MODELING SIMULATION AND HARMONIC ANALYSIS OF A SERIES RESONANT INVERTER FEEDING RL LOAD: CONSIDERING TRANSFORMER PARAMETERS

R K Keshri¹ and A. B. Chattopadhyay²,

¹Assistant Professor, Department of Electrical Engineering VNIT, Nagpur, India

²Professor, Department of Electrical Engineering, BITS, Pilani Dubai

{¹riteshkeshri@gmail.com, ²abc_28857@yahoo.co.in}

Abstract

Series Resonant Inverter (SRI) is a source of very high frequency energy and is used for high frequency applications, such as Induction heating, Metal and thin film plastic surface treatment, communication and AC power flow areas (HVDC and HVAC) etc. SRIs are linked with the load through high frequency transformers to improve the current gain. Inclusion of transformers and RL load leads to higher frequency harmonic components in the load voltage. The present papers includes the harmonic analysis of a basic SRIs (Class – A), feeding RL load with the consideration of transformer parameters. System is modeled first in continuous time domain and then harmonic analysis is carried out using MATLAB/SIMULINK which is extended to the filtering out the higher frequency harmonic components using Butterworth IIR filter.

Keywords: Series Resonant Inverter, Modeling, High frequency transformer, Harmonic analysis, Butterworth filter.

1. Introduction

SERIES resonant inverters are defined as sources of high frequency energy in power electronics. Resonant inverters have drawn attention of researchers [1-12]. Most of the works are focused on suggesting different topologies for the improvement of switching action, reduction of harmonics due to switching and different types of load [1-12], implementation to various areas like UPS, low temperature plasma generators [8], thin film surface treatment [11], synchronous rectifier [7] etc., considering transformers as ideal one to link load with the

inverter and finally the results were compared with the real data. In the present work we have concentrated ourselves onto analyzing the effect on the load voltage if transformer parameters are considered. System is first modeled and transfer function is obtained. System is represented in terms of block diagram and simulated using MATLAB/SIMULINK. Further using the tools available in MATLAB harmonic analysis and filtering of higher order frequency component has been carried out.

2. Problem Formulation

System considered for analysis is 2 – MHz, 2 – kW high frequency high power series resonant inverter: for

low temperature plasma generator [8]. Circuit is shown in Fig. 1.

Fig. 1 Circuit diagram for 2 MHz 2 kW high-frequency high-power series resonant inverter: for low temperature plasma generator

As our aim is to analyze the effect on the load voltage, when transformer parameters are considered. This can be done by considering a basic SRI (Class – A) in place of Class – D [5], [9] or Class – E Series resonant inverter [8]. Later on the analysis can be extended to Class – D or Class – E inverters without the loss of generality as here for our analysis we are concerned with output of the resonant inverter being fed to transformer connected in parallel

with the capacitor for current gain as shown in Figure 2a. Class – A Series resonant inverter in the shown circuit considered and corresponding waveform is shown below in Figure 2b. It has been considered that output frequency f_o and resonant frequency f_r is same. Operation of the considered circuit is shown below in Fig. 3

Fig. 2a Class – A Series Resonant Inverter Circuit

Fig. 2b Wave forms of primary current and voltage across capacitor

(a)

Fig.3 b Operation of basic Series resonant inverter

(a)

Fig. 4 Basic series resonant inverter feeding RL load and equivalent diagram of the transformer

(b)

A. Basic formulation of the circuit

$$L \frac{di_0}{dt} + \frac{1}{C} \int i_0 dt + v_c(0) = v_c = V_s$$

For initially relaxed system $v_c(0) = 0$, $i_L(0^+) = 0$ solution of the above differential equation is

For the present work we have considered that the R-L load is connected to inverter through high frequency transformer and the turn ratio of the transformer is 1:1. All the parameters of the transformer are considered in per

$$v_c(t) = V_s(1 - \cos \omega_r t)$$

For an ideal transformer considered secondary voltage (output voltage)

$$v_0(t) = v_c(t) = V_s(1 - \cos \omega_r t)$$

$$\omega_r = \frac{1}{\sqrt{LC}} \quad \text{Resonant frequency of the LC circuit.}$$

unit system. The system to be analyzed with the consideration and equivalent diagram of the transformer is shown in Fig. 4.

