L_r	L_m	Normalized f_{sw} range	φ_z range	Peak I_m	Peak I_r	ZVS
Design 1	0.5, 0.63, 7.2	3.95n	379μ	190μ	0.84 - 0.90	$22° - 60°$	3.44	3.54	ok
Design 2	0.89, 0.34, 8	5.93n	253μ	225μ	0.76 - 0.83	$30° - 61°$	3.16	3.24	ok
Design 3	1.23, 0.21, 10	6.14n	244μ	300μ	0.69 - 0.76	$31° - 62°$	3.11	3.17	ok

gain function and φ_z is designed to be sensitive to frequency variation in order to achieve high controllability.

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