Optimal Design of LLC Series Resonant Converter with Enhanced Controllability Characteristic

Ehsan Khoobroo [1], Mahdi Akhbari[2]
[1], [2] Electrical Power Eng. Dept., Faculty of Engineering, Shahed University, Tehran, Iran.
[1] ehsan.khoobroo@yahoo.com, [2] akhbari@shahed.ac.ir

Abstract—This paper proposes an optimization model for the determination of LLC resonant converter design parameters. The optimization model is developed based on the fundamental harmonic approximation (FHA) analysis and variable reluctance control method. The objective of the optimal design is to reach the maximum controllability characteristics by the resonant converter. The reluctance control strategy is used as converter controller because it presents a wide range controllability compared to switching frequency based control methods. To verify the optimization results, an accurate converter model is implemented by PSPICE software; the converter model takes into account the parasitic elements of the power semiconductor switches. Simulation results are presented for the resonant converter with optimal parameters. The results obtained from simulations show acceptable agreement with the theatrical analysis.

Keywords: variable reluctance control, LLC converter, optimal design

I. INTRODUCTION

High efficiency resulted from soft switching technique is the chief advantage of resonant converters compared to PWM converters. Depending the operation modes of the resonant converter (inductive or capacitive), ZVS or ZCS switching can be achieved. Soft switching decreases the switching losses and also it allows the resonant converter to be used in high switching frequency ranges. In other word, it improves resonant converters efficiency and reduces volume and/or weight; therefore higher power density can be achieved by resonant converters compared to PWM converters. The resonant converters are more attractive at very high switching frequencies due to their high efficiency.

Among the resonant converters, series resonant converters have not proper controllability in wide range of load variations also LCC resonant converters have high circulating current in inductive operation mode. However LLC series resonant converters present better behavior in wide range load variations compared to the mentioned resonant converters [1]-[2].

Traditionally resonant converters are regulated by switching frequency control method. In this method the output voltage is regulated by switching frequency over a predetermined frequency range, this method does not present acceptable performance in wide load variations, also at light loads it leads to very poor efficiency due to high switching losses at high switching frequencies.

There are two main criteria to evaluate control method performance [4]-[6]:

- *Converter output regulation capability in wide range of input voltage variations and load changes.*
- *Uniformity of converter efficiency profile in different conditions of input voltage and load.*

In order to amend the traditional control method, different approaches have been proposed in recent years. Most of them consider a constant switching frequency at all conditions i.e. load and input voltage changes [4-7]. In [4] the Asymmetric Pulse width modulation (APWM) control method has been introduced, in [5] switching pulse phase shifted control method is utilized as a complementary to the switching frequency control which is applicable for only heavy loads. Pulse density modulation (PDM) control method has been proposed in [6] and in reference [7] variable reluctance control method has been examined and an optimization method for determination a base value for resonant inductance in converter nominal operating point has been introduced. Magnetic regulators in general and variable inductors in particular have found a great application in power electronic converters [9]-[11].

Variable reluctance control method has some advantages over other control methods such as control by duty cycle and switching frequency. Due to constant switching frequency and also constant duty cycle the losses are likely unchanged over the range of control. In fact, only the reluctance of a magnetic circuit should be regulated to reach a desired value for inductance of the resonant circuit. This is performed by a low power auxiliary circuit. Therefore the losses remain unchanged over a wide range of load and input voltage variations and a flat profile is achieved by this method of control. Furthermore, considering the high sensitivity of the LLC converters voltage gain to the value of resonant inductance proper value of this element leads to a wide range control of converter.

Referring LLC converter theoretical analysis performed in many references it is relevant that a number of converter parameters should be determined for an optimal operation of

IEEE Catalog Number: CFP1211J-ART
ISBN: 978-1-4673-0113-8/12/$31.00 ©2012 IEEE

converter from control viewpoint. The authors of reference [7] have been suggested an optimization models for this purpose. They have considered just one parameter (i.e. resonant inductance) as variable of the model and other parameters such as resonant capacitor, switching frequency and transformer turn ratio have been predetermined.

