DEFINING THE OPTIMAL BANDWIDTH IN BRIDGE POWER CONVERTERS

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Abstract: *In this paper optimal bandwidth of power converters loaded with resonant circuit is defined based on calculations of the switching power losses. Switching power losses in IGBT bridge converters are analyzed depending of the converter's switching frequency. The operation of a full bridge serial resonant converter for switching frequency below and above the resonant frequency is analyzed. Typical application of such converter with variable resonant frequency is when the converter supplies a device for induction heating of metals. In the paper PowerSim and SemiSiel simulations programs are used.*
The obtained results are experimentally verified and on their basis an induction heating device for metals is constructed.

Keywords: POWER CONVERTER, BANDWIDTH, IGBT BRIDGE

1. Introduction

One of the basic requirements of power electronic converters is to convert the energy from one form to another with as high as efficiency possible. To achieve this, power electronic circuits utilize semiconductor devices as switches [1].

Size, weight and price reduction of the converters is also one of the major requirements in the design of power electronic circuits. The basic means to achieve this is by using a high operating frequency. The increased frequency allows obtaining the same reactance values (*ωL* and *1/ωC*) with reduced inductance and capacitance values [2], [8]. However, the increased operating frequency increases the switching power losses and degrades the power converter stability [4], [9].

To reduce the switching power losses at higher frequencies, resonant converter topologies are used which ensure low switching power losses. Circuits that allow zero voltage and zero current switching (ZVS and ZCS) of the power switches are used i.e. the resonant full bridge converter.

In this paper, analysis of the influence of the switching frequency on the switching power losses in IGBT bridge converter loaded with serial resonant circuit is presented. Then, a full bridge serial resonant converter operation is analyzed in the mode of induction heating of metals.

The metal work piece that is put for heating inside the inductor acts as a short circuit secondary transformer winding and load at the same time and together with the capacitor it can be modelled as series resonant *RLC* circuit. The parameters of this resonant load change during the metal treatment and have a dynamics that depends from these parameters and that affects the operation of the resonant converter. With such loads, converter output power depends not only from the voltage rms value, but from the switching frequency as well. The dynamics of the induction heating process is affected by the values of the primary inductance *L* and the resonant load. As the resonant frequency is determined by *L* and *C*, the operating frequency has to be changed according to the change of *L* and *C* to maintain constant output power.

2. Influence of the switching frequency on switching power losses

Power losses in IGBT modules

When semiconductor switching devices operate in Hard Switching mode a certain current is turned on or off at a certain voltage level whenever switching occurs, as shown in Fig. 1, [3]. This process results in switching losses. The higher the frequency is the switching losses are greater which obstructs the intention to increase the frequency.

Switching losses can be calculated in a simple way as:

(1) $$P_{sw} = \frac{1}{2} V_{sw} I_{sw} f_s (t_{on} + t_{off})$$

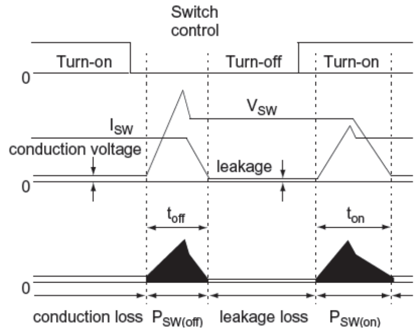

Fig. 1. Switching waveforms of a semiconductor switching device.

where,
P_{sw} - switching losses [W]
V_{sw} - switching voltage [V]
I_{sw} - switching current [A]
f_s - switching frequency [Hz]
t_{on} - switch turn-on time [s]
t_{off} - switch turn-off time [s]

For a hybrid power module with *n* IGBTs and *m* diodes the total power losses are:

(2) $$P_{tot/M} = nP_{tot/T} + mP_{tot/D}$$

where, $P_{tot/T}$ is total transistor power losses and $P_{tot/D}$ is total diode power losses.

Operating conditions

The operating of a full bridge converter in the mode of induction heating of metals is analyzed. In the simulation program for induction device design ELTA, a copper work piece with mass of 5 kg is thermally treated to melting temperature of 1083 ºC. In the simulation program ELTA the distribution on the inductance is obtained for thermal treatment of a copper work piece, Fig 2.