Referring to the circuit shown in Fig. 4, with the consideration that the turn ratio is 1:1 voltage balance equation of primary and secondary windings of the transformer in time domain can be written as:

$$r_1 i_1 + L_{11} \frac{di_1}{dt} + L_{12} \frac{di_2}{dt} = v_c(t) \quad (3.1)$$

$$r_2 i_2 + L_{22} \frac{di_2}{dt} + L_{12} \frac{di_1}{dt} = v_L(t) \quad (3.2)$$

$$\text{and } v_L(t) = R_L i_2 + L_l \frac{di_2}{dt} \quad (3.3)$$

By taking Laplace transform and solving the above equation and with the consideration that system is initially relaxed, transfer functions relating input voltage to transformer, primary current, secondary current and load voltage is obtained and given below

$$I_1(s) = G_1(s)V_c(s) \quad (3.4)$$

$$I_2(s) = G_2(s)I_1(s) \quad (3.5)$$

$$V_c(s) = \frac{V_s \omega_s^2}{s(s^2 + \omega_s^2)} \quad (3.6)$$

$$V_l(s) = (R_l + sL_l)I_2(s) = G_2(s)G_1(s)V_c(s) \quad (3.7)$$

$$\frac{I_1(s)}{V_c(s)} = \frac{s + a_1}{a_2 s^2 + a_3 s + a_4} = G_1(s) \quad (3.8)$$

$$\frac{I_2(s)}{I_1(s)} = \frac{a_0 s}{s + a_1} = G_2(s) \quad (3.9)$$

From the Mathematical modeling of the system, transfer function model is obtained; model is shown below in Fig. 5.

Fig. 5 Transfer function model of the series resonant inverter feeding R-L load through high frequency transformer

Expression for the load voltage and current in s domain are given below

$$V_l(s) = (R_L + sL_l)G_2(s)G_1(s)V_c(s)$$

$$V_l(s) = \frac{kR_l + skL_l}{a_2 s^4 + a_3 s^3 + (a_4 + a_2 \omega_s^2) s^2 + a_3 \omega_s^2 s + \omega_s^2 a_4}$$

$$I_2(s) = \frac{k}{a_2 s^4 + a_3 s^3 + (a_4 + a_2 \omega_s^2) s^2 + a_3 \omega_s^2 s + a_4 \omega_s^2}$$

Where,

$$k = a_0 V_s \omega_s^2$$

$$a_0 = \frac{L_{12}}{L_l - L_{22}}$$

$$a_1 = \frac{R_L - r_2}{L_l - L_{22}}$$

$$a_2 = L_{12} \left(a_0 + \frac{L_{11}}{L_{12}} \right)$$

$$a_3 = r_1 + a_1 L_{11}$$

$$a_4 = r_1 a_1$$

Parameters of the system considered in per unit and calculated coefficients of the transfer functions are shown in Table 1.

Table 1 : Circuit parameters and coefficients of transfer functions $G_1(s)$ and $G_2(s)$

L_{11}	L_{12}	L_{22}	r_1	r_2	V_s	ω_s	$k = a_0 V_s \omega_s^2$
0.55	0.5	0.55	0.1	0.1	1	1	a_0
R_l	L_l	Load Impedance	a_0	a_1	a_2	a_3	a_4
0.8	0.6	1	10	14	5.55	7.8	1.4

3. Matlab Simulation

Fig. 7a and 7b are the steady state and transient voltage across the load considered. Voltage across the load would have been same if transformer is not considered. From the

wave forms of the load voltage it is clear that higher frequency components are injected due to transformer.

Fig. 7a Steady State steady state response as obtained from the Matlab simulation

Fig. 7b Transient response as obtained from the MatLab simulation

A. Harmonic analysis of the load voltage

Harmonic analysis on the load voltage can be carried out using FFT tool available in Matlab. Results obtained are shown in Figure 8.

Fig. 8 Harmonic contents of the load voltage as obtained from the FFT analysis of the load voltage

Table 2 : Percentage Harmonic Contents Of The Load Voltage

Sampling time	0.237394 sec	
Samples per cycle	26.4598	
Fundamental	1.191(Peak)	0.8423 rms
Total Harmonic Distortion (thd)	1.50%	
Harmonic order	frequency (Hz)	% (relative to fundamental)
0 (Dc)	0	1.11
1	0.1591550	100
2	0.3183102	1.2
3	0.4774652	0.2
4	0.6380000	0.5
5	0.7960000	0.71

Table 2 details the harmonic analysis on load voltage using FFT tool available in Matlab. Filtering out the high frequency components from the load voltage using Butterworth IIR filter

Higher frequency components in the load voltage due to the consideration of transformer parameters and RL load are filtered out using 2nd order Butterworth IIR filter. Filtered load voltage is shown in figure 9. Figure 9a shows the load voltage with and without filter including the transients and Figure 9b shows the load voltage during steady state without and with filter.

