The Analysis and Design of Capacitor Voltage-Clamped Half-Bridge Series-Loaded Series Resonant Converter

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ABSTRACT

This study presents the analysis and design of Voltage Clamped Half Bridge Series-Loaded Series Resonant Converters.

In the first part, the lumped parameter model is formed and its analytical equations for various operating modes are developed.

The effect of design parameters is briefly discussed and the tools for optimised design are presented. The experimental and simulation studies are explained, results are noted. The correlation between simulation and experiment is verified.

1. Introduction

There have been steady improvements in power electronic circuits. Switched Mode Power Supplies produce regulated DC voltage for various applications. The need to produce the desired waveforms in power electronics circuits with high power/weight ratio, the high frequency switching is necessary. Thus, high switching losses and low efficiency are unavoidable unless a substantial reduction in switching losses is managed. Resonant converters (1) and, zero voltage (ZVS) and zero current switching (ZCS) techniques (2)(3) offer advantageous over conventional hard switching methods.

This paper presents the experimental and theoretical studies on a single and three-phase Capacitor Voltage-Clamped (CVC) Half-Bridge Series-Loaded Series Resonant Converter (HBSRC). This topology is known and presented hitherto (4). However, it is believed that the analysis and design of CVC-HBSRC needs further contributions, particularly in performance improvements and the design optimization points of view. Thus, the analysis of the equivalent circuit and the derivation of the analytical equations representing each modes of operation is initially studied. Detailed equations of CVC-HBSRCs are presented in Appendix 1.

The SPICE simulations are achieved and the validity of the developed analytical equations is verified. These studies are used to develop the design methodology for HBSRC. Two types of converters, single-phase and three-phase, are designed. The optimum design tools are developed and, 3.4 kW (57V, 60A) single-phase and 7.8kW (130V, 60A) three-phase HBSRCs are developed. Various prototypes are tested, and the validity of the theoretical study is evaluated by comparing the simulation results with those of experiments. Since the ultimate objective of this study is to develop commercially sound DC/DC converters, this paper gives a brief information about the final products, which are commercially available in the market. The characteristic values and the picture of converters are presented in Appendix 3.

2. The Analysis of Single and Three-Phase CVC-HBSRC

For few kW applications, the resonant converters are supplied by single-phase rectifiers with smoothing capacitor parallel connected to the output of the rectifier. For higher power ratings, three-phase rectifiers are used. The schematic representation of the single phase CVC-HBSRC is depicted in Figure 1. It is believed that the half-bridge configuration has lower cost than that of the full-bridge since it employs only two IGBT's instead of four.

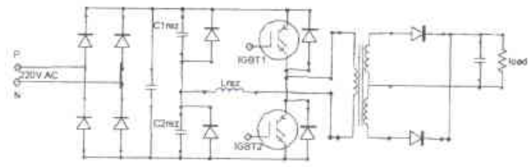


Fig.1. Circuit Diagram of the CVC-HBSRC

The main objective of this network is to produce a constant dc output voltage for wide range of mains-supply voltages. This is particularly important for the areas, where supply voltage fluctuations are observed during the day. As it is seen from Fig.1 that supply ac voltage is initially rectified, than converted to high frequency ac through resonant inverter and finally converted to dc again. Output voltage regulation is managed by Motorola MC34066 chip that basically controls the frequency of the inverter. In order to reduce the sizes and the cost of the passive elements the switching frequency is pushed up as high as possible. For single and three phase models, standard IGBTs are used and 40 kHz switching frequency is realized, which is higher than the hard-switching frequency limit of the standard power IGBT's used. In order to define the boundary conditions between continuous and discontinuous operation modes, and to obtain the optimum transformation ratio, the analysis of the network should be presented.

Similar to the other types of resonant converters, the CVC-HBSRC has various operating modes. The brief study of these modes is as follows;

Mode 1: Resonant Mode

This mode commences with the turning on the upper IGBT at which instant the upper capacitor voltage is equal to the dc bus value. The relevant circuit is shown in Figure 2.