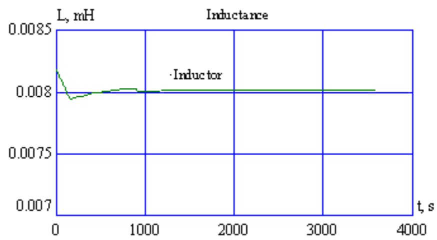

Fig. 2. Inductance change in induction device for thermal treatment of copper work piece to the melting temperature.

Also, values for the parameters of the supply voltage source, the average, minimal and maximal value of the inductance are obtained in the simulation program: the rms voltage is 56 V and the switching frequency is 6 kHz. The simulation results are given in Table 1.

Table 1. Simulation results

	L (μH)	R_e (Ω)	C (μF)	U_{source} (V)	f_o (kHz)
Average value	26	0.21	27	56	6
min	25.2	0.21	27	56	6.15
max	27	0.21	27	56	5.85

From Table 1 we can conclude:

- Thermal treatment of copper work piece with induction heating to melting temperature is dynamic and it dynamically impacts on inductance change and resonant frequency,
- The capacitor value for inductance compensation for practical applications is constant.

The values obtained in the program ELTA are used for the power converter design.

Simulation results in the PowerSim program

Based on the simulation results for parameters values obtained in Table 1, simulations are performed in the PowerSim simulation program [6] for full bridge IGBT power converter with resonant load circuit. In the Fig. 3 the simulation circuit in the PowerSim program of the full bridge converter is given.

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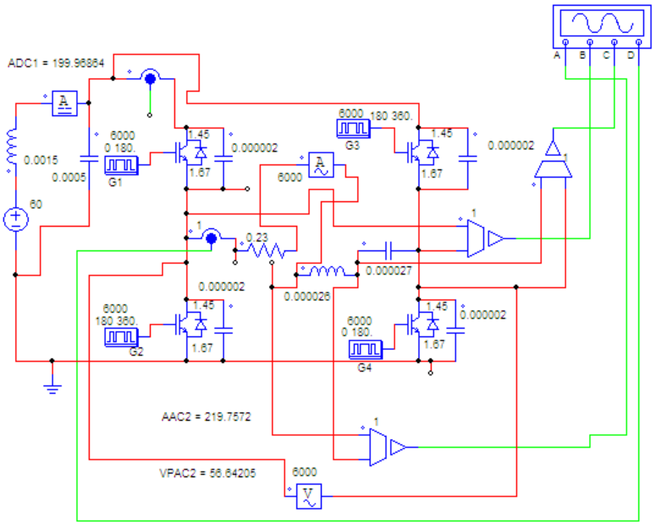

Fig. 3. The circuit for the full bridge converter simulation in the PowerSim program.

In the Table 2 values for the voltage, current, power and power losses in the full bridge converter with serial resonant circuit obtained with simulation of the circuit in the Fig. 3 are given with switching frequency of 6 kHz and inductance changes given in the Table 1. The circuit in the Fig. 3 is simulated with freewheeling diodes connected to the IGBT transistors of the power converter and without these diodes.

Table 2. Values for the voltage, current, power and power losses in the full bridge converter

