A Generalized Performance Analysis of a Family of the Frequency Modulated Transformer Isolated LLC Resonant Converter

*Aniagboso J. Onah[1] and Marcel U. Agu[2]

[1]Department of Electrical and Electroinics Engineering, Michael Okpara University of Agriculture, Umudike, Nigeria
[2]Department of Electrical Engineering, University of Nigeria, Nsukka
* aniagbosoonah@yahoo.com

Abstract

This paper presents a generalized performance analysis of six related topologies of the frequency modulated (FM) LLC dc/dc converter with transformer isolation. The traditional first harmonic approximation (FHA) is used to obtain the generalized converter dc output to input converter gain as the switching frequency and the output load vary and an example actual converter dc gain (obtained by Matlab/Simulink simulation) is used to show the degree of accuracy of the FHA analysis relative to the actual dc gain over a specified converter switching frequency variation range. At the LLC converter specified rated output power of 300W and 400V constant output voltage, the converter circuit design parameter values and the transformer turns ratio are determined at the assumed tank resonant frequency of 100 kHz using the FHA analysis. For the designed converter, it is found that to maintain the output voltage constant at the rated value under load variation from no load to rated load, the required converter switching frequency obtained using FHA analysis does not correctly predict the actual required frequency obtained using Matlab/Simulink simulation. With the converter switching frequency limited to ensure converter operation only in the inductive mode in regions less than or equal to the tank resonant frequency, the converter steady state performance (studied using Matlab/Simulink simulation) show ZVS turn on and relatively low current turn off of the converter semiconductor switches and ZCS turn on and turn off of the converter rectifier diodes under load variations from no load to full load for all values of the specified dc input voltage range.

Keywords: LLC Converter, frequency modulation, first harmonic approximation, resonant frequency, matlab/simulink.

1. Introduction

The application of high frequency resonant dc to dc converters in consumer electronics, computer/server and telecommunications systems, battery charging, LED lighting and front end for micro-inverters has significantly increased in recent years. Research effort on these resonant converters has been mainly directed towards achieving improved converter down sizing, minimal component count, high efficiency and low EMI noise. The frequency modulated LLC resonant converter with inbuilt transformer isolation has been reported by many researchers to have the desired characteristics of high power density, high efficiency and low EMI noise over a stipulated high frequency range of operation. In most of the reports (usually made on a specific LLC converter topology [1,2,3,5,6,9]), the first harmonic approximation (as against actual converter analysis [7, 8]) has been used to derive the converter output to input dc voltage gain and other relations used in the study, design and realization of a given converter.

In this paper, a generalized performance analysis of six related topologies of the transformer isolated LLC dc/dc converter is presented. First harmonic approximation (FHA) is used to obtain a general expression of the output to input voltage gain of the six converters and an example actual converter gain (obtained using Matlab/Simulink simulation) is used to show the degree of inaccuracy of the FHA method for converter switching frequency deviations from the converter load independent tank resonant frequency. Relevant FHA derived design equations and plots are used to design an example 300W FM transformer isolated LLC dc/dc converter operating at 400V constant output voltage and capable of delivering rated load power over a specified range of input dc voltage. The designed converter steady state performance (studied using Matlab/Simulink simulation) clearly show the inadequacy of the FHA analysis in correctly predicting the converter performance. By restricting the converter operation to the inductive mode for switching frequencies not higher than the tank resonant value ensures ZVS turn on and relatively low current turn off of the converter semiconductor switches and ZCS turn on and turn off of the converter rectifier diodes under load variations from no load to rated load for all values of the specified dc input voltage range.

2. The LLC Transformer Isolated Resonant Converter

Fig. 1 is the illustrative generalized diagram of the LLC resonant converter. The converter input dc voltage V_s is usually derived from the utility supply voltage, a renewable energy source, a battery bank or a combination of a number of these three power supply sources. The static switched input stage supplies a voltage of commonly two or more distinct levels to the LLC resonant tank circuit. Any of the two-level full/half bridge inverter or inverter leg of Figs. 2 (a, b, c) is very often used as the static switched input stage in Fig.1. Depending on the output rectifier circuit type, the isolation transformer can be the simple two-winding or more than the two-winding type. Fig. 3a shows the LLC resonant tank connected to the output load through a two-winding isolation transformer and a full bridge diode rectifier while Fig. 3b shows the LLC resonant tank connected to the output load through a three-winding isolation transformer and a two diode full wave rectifier. In both Figs 3a and 3b, the transformer leakage inductance L_k and magnetizing inductance L_m participate (with the resonant capacitance C_r) in the resonant action of the LLC tank circuit as the series resonant inductance $L_r = L_k + L_{ext}$ and the

Fig. 1: Illustrative generalized diagram of the LLC resonant converter.

parallel inductance $L_p = L_m$, where L_{ext} is an external inductance added to L_k if needed. The output resistance R_O represents the equivalent resistance of the load at the resonant converter output.

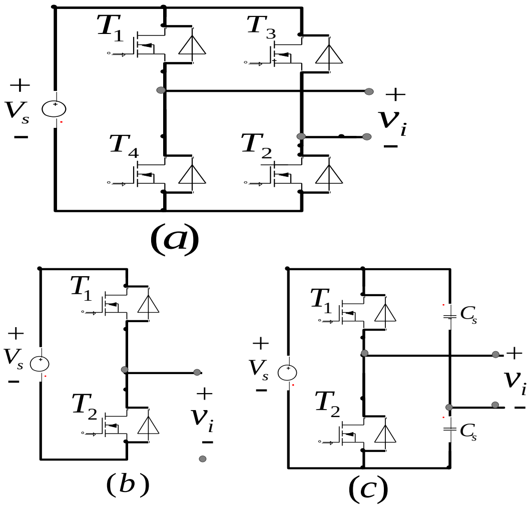


Fig. 2: Static switched LLC converter input stage types: (a) H-Bridge inverter, (b) 2=level inverter leg, (c) midpoint inverter.