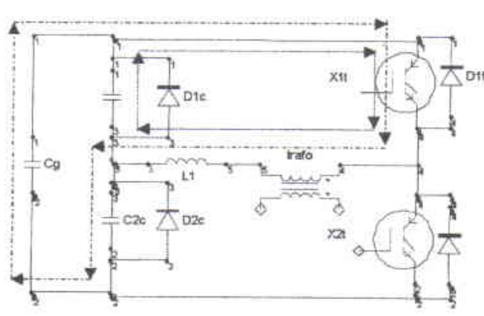


Figure 2. The current ways of the positive alternate.

There are two current loops in the circuit. The half of the sinusoidal resonant current flows through upper capacitor and upper IGBT, series resonant inductor and transformer. The other half flows through dc bus capacitor, upper IGBT, resonant inductor, transformer and the lower capacitor. During this process, while the upper capacitor discharges and its voltage reduces, the lower one charges and its voltage increases towards dc bus voltage level. The inductor current equation is derived and presented in Appendix 1 as,

$$i_L(t) = (V_{dc} - aV_o)\sqrt{\frac{Cr1 + Cr2}{L}} \sin wt \quad \text{Eq.1}$$

If we integrate this equation we derive the upper capacitor voltage equation as,

$$V_c(t) = (V_{dc} - aV_o)\cos wt + aV_o \quad \text{Eq.2}$$

When the upper capacitor is fully discharged and its terminal voltage becomes zero, the other capacitor is fully charged and its voltage increases up to the dc bus voltage level. At this instant, the upper diode turns on and Mode 1 ceases and Mode 2 commences.

Mode2: Linear Mode

As soon as the upper diode turns on, the stored magnetic energy in resonant-inductor forces the current to flow through the upper IGBT, upper clamped diode, inductor and transformer. Therefore, there is no longer resonance condition. During Mode 2, the current equation is given as,

$$I(t) = \frac{-kV_o}{L}t + I_o \quad \text{Eq.3}$$

It is seen that the current waveform is linear and has a negative slope. In other words, stored energy is transferred to the output of the converter. The upper IGBT is turned off when current drops below a predetermined value. This value is approximately equal to the magnetizing current of the isolating transformer. If the transformer is specially designed to decrease the magnetizing current, the turn-off switching loss can be ignored. Otherwise, the turn-off instant defines the turn-off loss of the IGBT, which is an important design parameter at high frequency.

Mode 3: Rest Mode

Following the turning off the IGBT, the magnetizing current is transferred to the load. If the rest mode duration (in the constant on-time operation control mode) is long enough the magnetising current extinguishes. This situation effects the design of isolation transformer. If the magnetizing current is discontinuous, the transformer uses only the B-H curve from zero to Bmax value for a half period of operation. But, in constant off-time operation control mode, magnetizing current doesn't go to zero, therefore the transformer utilize the B-H curve fully from -Bmax to Bmax for a half period of operation. Since there is no energy transfer to output in the circuit (except the energy of magnetizing inductor), this operation is called the Rest Mode. The duration of the rest time depends upon the power transferred (in the constant on-time operation control mode), thus controllers defines that time.

Above, the operation of the resonant converter is presented in three steps. The period covers the half cycle of the converter. This half cycle is related to the upper circuit of the resonant converter, which is started by turning on the upper IGBT. For the lower circuit, the similar process will be observed. The equivalent circuit and equations are symmetrical for lower IGBT, lower capacitance and lower clamped diode. Therefore, it is not presented here. The relevant circuit diagram is given at Figure 3.

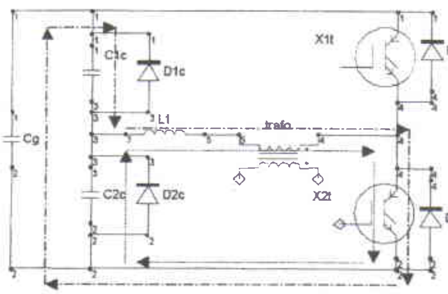


Figure 3. The current ways of the negative alternate.