In this article an optimization model with the main LLC converter parameters as variable is proposed. The proposed model is developed based on the controllability viewpoint which uses the resonant inductance as the core variable. Other affecting parameters are switching frequency, resonant capacitance, transformer magnetizing inductance and transformer turn ratio. The optimization problem is treated by means of genetic algorithm. An LLC resonant converter is designed and the optimal values of its parameters are determined by the proposed method. To evaluate the converter performance and study the impact of the parasitic elements in converter characteristic, the converter is simulated by an accurate SPICE model. The simulation results show good performance of the converter over a wide range of input voltage changes and load conditions.

II. LLC SERIES RESONANT CONVERTER

A. theoretical analysis

The topology and key waveforms of an LLC resonant converter are shown in Fig. 1 [3]. Its principle and operation modes have been discussed in many papers [12]-[16].

Fundamental harmonic approximation (FHA) method is used to simplify analytical studies of resonant converters [1], [8] this method leads to an ac equivalent circuit of the LLC converter as shown in Fig. 2.

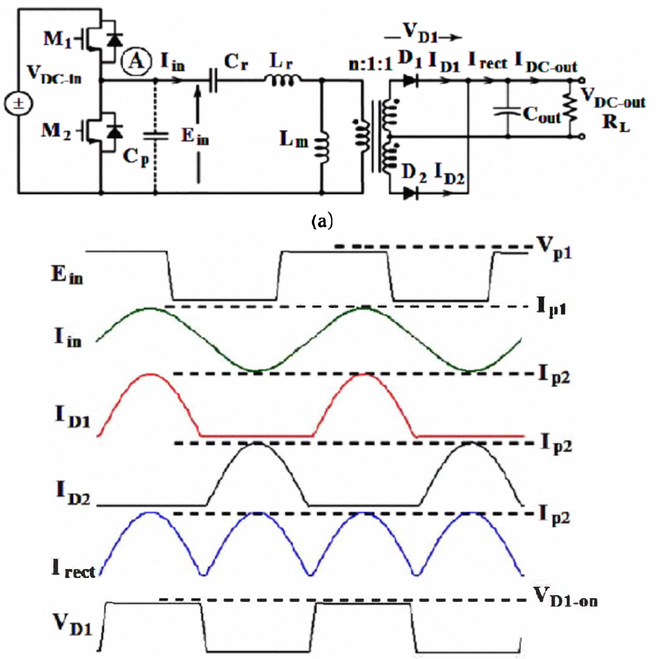

Fig. 1 (a).LLC resonant converter topology. (b) Typical waveforms.

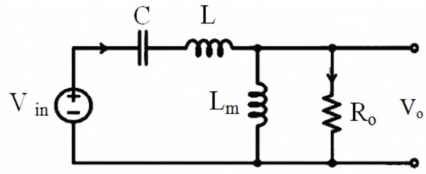

Fig. 2 AC equivalent circuit of LLC converter based on FHA approach

In Fig. 2, V_{in} shows the magnitude of the first harmonic of input voltage square waveform:

$$V_{\text{in}} = \frac{2}{\pi} V_{\text{DC}} \tag{1}$$

where V_{DC} is the magnitude of the input voltage. According to the FHA method, ac equivalent resistance referred to the primary side of the transformer is expressed as:

$$R_o = \frac{n^2}{2} \frac{[1-(\lambda/\pi)^2]^2}{cos^2(\lambda/2)} R_L \tag{2}$$

where R_L and λ are the load resistance and the conduction angle respectively. Assuming the converter operates in CCM mode and take $\lambda = \pi$ into the expression (2), expression (3) is obtained as below:

$$R_o = \frac{8n^2}{\pi^2} R_L \tag{3}$$

Fig. 3 shows the voltage gain of the LLC converter as a function of normalized frequency for various load values [16].