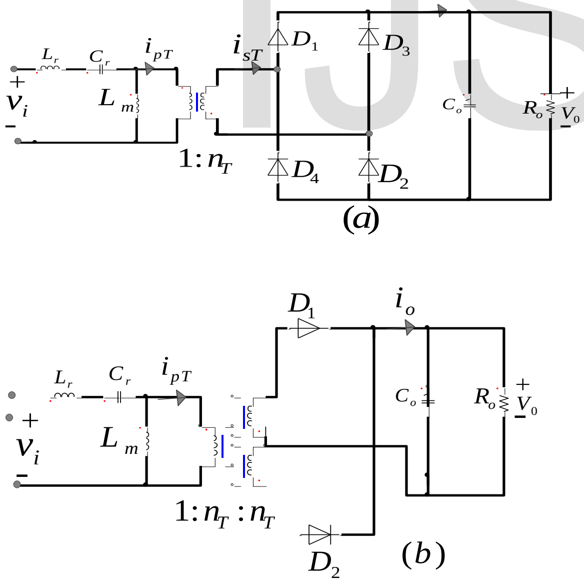


Fig.3: LLC resonant tank circuit with diode rectifier circuit types

((a) H-Bridge diode rectifier, (b) push-pull two diode full wave rectifier.

3. The Transformer Isolated Inverter Leg Fed LLC Resonant Converter

Fig. 4a is one of the six LLC resonant converter topologies that can be realized by connecting one of the three static switched input stages of Fig. 2 to one of the two LLC transformer isolated sub network of Fig. 3. Transistors T1 and T2 are alternatively switched on and off at a frequency f_s to impress a voltage v_i (Fig. 4b) of 50% duty cycle (neglecting the usually required very small transistor gating signal dead time) at the input of the LLC resonant tank. At the tank resonant frequency under load conditions, Fig. 4b show an example of the resultant flow of the resonant inductor current i_{Lr}, the secondary side current i_{sT} and the rectifier output current i_o thus causing the square wave ac voltage of amplitude V_o (Fig. 4b) to be impressed across the transformer secondary winding.

Under operating conditions, the LLC tank circuit blocks dc current flow through it and under loaded conditions (at operating frequency close to or above the tank resonant frequency $f_r = \frac{1}{\sqrt{L_r C_r}}$) presents relatively high impedance to input voltage harmonics higher than the fundamental.

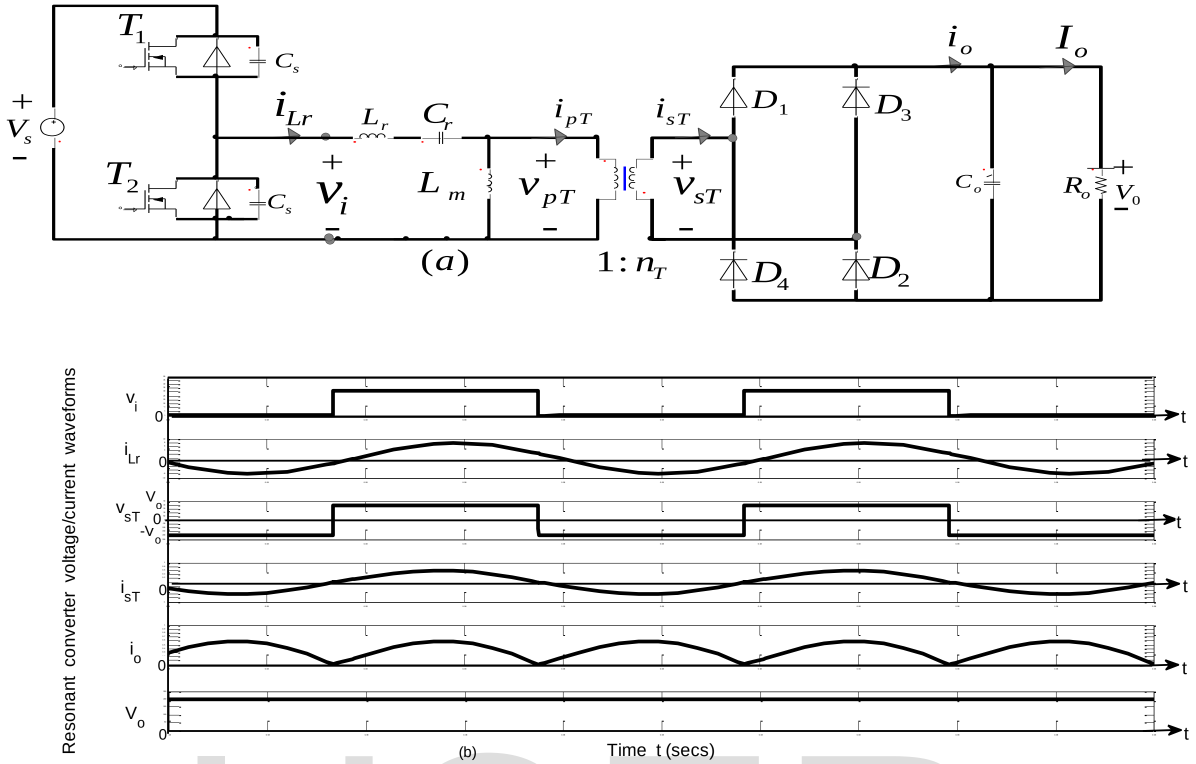


Fig. 4: (a) An example LLC resonant converter and (b) converter voltage and current waveforms under load at LLC tank resonant frequency.