For three-phase supply, dc bus bar voltage is higher than the single phase one, resonant network is the same. However, input current and input power factor will be different. In single phase, it's possible to make the power factor greater than 0.98 by choosing the transformer turn-ratio as step-up and dc stabilizer capacitor value very low (dc stabilizer capacitor must always be greater than resonant capacitor). The philosophy of having high power factor at the input is to carry the energy to the output of the system although main voltage is very low. Choosing the power factor high enough causes semiconductors having large current rating to be used. This means that the cost of the system is high. Our practice showed us that the single-phase resonant converter should not use to correct the power factor. Otherwise, a poor design will arise. If the power factor correction is necessary, boost type topology should be used at the input of the resonant converter. It is also possible to use soft switching in boost type topology not to emit large amount of EMI. For three phase resonant converter, it is possible to correct the power nearly up to 0.95 by choosing the dc stabilizer capacitor value very low (but high with respect to resonant capacitor). Since the dc bus bar voltage of the three-phase system does not go to very low voltage value, it is possible to correct the power factor and make cost-effective design by using small capacitor value at the dc bus bar.

3. Design Tools

During the design process the following points are defined as design criteria's;

- Since power transferred from resonant circuit is proportional with the square of dc bus bar voltage, the input voltage and its tolerances are decisive.
- The transformer turns ratio affects the operation modes and the losses. For maximum energy transfer to the load, the resonant capacitors should be discharged completely. If the transfer ratio is chosen larger than the suitable value, resonant capacitors can not be discharged completely. Therefore maximum energy transfer can not be achieved. The optimum turn's ratio calculation is presented in Appendix 2.
- The operation frequency is defined by considering the properties of switching devices, transformer cores and other passive elements.
- As far as, EMC and PF points of view, some priorities should be adopted.
- Thermodynamics and reliability of the system should be considered for the configuration of the final product.

4. Simulation and Experimental Study

The SPICE simulation of the converter is achieved and performance curves for each operation modes are computed and plotted. Spice simulation is repeated for various hypothetical-operating conditions and, various design configurations are evaluated. In Figure 4. and 5. the inductor current and capacitor discharge voltage curves are given.

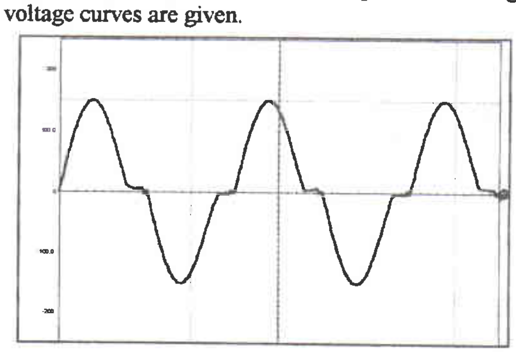


Figure 4. Inductor Current (spice)

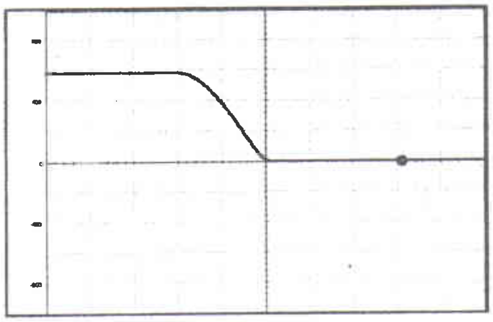


Figure 5. Capacitor discharge voltage (spice)

The experimental study is conducted on 3-phase 380V AC input, 130V DC output, and 7.8 kW resonant converter. The switching frequency is varied between zero and 40 kHz by using IGBT's having a maximum frequency of 10 kHz in hard switching. The experimental resonant current and voltage curves are recorded by 500 MS/s digital oscilloscope.
In Figure 6 and 7 the experimental inductor-current and capacitor discharge voltage curves are presented.

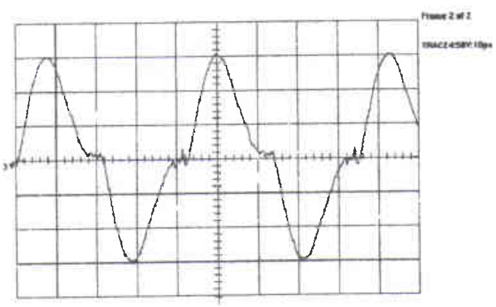


Figure 6. Inductor Current (experiment)

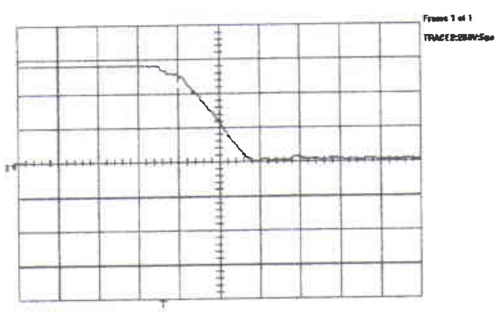


Figure 7. Capacitor discharge voltage curves (exp.)