L (μH)	C_{reson} (μF)	R_e(Z) (Ω)	I_{outrms} (A)	U_{outrms} (V)	$S_{conv.}$ (kVA)	I_{DC} (A)	U_{DC} (V)	P_{DC} (kW)	P_R (kW)	f_{sw} (kHz)	f_o (kHz)	P_{cz} (W)	P_{Tz} (W)	η_{conv} (%)
With freewheeling diode and resonant frequency														
26	27	0.21	240	56.6	13.58	219	60	13.14	12.1	6	6	1040	260	92
With freewheeling diode and below resonant frequency														
25.2	27	0.21	236	57	13.4	213	60	12.78	11.7	6	6.15	1080	270	92
25.2	27	0.21	212	57	12.08	176	60	10.56	9.44	5.75	6.15	1120	280	90
25.2	27	0.21	202	57	11.5	169	60	10.14	8.57	5.5	6.15	1571	392	85
With freewheeling diode and above resonant frequency														
27	27	0.21	237	57	13.5	215	60	12.9	11.8	6	5.85	1104	276	92
27	27	0.21	212	57	12.08	177	60	10.62	9.44	6.25	5.85	1180	295	90
27	27	0.21	199	57	11.3	165	60	9.9	8.3	6.5	5.85	1583	395	84
Without freewheeling diode and resonant frequency														
26	27	0.21	238	57	13.57	217.5	60	13.05	11.89	6	6	1154	290	91
Without freewheeling diode and below resonant frequency														
25.2	27	0.21	236	57	13.5	215	60	12.9	11.7	6	6.15	1200	300	90
25.2	27	0.21	226	57	12.88	202	60	12.12	10.73	5.75	6.15	1394	348	88
25.2	27	0.21	210	57	11.97	189	60	11.34	9.26	5.5	6.15	2079	519	81
Without freewheeling diode and above resonant frequency														
27	27	0.21	236	57	13.5	216	60	12.96	11.7	6	5.85	1260	315	90
27	27	0.21	223	57	12.7	204	60	12.24	10.44	6.25	5.85	1796	449	85
27	27	0.21	199	57	11.3	189	60	11.34	8.316	6.5	5.85	3023	755	73

The work on the converter is simulation with IGBT transistor by V_{cesat}=1.67V and diode voltage V_F=1.45V.

In the Table 2 the magnitudes are:

- $U_{outrms} = \sqrt{\frac{1}{T}\int_0^T u_{out}^2(t)dt} = U_{DC} - 2V_{cesatIGBT} = 60 - 3.34 = 56.4V$,
- $P_R = I_{outrms}^2 R_e$ power on load resistance R_e ,
- $P_{DC} = U_{DC} I_{DC}$ power on the DC link circuit,
- $\eta_{conv} = \frac{P_R}{P_{DC}} 100\%$ converter efficiency,
- $P_{cz} = P_{DC} - P_R = P_{tot/M}$ total power losses of the converter,
- $P_{cz}/4 = P_{Tz}$ total power losses in one transistor module P_{Tz} (transistor and diode).

From Table 2 we can conclude:

- On the switching frequency same with the resonant the power losses are lowest,
- On the switching frequency below and above the resonant frequency converter power losses are increased and the efficiency of the converter is decreased,
- In the topology of the power converter with IGBT modules with freewheeling diodes the power losses are decreased and the efficiency of the converter is increased compared to the topology of power converter with IGBT modules without freewheeling diodes,
- Values for the power losses given in the Table II define optimal bandwidth of the converter (from 5.75 kHz to 6.25 kHz) for which the efficiency of the converter is greater than 90% (converter topology with freewheeling diodes).

On the Fig. 4 is given change of the power losses of IGBT module to the change switching frequency for IGBT module with freewheeling diode and without diode. Fig. 4 is obtained from the values on the Table 2.

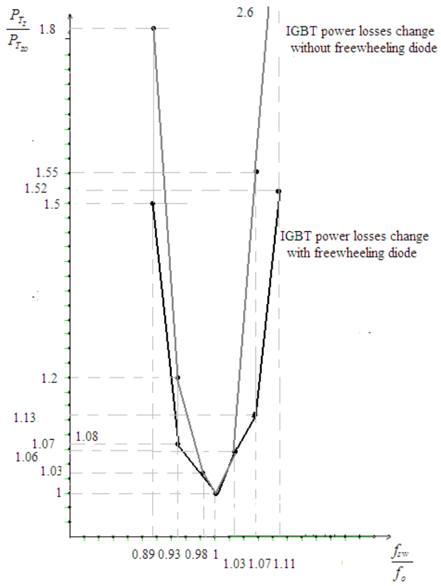

Fig. 4. Dependence of the power losses of IGBT module to the change switching frequency $P_{Tz} = F(f)$.

Simulation results in the SemiSiel program

Simulations are done in the SemiSiel [7] program for the full bridge converter with parameters defined in the Table 2. The power losses values of the converter are given in the Table 3. In the simulations two IGBT modules type SKM195GB066D are used in each branch, which means that there are eight semiconductor switches in the converter.