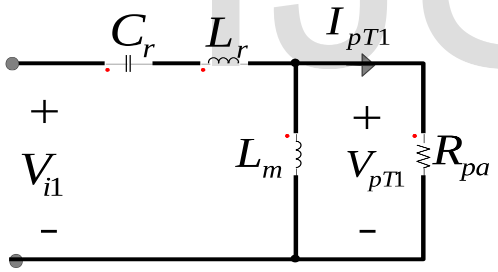


Fig. 5: The resonant converter ac equivalent circuit referred to the transformer primary side.

The fundamental frequency (that is the FHA) equivalent circuit of the converter referred to the primary side of the isolation transformer is therefore as shown in Fig. 5 where V_{i1}, V_{pT1} and I_{pT1} are respectively the fundamental rms values of the input static switched stage voltage v_i, the transformer primary winding voltage v_{pT} (which is the transformer secondary winding voltage referred to the primary side) and the transformer primary side input current i_{pT} while R_{pa} is the equivalent converter output load resistance referred to the transformer primary side.

From Figs 4(a & b) and 5, R_{pa} is easily derived $[1,2,3,5,6,9]$ as

$$R_{pa} = \frac{V_{pT1}}{I_{pT}} = \frac{8V_o}{{n_T}^2\pi^2 I_o} = \frac{8}{{n_T}^2\pi^2} R_o \qquad (1)$$

where n_T is the transformer secondary to primary winding turns ratio $\frac{N_s}{N_p}$.

From the equivalent circuit of Fig. 5, the resonant converter gain $\frac{V_{pT1}}{V_{i1}}$ under fundamental frequency analysis and by implication $\frac{V_o}{V_s}$ is determined.

$$\frac{V_{pT1}}{V_{i1}} = \frac{j\omega_s L_m // R_{ap}}{1/(j\omega_s C_r) + j\omega_s L_r + j\omega_s L_m // R_{ap}} \quad (2)$$

where $\omega_s = 2\pi f_s$ is the converter switching/operating frequency in rad/sec. The re-arrangement and simplification of equation 2 gives the converter dc voltage gain $\frac{V_o}{V_s}$ using FHA analysis as

$$\frac{V_o}{V_s} = \frac{n_T}{2} * [\frac{-f_n^{\,2} L_n}{1 - f_n^{\,2}(1+L_n) + j(1-f_n^{\,2}) f_n L_n Q}] \quad (3)$$
$$= K_c * G_c(Q, L_n, f_n)$$

where

$K_c = \frac{n_T}{2}$ for the example resonant converter of Fig. 4a (4a)

$$G_c(Q, L_n, f_n) = [\frac{-f_n^{\,2} L_n}{1 - f_n^{\,2}(1+L_n) + j(1-f_n^{\,2}) f_n L_n Q}] \quad (4b)$$

The LLC tank resonant frequency f_r due to L_r and C_r , the converter normalized switching frequency f_n in p.u. of the tank resonant frequency, the normalized transformer magnetizing inductance L_n in p.u. of the LLC tank resonant inductance L_r and the LLC converter tank circuit loading/quality factor Q are given as

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (5a)$$

$$f_n = \frac{f_s}{f_r} \quad (5b)$$

$$L_n = \frac{L_m}{L_r} \quad (5c)$$

$$Q = \frac{\sqrt{L_r / C_r}}{R_{pa}} \quad (5d)$$

4. The Generalized Converter Output/Input Expression [$K_c * G_c(Q, L_n, f_n)$]

In general, the factor K_c is $\frac{n_T}{2}$ for LLC resonant converter topologies that have the inverter leg of Fig. 2b or the midpoint inverter of Fig. 2c as the static switched input stage to either of the two LLC resonant sub-circuits of Fig. 3. On the other hand, K_c is n_T for LLC resonant converter topologies that have the H-Bridge inverter of Fig. 2a as the static switched input stage to either of the two resonant sub-circuits of Fig. 3, For all the six LLC resonant converter circuits that can be realized from the combinations of the three input circuit stages of Fig. 2 and the two resonant sub-circuits of Fig. 3, the expression for $G_c(Q, L_n, f_n)$ as given in equation 4b applies.

It is relevant, at this stage, to point out that the actual LLC converter output to input voltage gain (as against that obtain by fundamental frequency approximation) can also be expressed as

$$\frac{V_o}{V_s} = K_c * G_{cr}(Q, L_n, f_n)] \quad (5e)$$

where K_c is as defined above but the gain factor $G_{cr}(Q, L_n, f_n)]$ is determined taking into consideration all harmonics and nonlinear nature of the converter circuit.

For a given LLC resonant converter dc input and output operating conditions, the variables of the gain factor $G_c(Q, L_n, f_n)$ and/or $G_{cr}(Q, L_n, f_n)]$ are determined to realize the specified operating conditions. Fig. 6 is a plot of the magnitude $|G_c(Q, L_n, f_n)|$ against the normalized converter operating frequency f_n with the quality factor Q as the varying parameter and the normalized tank circuit magnetizing inductance L_n maintained constant at L_n=6. Fig. 5b shows an example comparison plot of the approximate and actual gain factors ($G_c(Q, L_n, f_n)$ and $G_{cr}(Q, L_n, f_n)$ for $L_n = 6$ and $Q = 3$ .The figure shows clear disparity between the actual G_{cr} and the approximate G_c gain factors at normalized switching frequency values relatively significantly different from the resonant frequency f_r or ($f_n = 1$).

From equation 4b and/or the gain factor plots of Fig.6a, it is observed that the gain factor $|G_c(Q, L_n, f_n)|$ is unity for all values of Q at the converter switching frequency equal to the LLC tank resonant frequency f_r (that is at $f_n = \frac{f_s}{f_r} = 1$). Also each plot for a given value of the quality factor Q has a maximum value $G_{c\max}$ at a normalized switching frequency f_{nm} equal to or less than the LLC tank resonant frequency (that is at $f_{nm} \leq 1$). At no load (that is $Q = 0$), f_{nm} is the normalized second LLC resonant tank frequency due to the resonating action of C_r in series with $L_r + L_m$ (that is, $f_{nm}|_{Q=0} = f_{r2n} = \sqrt{\frac{L_r}{L_r + L_m}}$).