Fig. 9 Harmonic contents of the load voltage as obtained from the FFT analysis of the load voltage

Table 3 : Percentage Harmonic Contents Of The Load Voltage With Filter

Sampling time	0.237394 sec	
Samples per cycle	26.4598	
Fundamental	0.9567(Peak)	0.6575 rms
Total Harmonic Distortion (thd)	0.12%	
harmonic order	frequency (Hz)	% (relative to fundamental)
0 (DC)	0	0.12
1	0.1591550	100
2	0.3183102	0.21
3	0.4774652	0.05
4	0.6380000	0.03
5	0.7960000	0.03

4. Conclusion

Effects of considering transformer parameters on the load voltage of a series resonant inverter have been analyzed using obtained transfer function model. From the harmonic analysis using FFT it is clear that significant amount of harmonic contents are injected in the load voltage due to transformer and RL load. From the tables II and III it is clear that by using Butterworth IIR filter unwanted harmonic contents are reduced up to much extent. The analysis carried out can be extended to Class – D and Class – E series resonant inverters and the consideration of transformer parameters may reduce the error between experimental results and that obtained from the models used for the analysis and filter design.

References

- [1] R. M. Nelms, "Harmonic Analysis of a Parallel – loaded Resonant converters", IEEE transaction on power electronics , Vol 27, No. 4, July, 1991.
- [2] Jain, Prveen K. and Dewan, Sashi B., "Performance comparison of full and half bridge series resonant inverters in high frequency high power application", in *IEEE Transaction on Industry Applications*, vol. 26 No. 2, March/April 1990.
- [3] Francoeur, B., Viarogue, P. and Le-Huy, H., "Use of GTO as a zero turn off-time thyristor in a series resonant inverter ,CH2853-0/90/0000-0668 \$1.00 © 1990 IEEE.
- [4] Jain, Prveen K. and Dewan, Sashi B., "Analysis and design of a high-frequency high-power series resonant inverter using asymmetrical thyristors", in *IEEE Transaction on Power Electronics*, vol. 7, No. 4, October 1992.
- [5] Kazimierczuk, Marian K. and Mescher, Mark J., "Class-D converter with half wave regulated synchronous rectifier", 0-7803-1 456-5194 \$4.00 © 1994 IEEE.
- [6] Czarkowski, Dariusz and Kazimierczuk, Marian K., "ZVS Class D Series Resonant Inverter- Discrete time state – space Simulation and experimental results", in *IEEE Transactions on Circuits and Systems-I: Fundamental Theory and Applications*, vol. 45, no. 11, November 1998.
- [7] Chang, Chin, Chang, Joseph and Bruning, Gert W., "Analysis of the Self-Oscillating Series Resonant Inverter for Electronic Ballasts", in *IEEE Transactions On Power Electronics*, vol. 14, NO. 3, May 1999.
- [8] Fujiita, Hideaki and Akagi, Hirofumi, "A 2-MHz 2-kW Voltage-Source Inverter for Low-Temperature Plasma Generators: Implementation of Fast Switching with a Third-Order Resonant Circuit", in *IEEE Transaction on Industry Applications*, vol. 35, NO. 1, January/February 1999.
- [9] Wang, Chien-Ming and Hsieh Guan-Chyum, "Nonlinear-Control Strategy for the Half Bridge Series Resonant Inverter", in *IEEE Transaction on Industrial Electronics*, vol. 50, No. 2, April 2003.
- [10] Burdfo, Jose M., Barragan, Luis A. Monterde, Fernando, Navarro, Denis and Acero, Jesus, "Asymmetrical Voltage –Cancellation Control for Full-Bridge Series Resonant Inverters", in *IEEE Transaction on Power Electronics*, vol. 19, No. 2, March 2004.
- [11] Liu, Yong and He, Xiangning, "A Series Resonant Inverter System with PDM and PFM hybrid Control for Plastic Film Surface Treatment", *IAS 2005*, 0-7803-9208-6/05/\$20.00 © 2005 IEEE.
- [12] Samuel S. M. Chan, Henry S. H. Chung and S. Y. (Ron) Hui, "Design and Analysis of an IC-Less Self-Oscillating Series Resonant Inverter for Dimmable Electronic Ballasts", in *IEEE Transactions on Power Electronics*, Vol. 20, No. 6, November 2006.
- [13] Chitode J. S., "Digital Signal Processing & Applications", 1st Edition Technical Publications, Pune, India 2000.