Table 3. Simulations results obtained in SemiSiel program

	SKM195GB066D 4 modules on resonant frequency f_0 = 6 kHz , f_{sw} = 6 kHz	**SKM195GB066D** 4 module below resonant frequency f_0 = 6.15 kHz , f_{sw} = 6 kHz	**SKM195GB066D** 4 module above resonant frequency f_0 = 5.85 kHz , f_{sw} = 6 kHz
$P_{cond\ tr}$	115 W	116 W	118 W
$P_{swT}=P_{on/T}+P_{off/T}$	6.78 W	6.89 W(P_{on})	7.01W($P_{off/T}$)
P_{Tr}	122 W	123 W	125 W
$P_{cond\ d}$	0.00 W	0.00 W	0.00W
$P_{sw/d}$	8 W	12W($P_{off/d}$)	11W($P_{on/d}$)
P_d	8 W	12 W	11 W
$P_{cz}=P_{total}$	1040W	1080 W	1088W

From the Table 3 losses of the transistors and diodes in the converter can be read. Table 3 shows that:

- On switching frequency below the resonant frequency transistors in the converter are switching with hard turn on (non ZVS) and soft turn off (ZCS). Diodes are switching with hard turn off and soft turn on, and the power losses occur as a result of their switching,
- On switching frequency above the resonant frequency transistors in the converter are switching with hard turn off (non ZCS) and soft turn on (ZVS). Diodes are switching with hard turn on and soft turn off, and the power losses occur as a result of their switching.

Summary of the results

The results in the program ELTA show that for induction heating of copper work piece to melting temperature the circuit inductance is changing in the range from 25.2 µH to 27 µH, and the required resonant frequency changes from 5.85 kHz to 6.15 kHz.

The results obtained from the ELTA program for the power converter which supplies an induction device are used in

the PowerSim and SemiSiel programs to obtain the power losses and they are given in the Table 2.

Based on the results for the power losses efficiency of the power converter can be calculated and also the optimal bandwidth in which the converter will operate with efficiency greater than 90% can be defined.

The calculations show that optimal bandwidth is in the range from 5.75 kHz to 6.25 kHz. This frequency range is wider than the resonance range which is from 5.85 kHz to 6.15 kHz defined in the Table 1.

3. Experimental results

In this section we are interested for the total power losses in a practically constructed power converter obtained with measurement. Topology of IGBT full bridge power converter with serial resonant load with parameter values as in the Table 1 and 2, is used for supplying induction heating device used for melting of a copper work piece with mass 5 kg.

The Table 4 shows values of the magnitudes obtained with measurement in a practically constructed power converter with switching frequency of 6.15 kHz, operating slightly above the resonant frequency 6 kHz. In the converter two IGBT modules type SKM195GB066D are used in each branch.

Table 4. Power losses in a practically constructed power converter in mode of induction heating device obtained with measurement

I_{DClink} (A)	U_{DClink} (V)	P_{DC} (kW)	I_{outrms} (A)	U_{outrms} (V)	$S_{out} \approx P_{out}$ (kVA)	η_{conv} $(\%)$
225	60	13.5	225	55	12.38	92

Table 4 shows that:

- $P_{DC} = I_{DClink} U_{DClink}$ is the power on the DC link circuit, this is the input power of the converter,
- $S_{out} \approx P_{out} = I_{outrms} U_{outrms}$ is the apparent output power of the converter, because the converter operates close to resonant frequency, the apparent output power is close to the active power,
- $P_{DC} - P_{out} = 1120W$ is the total power loss in the converter, and it is close to the total power losses given in the Table II and III.
- $\frac{P_{out}}{P_{DC}} = \eta_{conv} = 92\%$ is the efficiency of the power converter.

In the Fig. 3 the practically constructed converter is given on which the above measurements were performed.

Fig. 3. Practically constructed power converter

4. Conclusion

In this paper is show a procedure for optimal bandwidth of power converters loaded with resonant circuit. The bandwidth is defined based on calculations of the switching power losses. Switching power losses in IGBT bridge converters are analyzed depending of the converter's switching frequency. The operation of a full bridge serial resonant converter for switching frequency below and above the resonant frequency is analyzed. Also here are give results from practical application on this power converter in induction device for melting on work piece copper.

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