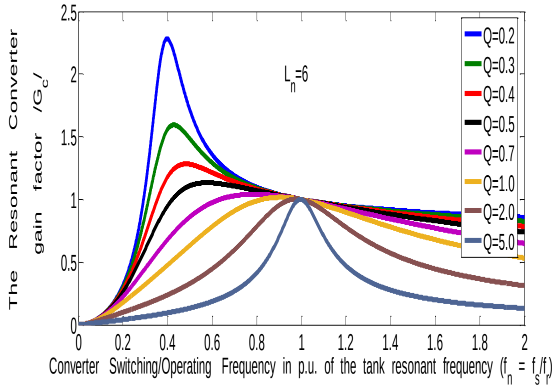


Fig. 6a: Plot of $|G_c(Q, L_n, f_n)|$ based on fundamental frequency analysis against the normalized converter operating frequency f_n with Q as the varying parameter and L_n =6.

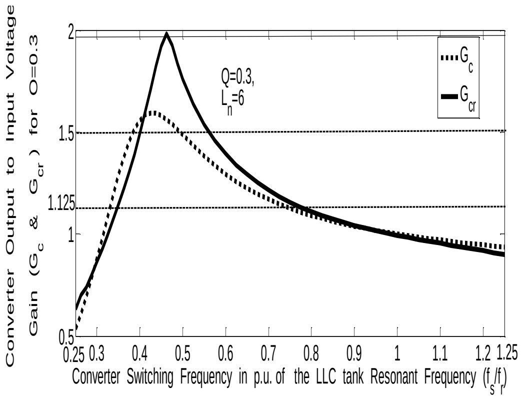


Fig. 6b: Example comparison plot of $|G_{cr}(Q, L_n, f_n)|$ based on actual analysis and $|G_c(Q, L_n, f_n)|$ based first harmonic analysis versus the normalized converter operating frequency f_n for $Q = 0.3$ *and* L_n =6.

For normalized converter switching frequencies less than f_{nm} for a given gain factor plot (that is, G_c *or* G_{cr} plot for given Q *and* L_n), the resonant tank circuit presents capacitive impedance to the input drive voltage v_i thus making the current i_{Lr} lead the input voltage v_i . On the other hand, if $f_{n.} > f_{nm}$ for a given gain plot, the resonant tank circuit presents inductive impedance to its input drive voltage v_i thus making the current i_{Lr} lag the input voltage v_i . In Fig. 7 are plots of the gain factor maximum values $|G_{c\max}|$ against the normalized tank circuit magnetizing inductance L_n with the quality/loading factor Q as the parameter while Fig. 8 gives plots of the normalized frequencies f_{nm} (at which the maximum gain factors occur) against L_n with Q as the parameter. Both Figs. 7 and 8 facilitate the determination of appropriate tank circuit storage elements for specified converter operating requirements.

The resonant converter operation is usually restricted to the inductive impedance region .(in Figs. 6(a &b)) where the converter semiconductor switch zero voltage turn on is assured so as to enhance converter efficiency and significantly reduce noise and EMI effects. The snubber capacitance C_S value is usually such as to ensure much reduced semiconductor switch turn off loss by the much slower dv/dt ramping of the voltage across the semiconductor switch during its turn off transition under relatively small inverter output current equal to the peak $\hat{i}_{Lm}$ of the transformer magnetizing inductance current.

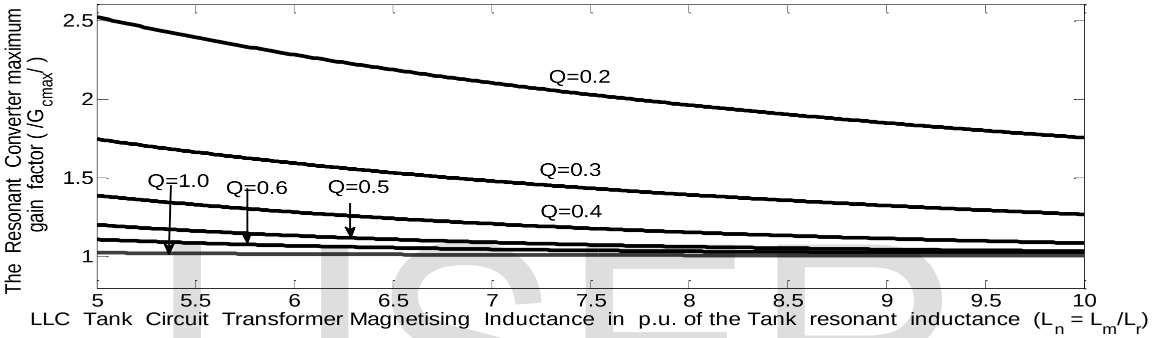


Fig. 7: The maximum gain factor $|G_{c\max}|$ versus the p.u. magnetizing inductance L_n .