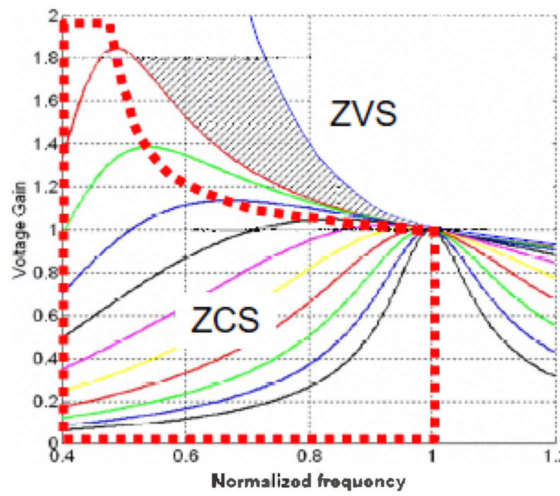

Fig. 3 DC gain characteristics of LLC converter

This is obvious from Fig. 3 that at the regions that the normalized frequency is greater than one the converter operates in inductive mode and ZVS switching is achieved. It means that to have a proper soft switching for all of load conditions, the converter must be forced to operate in switching frequencies greater than the resonant frequency.

Based on the FHA approach the equivalent input impedance of an LLC converter is expressed as (4).

IEEE Catalog Number: CFP1211J-ART
ISBN: 978-1-4673-0113-8/12/$31.00 ©2012 IEEE

$$Z_{in} = \frac{\omega^2 {L_m}^2 R}{R^2+(\omega L_m)^2} + j\left[\omega L - \frac{1}{\omega C} + \frac{\omega L_m R^2}{R^2+(\omega L_m)^2}\right] \quad (4)$$

where R , n, L_m and ω_S are the ac equivalent resistance, transformer turn ratio, transformer magnetizing inductance, and switching frequency respectively. The relation between input and output voltage can be expressed as:

$$V_{out} = \frac{V_{in}}{Z_{in}}\left(\frac{\omega L_m R^2 - j(\omega L_m)^2 R}{R^2+(\omega L_m)^2}\right) \quad (5)$$

According to the expressions (1) , (5) the voltage gain can be determined.

$$M \triangleq \frac{V_{out}}{V_{DC}} = \frac{2}{\pi}\frac{\sqrt{(\omega L_m R^2)^2+(\omega L_m)^4 R^2}}{R^2+(\omega L_m)^2\sqrt{\alpha^2+\beta^2}} \quad (6)$$

Where α and β are defined by:

$$\alpha = \frac{(\omega L_m)^2 R}{R^2+(\omega L_m)^2}$$

$$\beta = \omega L - \frac{1}{\omega C} + \frac{\omega L_m R^2}{R^2+(\omega L_m)^2}$$

The last equation can be simplified to a standard equation for L in term of other variables as below:

$$aL^2 + bL + c = 0 \quad (7)$$

where the factor a, b and c are given in appendix. By solving the last equation for L the expression (8) will be resulted.

$$L = \frac{\left[C^2 M^2 \omega^3 \pi\left[R^2 + L_m \omega^2 (L_m - R^2 C)\right]\right] + \sqrt{\Delta}}{\left(C^3 M^2 \omega^5 \pi\left(R^2 + {L_m}^2 \omega^2\right)\right)} \quad (8)$$

where Δ is given in appendix.

III. Optimization Model

From controllability viewpoint an optimum design is achieved when the converter is able to provide regulated voltage by limited changes in the resonant inductance of the converter. To meet this purpose an objective function is defined, it corresponds to the inductance range width. The need for the inductance variation is determined by regulation requirement when the load and the input voltage are subject to sever variations.

Referring to the complexity of the model, the optimization problem will be treated by genetic algorithm. Therefore, it is required to define a fitness function as the objective function of the problem.

There are two worst case conditions in which the inductance should be taken its minimum and maximum value. These worst-case conditions are described as below:

- *Minimum input voltage and maximum output load.*
- *Maximum input voltage and minimum output load.*

Based on the above cases the fitness function is defined as the ratio of the minimum inductance to the maximum inductance. This ratio must be minimized to achieve a feasible variable reluctance.

$$L_{ratio} = \frac{L_{max}}{L_{min}} = \frac{L|(R_L = 0.1R_{min}, M = 0.14n)}{L|(R_L = R_{min}, M = 0.24n)} \quad (9)$$

There are four variables in the fitness function to be determined. These four variables are:

- *C: resonant capacitor*
- *Lm: transformer magnetizing inductance*
- *fs: switching frequency*
- *n: transformer turn ratio*

Once the optimal value of the above parameters are determined, minimum and maximum values of the resonant inductance can be obtained by using the relations (8) and (9).