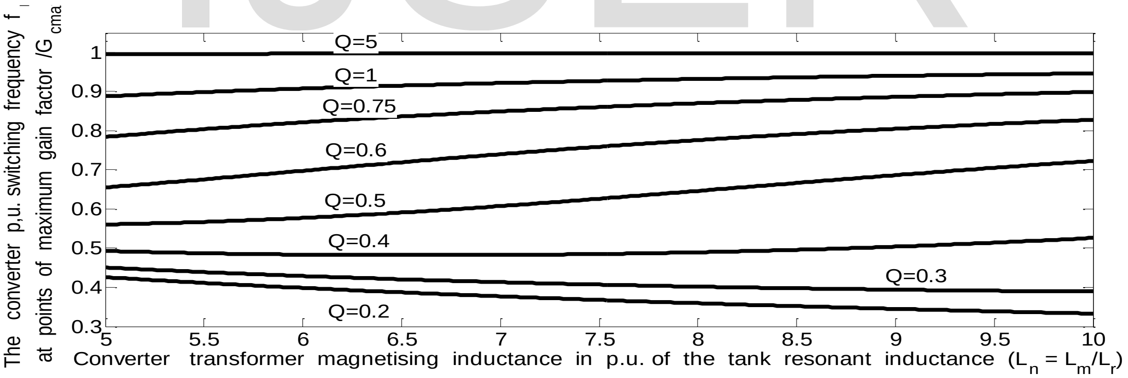


Fig. 8: The normalized frequency $f_n = f_{nm}$ at points of maximum gain factor $|G_{c\max}|$ versus the p.u. magnetizing inductance L_n .

5. Design Considerations

As is generally the case, the given converter input voltage source conditions and the specified converter output load requirements determine the values and ratings of the LLC converter circuit elements. For some applications, both the converter dc input voltage V_s and output voltage V_o vary over specified ranges under varying load conditions. For some other applications, the converter dc input voltage varies over a specified range while the output voltage is maintained constant under varying load conditions. For all converter design specifications of input and output voltage variation ranges, rated output power and the LLC tank resonant frequency f_r, the converter resonant tank circuit parameters (n_T, L_r, C_r, L_m) determined using the FHA analysis equations and/or design plots of Figs. 7 and 8 give desired converter performance. In Table 1 is given an example specification of an LLC resonant dc to dc converter which has a dc input voltage that has a nominal value V_{snom} and varies from a minimum to a maximum value ($V_{s\min}$ to $V_{s\max}$). The resonant frequency f_r is specified as 100 kHz while the converter output voltage is maintained constant at $V_o = V_{or}$ by frequency modulation over a varying output load that takes maximum/rated power $P_o = P_{or}$. The converter is to be designed to be able to deliver rated output power even at the minimum value $V_{s\min}$ of the input dc voltage.

Table 1: Example LLC Resonant Converter Specifications

Input dc voltage V_s	Minimum input dc voltage $V_{s\min}$	24 V
	Nominal input dc voltage V_{snom}	32 V
	Maximum input dc voltage $V_{s\max}$	36 V
Output dc voltage V_o	Constant at rated output voltage $V_o = V_{or}$	400 V
Rated output power $P_o = P_{or}$		300 W
Tank resonant frequency f_r		100 kHz

To ensure that the load voltage is maintained constant at $V_o = V_{or}$, under the converter semiconductor switch turn on at zero voltage over the specified converter input voltage range, appropriate values of the loading/quality factor $Q = Q_r$ at converter rated output ($V_o = V_{or}$, $P_o = P_{or}$) has to be selected for a given value of the normalized transformer magnetizing inductance L_n. The initial step to be taken in making appropriate selection of $Q = Q_r$ is the choice of the converter input voltage V_{sfr} (from the specified input range) that results in the determination of the transformer turns ratio when the converter is operating at a frequency equal to the LLC tank resonant frequency (that is $f_n = \frac{f_s}{f_r} = 1$).

$$\frac{V_o}{V_{sfr}} = K_c * \left|G_c(Q, L_n, f_n = 1\right| \qquad (6a)$$

Since the gain factor $|G_c(Q, L_n, f_n)|$ is unity at $f_n = 1$ for all $Q \; and \; L_n$ equation 6a becomes

$$K_c = \frac{V_{or}}{V_{s\,fr}} \qquad (6b)$$

To maintain the output voltage V_o constant at the specified value, the required inverter switching frequency variation range depends on the choice of V_{sfr} from the specified dc input voltage range. V_{sfr} is optimally chosen to be equal to the maximum dc input voltage $V_{s\max}$ so that the converter switching frequency is restricted in the range $f_r \geq f_s \leq f_{Lm}$ where f_{Lm} is the switching frequency at which the gain factor $\left|G_c(Q, L_n, f_n)\right|_{Q=Q_r}$ in the inductive region is $\frac{V_{s\,fr}}{V_{s\min}}$, ($that \; is \; \frac{V_{s\max}}{V_{s\min}}$). This operating condition has the added advantage of making the rectifter diodes turn on and off at zero current (that is ZCS operation of the rectifier diodes) for all loading conditions..

6. Design Example

A design example is illustrated using the LLC converter of Fig. 9 and choosing $V_{sfr} = V_{s\max}$ (in order to ensure ZVS turn on and minimal turn off loss operation of the input inverter semiconductor switches and ZCS operation of the rectifier diodes). For the converter specifications in Table 1, this choice restricts the gain factor $|G_c(Q, L_n, f_n)|$ in the range

$$\frac{V_{sfr}}{V_{s\min}} = \frac{36}{24} = 1.5 \geq |G_c(Q, L_n, f_n)| \geq \frac{V_{s\,fr}}{V_{s\max}} = 1 \quad (7)$$

Therefore, the appropriate values of $Q = Q_r$ and L_n are such that make the maximum value $G_{c\max}$ of $|G_c(Q, L_n, f_n)|$ have a maximum value slightly greater than 1.5. From Figs. 7 and 8, it is seen that $G_{c\max}$ for $Q = Q_r = 0.3$ *and* $L_n = 6$ gives $G_{c\max}$ and the normalized frequency at which $G_{c\max}$ occurs as 1.5937 and 0.4289 respectively (as against the actual calculated values of $G_{cr\max}$ =1.9804 and f_n = 0.4625) and therefore these two parameters ($Q = Q_r = 0.3 \text{ and } L_n = 6$) are chosen to determine resonant circuit parameters (L_r, C_r and L_m).