The optimization model is completed by defining the constraints, some constraints are considered on the variables which define the search space. These constraints are specified based on the experience with resonant converters design and feasible parameter limits. For the converter to operate in ZVS mode, the switching frequency following constraint must be satisfied as well:

$$\frac{\omega_S}{\omega_0} > 1 \quad (10)$$

where ω_S is the switching frequency and ω_0 is the resonant frequency.

IV. Optimization Results

In first step, the requirement of the design should be specified. The main requirements considered in this paper are:

- *Input DC voltage: 200-340V*
- *Output voltage: 48V*
- *Output power:10-100W*

Then the converter voltage gain should be regulated between 0.14 and 0.24 by controller i.e:

$$M_{max} = \frac{V_{out}}{V_{DC}} = \frac{48}{200} = 0.24,\ M_{min} = \frac{V_{out}}{V_{DC}} = \frac{48}{340} = 0.14$$

According the mentioned principles discussed in section II and considering the transformer turn ratio in the ac equivalent based on FHA, the required voltage gain referred to primary side should change between 0.14n to 0.24n where n indicates the transformer turn ratio.

The allowed variable ranges, are specified such that the values are feasible; for the LLC converter requirements

$$20\mu H < L_m < 200\ \mu H$$

$$1\text{nF} < C < 200n\text{F}$$

$$200000 \text{ rad/sec} < \omega < 800000 rad/sec$$

MATLAB function of genetic algorithm is used for solving the optimization problem, optimization is performed for different values of transformer turn ratio: n=1, 2, 3. The resulting optimal values for fitness function and the optimal values of the parameters are reported in the Table I.

TABLE I. RESULTS OF OPTIMIZATION

Transformer turn ratio	n	1	2	3
Magnetizing inductance	L_m	20uH	20uH	20uH
Resonant capacitor	C	68nF	29nF	28nF
Switching frequency	f_s	110 kHz	107 kHz	99kHz
Fitness function: inductance ratio	L_{ratio}	1.69	1.23	1.13

The results presented in Table. I show that the lower value of objective function, L_{ratio}, can be attained by greater transformer ratios. However it causes the rise of the transformer primary voltage and current, therefore by the same magnetizing inductance it may lead to increase of the transformer losses in practical design. It should be noted that if the maximum limit value of the resonant inductance is increased, the results for L_{ratio} function will be better than reported results, however we are investigating practical issues related to construction of such a variable inductance by using a DC biased winding.

V. SIMULATION RESULTS

The complete topology of the considered LLC resonant converter is shown in Fig. 4. The circuit is model with the optimal values obtained for the transformer turn ration n=1 given in Table I. The PSPICE software is used to validate the proposed approach of converter design.

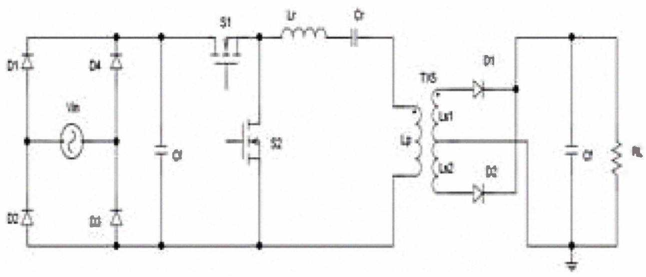

Fig. 4 Complete topology of LLC converter

The required inductance values for output voltage regulation fixed at 48V can be obtained at different load resistance and input voltage conditions by some try and error. Also the required values of inductance to regulate output in various operating points can be calculated by using the analytical relations given in section II.

Fig. 5 illustrates the required inductance values versus the input voltage variations in nominal load condition. Two presented curves compare the results of simulation and the results of analytical calculation. The comparison of the curves shows a good agreement in trend which is the base for the implementation of control unit. The same comparison is performed in minimum load condition. The results are given in Fig. 6. Again the trends are comparable but the values are linearly different which is related to the switches and diodes voltage drops in PSPICE model. Furthermore in theoretical analysis all of the input voltage harmonics are neglected which can affect the results.