At rated output voltage and power and switching frequency equal to the resonant frequency ($f_s = f_r$), the minimum allowed equivalent load resistance ($R_o = R_{or}$) is determined as

$$R_o = R_{or} = \frac{{V_{or}}^2}{P_{or}} \quad (8)$$

Simultaneous solution of equations 1, 5a, 5b and 5d, 6a and 8 using the values $Q = Q_r = 0.3$, $L_n = 6$ and the converter specifications in Table 1 gives the minimum load resistor, R_{or} and the resonant tank parameters L_r, C_r L_m and n_T as listed in Table 2.

For any given converter input voltage V_s within the specified input voltage range in Table 1, the converter output voltage is maintained constant at $V_o = V_{or} = 400V$ as the output load varies from the rated value ($R_o = R_{or}$ or $Q = Q_r$) to no load value ($R_o = \infty$ or $Q = 0$) by converter switching frequency variation.

For example, at minimum, nominal and maximum converter input dc voltages ($V_{s\min} = 24V; V_{snom} = 32V; V_{s\max} = 36V$), Figs. 10a, 10b and 10c respectively show the theoretically FHA and the actual predicted variation of the converter normalized switching frequency f_n to maintain the converter output voltage V_O constant at $400V$ as the loading/quality factor in p.u. of the rated value ($\frac{Q}{Q_r}$) varies from unity to zero (by increasing R_o from its rated value of 533.333Ω to open circuit condition). As $\frac{Q}{Q_r}$ is decreased from unity to zero (with $V_{s\min} = 24V; V_{snom} = 32V; V_{s\max} = 36V$) the normalized frequency f_n increases to maintain the gain factor $|G_c(Q, L_n, f_n)|$ respectively at 1.5, 1.125 and 1 so that V_O remains constant at $400V$.

From Figs. 10(a, b & c), the relatively significant disparity in the FHA and actual converter performance plots clearly show the limitations of the FHA analysis.

7. Performance of the Design Example

The design example LLC Converter of Fig. 9 for which the input and output voltages, the rated power output and the tank circuit parameters are specified in Tables 1 and 2 has its circuit voltage and current waveforms under constant rated output voltage obtained using Matlab/Simulink simulations. Figs. 11a to 11d show some time variations of the LLC resonant converter voltages and currents ($v_{T1}, i_{T1}, v_t, i_{Lr}, i_o$ and V_o) under varying converter input and load conditions.

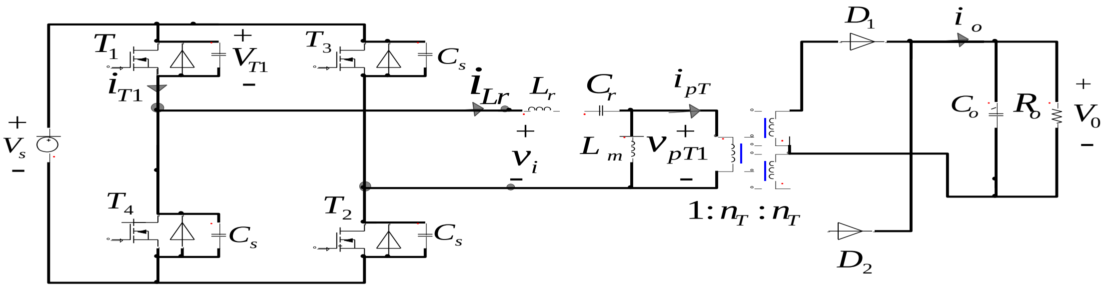
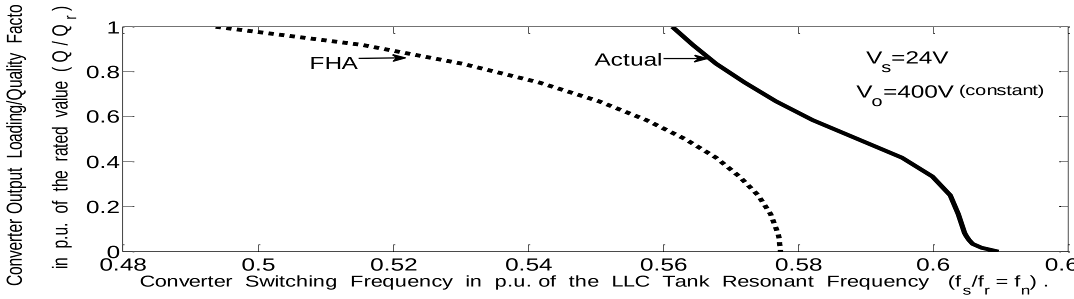


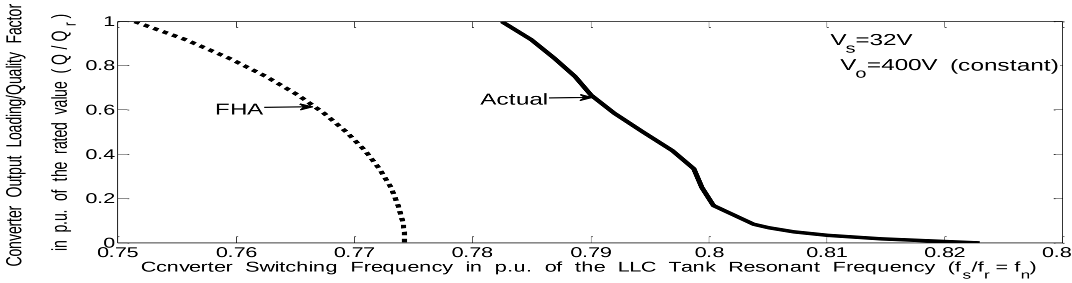
Fig. 9: LLC Converter for the design example

Table 2: LLC Converter Circuit Design Values Based on Table 1

Converter resonant tank components	Resonant Tank Capacitor C_r 1.5150 μF Resonant Tank Inductor L_r 1.6719 μH Transformer Magnetizing Inductance 10.032 μH
Transformer secondary or tertiary to primary turns ratio	n_T 11.1111
Effective Load Resistance R_o	$533.3333\Omega \le R_o \le \infty\Omega$



(a)



(b)

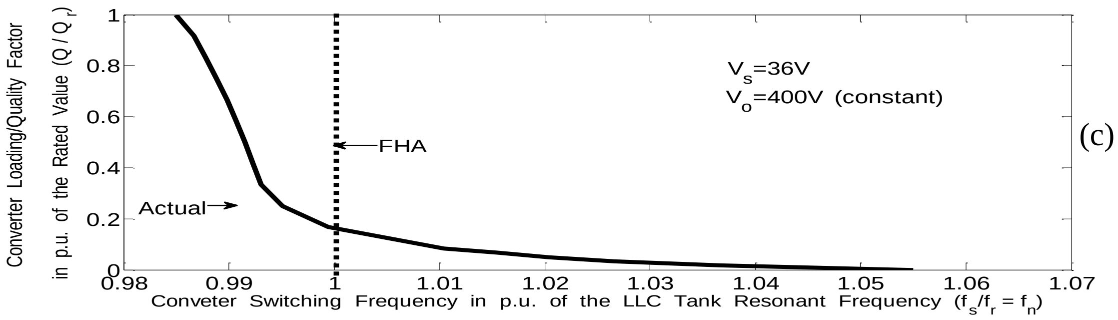
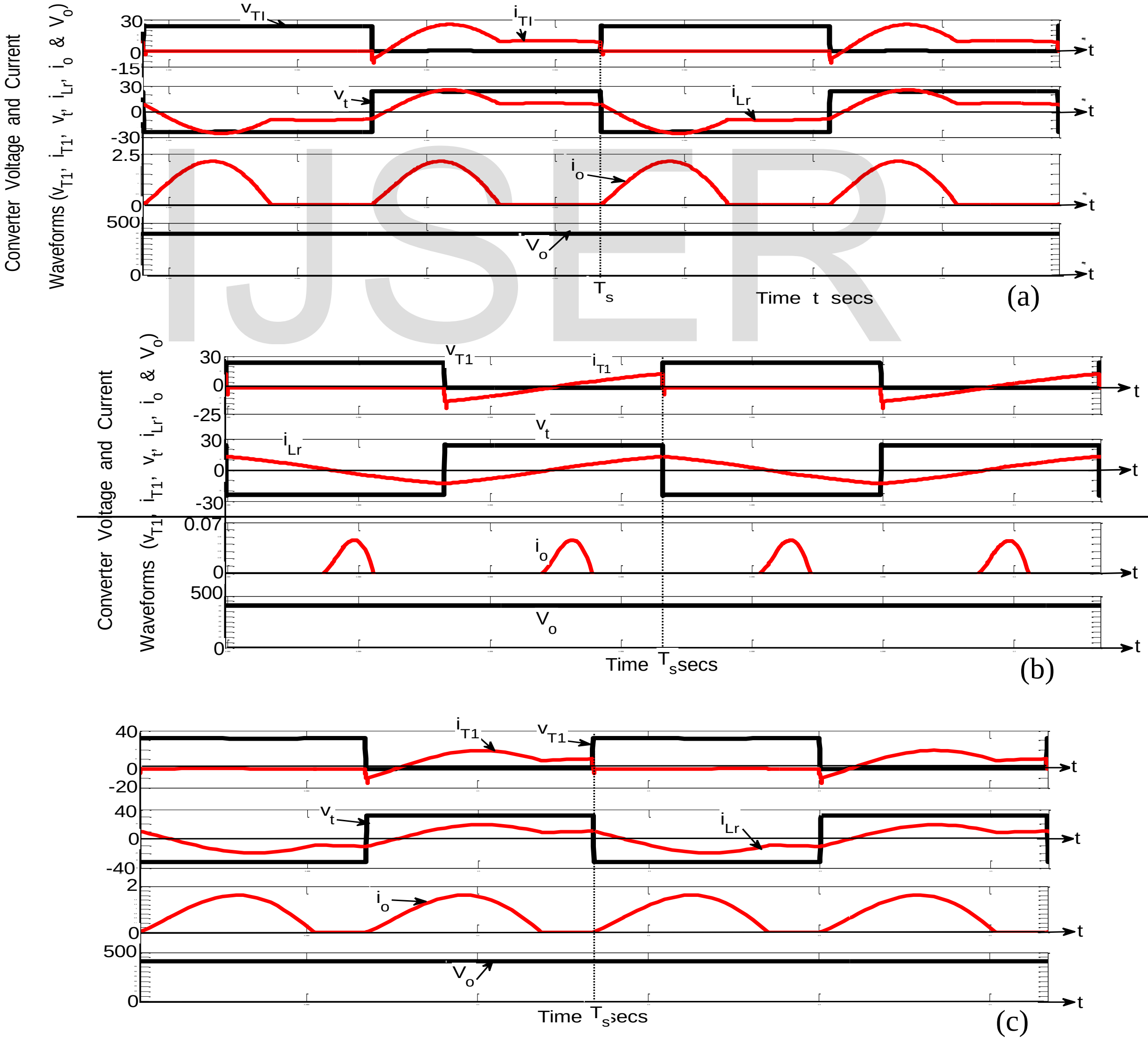


Fig. 10: Converter output Loading/Quality Factor in p.u. of the rated value ($\frac{Q}{Q_r}$) (for $Q_r = 0.3\,and\;\; L_n = 6$) versus the Normalized Converter Switching Frequency at (a) $V_s = V_{s\min} = 24V$, (b) $V_s = V_{snom} = 32V$ and (c) $V_s = V_{s\max} = 36V$, for V_O to be constant at $400V$.