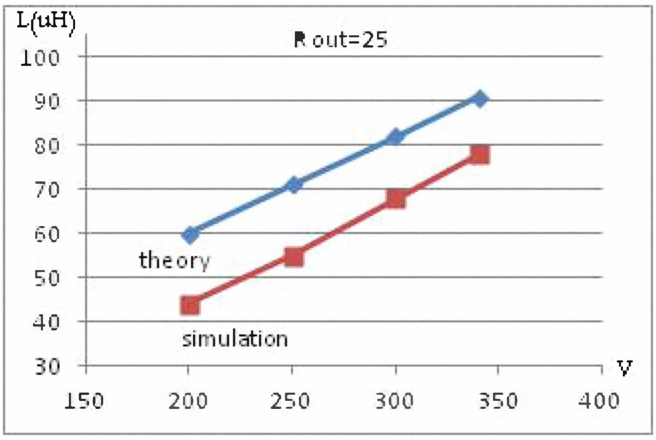

Fig. 5 Analytical and simulation results for resonant inductance at nominal load

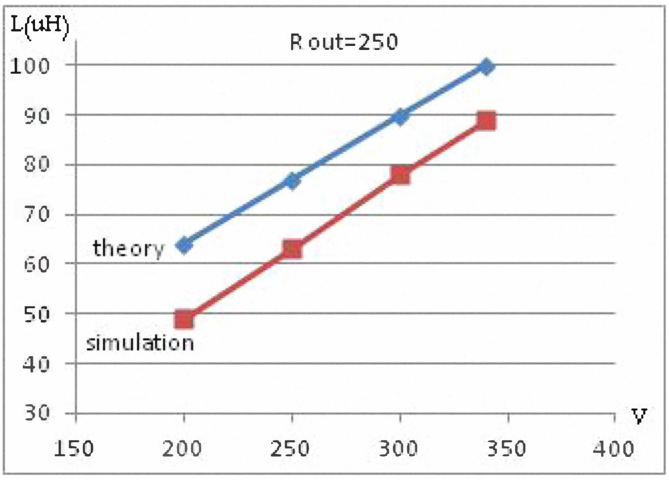

Fig. 6 Analytical and simulation results for resonant inductance at minimum load

VI. CONCLUSION

In this paper a new optimization model is proposed for determination of LLC resonant converter parameters. The converter is controlled by variable reluctance (inductance). In the optimization model the objective function is defined such that it guarantees the system controllability in a wide range of input voltage and load variations. Then the proposed approach overcomes the negative issues associated with existing resonant converter control methods. The designed converter by this method operates in ZVS mode for all line voltage and load

IEEE Catalog Number: CFP1211J-ART
ISBN: 978-1-4673-0113-8/12/$31.00 ©2012 IEEE

conditions. The proposed approach is applicable to other types of resonant converter. The optimization model is applied for designing a 48V, 100W LLC series resonant converter operating at 110 kHz switching frequency. The converter was simulated using PSPICE software; and the results are discussed. The comparison between simulation results and analytical calculations related the required inductance control shows good agreements especially on the inductance variation trends.

REFERENCES

[1] R.W. Erickson and D. Maksimovic, "Resonant converters," in *Fundamentalsof Power Electronics*, 2nd ed. Boulder, CO: Kluwer, 2001, ch.19,pp. 705–759.

[2] R.L. Steigerwald, "A Comparison of Half-Bridge Resonant Converter Topologies," IEEE Trans. Power Elec., vol. 3, pp. 174-182, April 1988.

[3] R. Beiranvand, B. Rashidian, M. R. Zolghadri,and Seyed Mohammad H. Alavi"Designing an Adjustable Wide Range RegulatedCurrent Source" IEEE Trans. Power Electron., vol. 25, no. 1,pp.,197-208 Junuary. 2010.

[4] Darryl J. Tschirhart, and Praveen K. Jain, "Design Procedure for High Frequency Operation of theModified Series Resonant APWM Converter withImproved Efficiency and Reduced Size" in ProcIEEE Applied Power electronicConfrence and Exposition(APEC). Feb2010 .pp.14-18.

[5] Yu-Kang Lo, Member, IEEE, Chung-Yi Lin, Min-Tsong Hsieh, and Chien-Yu Lin" Phase-Shifted Full-Bridge Series-ResonantDC-DC Converters for Wide Load Variations" IEEE Trans. Power Electron., vol. 58, no. 6,pp., 2572-2575June. 2011.

[6] S. Dalapati, S. Ray, S. Chaudhuri, and C. Chakraborty, "Control of a series resonant converter by pulse density modulation," in Proc. IEEE India Annual Conf. (INDICON), 2004, pp. 601-604.

[7] Stefan V. Mollov* and Michael P. Theodoridis" A Comparison and Optimum Design of Reluctance-Controlled Classical Load-Resonant Converters"IEEE 13th International Power Electronics and Motion Control Conference. 2008 (EPE-PEMC 2008),pp.350-356

[8] G. Ivensky, S. Bronstein, and S. B. Yaakov, "Approximate analysis of the resonant LCL DC-DC converter," in Proc. IEEE Electr. Electron. Eng. Israel, 2004, pp. 44–47.

[9] D. Medini, S. Ben-Yaakov; "A current-controlled variable inductor for high frequency resonant power circuits," IEEE Applied Power Electronics Conference, pp 219-225, 1994.

[10] S. Ben-Yaakov and M. M. Peretz; "A self-adjusting sinusoidal power source suitable for driving capacitive loads," IEEE Trans. on Power Electronics, vol. 21, No. 4, July 2006, pp. 890-898.

[11] J. M. Alonso, M. A. Dalla Costa, M. Rico, J. Cardesín, J.García; "Investigation of a New Control Strategy for Electronic Ballasts Based on Variable Inductor", IEEE Transaction on Industrial Electronics, Vol. 55, N° 1, pp. 3-10, January2008.

[12] B. Lu, W. Liu, Y. Liang, F. C. Lee, and J. D. van Wyk, "Optimal design methodology for LLC resonant converter," in Proc. IEEE APEC 2006, pp. 533–538.

[13] X. Xie, J. Zhang, C. Zhao, Z. Zhao, and Z. Qian, "Analysis and optimization of LLC resonant converter with a novel over-current protection circuit," IEEE Trans. Power Electron., vol. 22, no. 2, pp. 435–443, Mar.2007.

[14] G. C. Hsieh, C. Y. Tsai, and S. H. Hsieh, "Design considerations for LLC series-resonant converter in two-resonant regions," in Proc. IEEE Power Electron. Spec. Conf. 2007 (PESC 2007), Jul., pp. 731–736.

[15] Y. Gu, Z. Lu, L. Hang, Z. Qian, and G. Huang, "Three-level LLC series resonant DC/DC converter," IEEE Trans. Power Electron., vol. 20, no. 4, pp. 781–789, Jul. 2005.

[16] D. Fu, B. Lu, and F. C. Lee, "1 MHz high efficiency LLC resonant converterswith synchronous rectifier," in Proc. IEEE Power Electron. Spec.Conf. (PESC 2007), Jul., pp. 2404–2410.

APPENDIX

The factors a, b and c of the relation (7) are given by the following expressions:

$$a = \omega^2(R^2 + (\omega L_m)^2)^2$$

$$b = 2\left((\omega^2 L_m R^2)(R^2 + (\omega L_m)^2) - \frac{\left(R^2+(\omega L_m)^2\right)^2}{C}\right)$$

$$c = \frac{-4}{\pi^2 M^2}((\omega L_m R^2)^2 + (\omega L_m)^4 R^2) - ((\omega L_m R^2)^2 +$$
$$\omega Lm4R2+2\omega C\omega LmR2R2+\omega Lm2-R2+\omega Lm22\omega C2$$

Delta in the relation (8) is calculated by the following expression:

$$\Delta = C^3 M^2 R^2 \omega^7 \mathrm{L_m} \left\{-2M^2\pi^2\left(R^2 + \mathrm{L_m}^2\omega^2\right) + \left[C\omega\left[4\omega^2 C\mathrm{L_m}\left(R^2 + \mathrm{L_m}^2\omega^2\right) + M^2\pi^2\left(2R^2 + \mathrm{L_m}^2\omega^2(2 - \mathrm{L_m}\omega^2 C)\right)\right]\right]\right\}$$

IEEE Catalog Number: CFP1211J-ART
ISBN: 978-1-4673-0113-8/12/$31.00 ©2012 IEEE