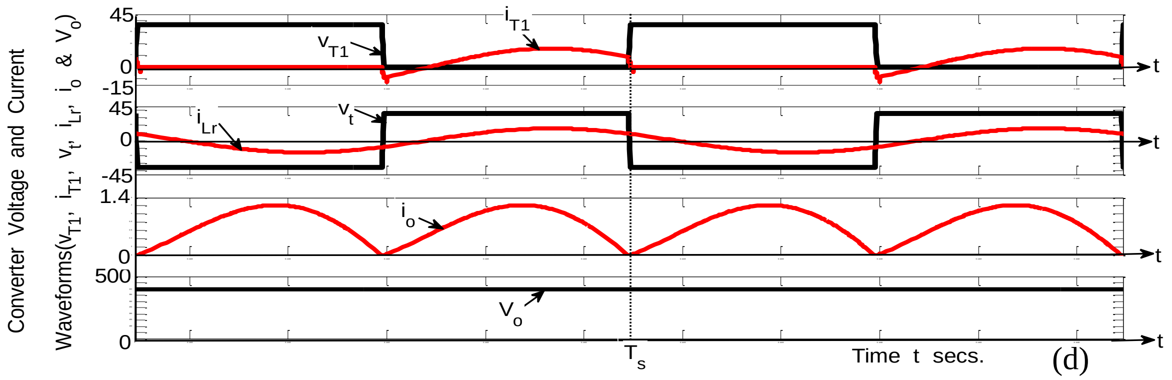


Fig. 11: Steady State Voltage and Current Waveforms ($v_{T1}, i_{T1}, v_t, i_{Lr}, i_o$ & V_o) of the Converter of Fig.8 (with specifications given in Tables 1 & 2) under (a ,c & d) rated and (b) no load Operations for input dc voltages and switching frequencies of (a) [$V_s = 24\,V$); $f_s = \frac{1}{T_s} = 56.130\ kHz$;], (b) [$V_s = 24\,V$, $f_s = \frac{1}{T_s} = 60.95\ kHz$;], (c) [$V_s = 32\,V$, $f_s = \frac{1}{T_s} = 78.25\ kHz$;], (d) ($V_s = 36\,V$,; $f_s = \frac{1}{T_s} = 100\ kHz$)].

It is relevant to note that in Figs 10a to 10d, it is easily seen that the input inverter semiconductor switch voltage waveform v_{T1} in relation to its current i_{T1} and the diode rectifier output current waveform i_o respectively ensure ZVS turn on operation of the inverter semiconductor switches and ZCS turn on and off of the rectifier diodes.

8. Conclusions

In this paper, generalized performance analysis of six topologies of the LLC dc/dc resonant converter with transformer isolation has been presented. The converter output to input dc voltage gain has been expressed as a product of two multiples or factors. One factor is a function of the isolation transformer turns ratio and the switching action of the LLC tank input voltage generator stage. The second factor (which is the same for all the six topologies) is a function of the LLC tank circuit storage elements, the output load and the converter switching frequency. Analysis by both the first harmonic approximation (FHA) and by actual analysis show the level of inaccuracy of the FHA method as the switching frequency relatively deviate significantly from the converter load independent resonant frequency. From relevant derived design characteristic plots and equations, an example 300W, 400V LLC converter with specified varying dc input voltage range was designed and its steady state performance evaluated using Matlab/Simulink simulation. The performance study shows ZVS turn on and relatively low current turn off of the converter semiconductor switches and ZCS turn on and turn off of the converter rectifier diodes under load variations from no load to full load for all values of the specified dc input voltage range.

9. References

[1] Junming, Z., Guidong, Z., Samson S.Y., Zhang, B. and Yun Z.: 'LLC Resonant Converter Topologies and Industrial Applictions- a Review', Chinese Journal of Electrical Engineering, 2020, 6, (3), pp.74-84.

[2] Jong, W.K., Moo-Hyun, P., Byoung-Hee L., et al: ‘Analysis and Design of LLC Converter Considering Output Voltage Regulation under No-Load Condition’, IEEE Transactions on Power Electronics, 2020, 35, (1), pp. 522-534.

[3] Yuqi, W., Quanming, L. and Alan M.: ‘Comparative Analysis and Design of LLC Resonant Converter with Magnetic Control’, CPSS Transactions on Power Electronics and Applications, 2019, 4, (4), pp. 265-275.

[4] Wei, Y., Luo, Q., Chen, S., et al: ‘Comparison among Different Analysis Methodology for LLC Resonant Converter’, IET Power Electronics, 2019, 12, (9), pp. 2236-2244.

[5] Sheng-Yang, Y., Runruo, C. and Ananthakrishnan V.: ‘Survey of Resonant Converter Topologies’, Texas Instruments Power Supply Design Seminar, 2018, pp.I-1 to I-23.

[6] Sam., A.: ‘Resonant LLC Converter: Operation and Design (250W, 33V_{in}, 400V_{out} Design Example)’, Infineon Technologies, North America, 2012, pp. 1-19.

[7] Bing. L., Wenduo, L., Yan L., et al: ‘Optimal Design Methodology for LLC Resonant Converter’, Centre for Power Electronics Systems, Virginia Polytechnic Institute and State University, USA, 2006 IEEE, pp.533-538.

[8] Bo Y., Fred, C., Alpha J., et al: ‘LLC Resonant Converter Front-End dc/dc Conversion’, APEC, 2002, pp. 1108-1112.

[9] Isaa, B.: ‘Resonant Converter Topologies with three and four energy Storage Elements’, IEEE Transactions on Power Electronics, 1994, 9, (1), pp. 64-73.