5. CONCLUSIONS

- 3.4kW power output for single-phase, 7.8kW power output for three-phase converters are developed with the efficiency of 94 % or above.
- This topology has inherently zero current switching property. For turn on there is absolute zero current switching. For turn off there is very low current switching which is equal to the magnetizing current of the transformer.
- Since this topology reduces the switching losses, it is possible to increase the operating frequency, even above the frequency limit of the IGBT's.
- There is an optimum turns-ratio for transformer.
- There is a good agreement between the spice simulation and experimental curves.
- It is possible to correct the power factor by using small capacitor value at the input dc bus. And it is also possible to decrease input harmonics by using serial inductor.
- System is robust, power to weight ratio and efficiency is high, cost is low with respect to both SMPS and conventional thyristorised dc supply.

APPENDIX 1

$$\begin{bmatrix} 2X_C & -X_C \\ -X_C & X_C+X_L \end{bmatrix}\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} \frac{V_{dc}}{s} - \frac{V_{dc}}{s} \\ \frac{V_{dc}}{s} - \frac{aV_o}{s} \end{bmatrix}$$

$$2X_C i_1 - X_C i_2 = 0 \rightarrow i_1 = \frac{X_C}{2X_C} i_2 \rightarrow \underline{i_1 = \frac{1}{2} i_2}$$

$$-X_C i_1 + (X_C + X_L) i_2 = \frac{V_{dc}}{s} - \frac{aV_o}{s}$$

$$-X_C \frac{1}{2} i_2 + (X_C + X_L) i_2 = \frac{V_{dc}}{s} - \frac{aV_o}{s}$$

$$i_2 \left(\frac{1}{2} X_C + X_L\right) = \frac{V_{dc}}{s} - \frac{aV_o}{s}$$

$$i_2 = \frac{V_{dc} - aV_o}{s(\frac{1}{2} X_C + X_L)} = \frac{V_{dc} - aV_o}{s(\frac{1}{2}\frac{1}{sC} + sL)} = \frac{V_{dc} - aV_o}{(\frac{1}{2}\frac{1}{C} + s^2 L)} = \frac{V_{dc} - aV_o}{L(\frac{1}{2CL} + s^2)}$$

$$i_2 = \frac{V_{dc} - aV_o}{L} \frac{\frac{1}{\sqrt{2CL}}}{\frac{1}{\sqrt{2CL}}} \frac{1}{\left[s^2 + \left(\frac{1}{\sqrt{2CL}}\right)^2\right]}$$

$$i_2(t) = \frac{V_{dc} - aV_o}{L} \sqrt{2CL} \sin\left(\frac{1}{\sqrt{2CL}} t\right)$$

$$\underline{\underline{i_2(t) = (V_{dc} - aV_o)\sqrt{\frac{2C}{L}} \sin wt}}$$

$$w = \frac{1}{\sqrt{2CL}} = \frac{1}{\sqrt{C_r L_r}}$$

APPENDIX 2

$$0=(V_{co}-aV_o)\cos 180^0+aV_o$$

$$0=(V_{co}-aV_o)(-1)+aV_o$$

$$V_{co}=2aV_o$$

$$\underline{a=\frac{V_{co}}{2V_o}}$$

Where "a" is the optimum transformer ratio.

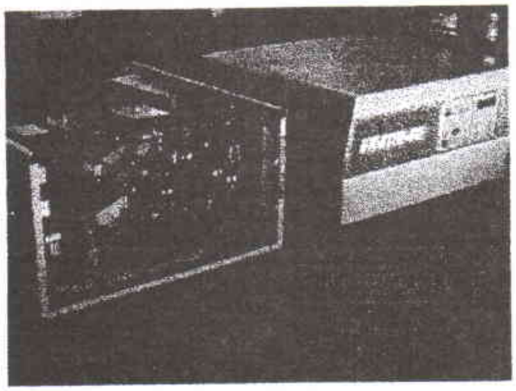
APPENDIX 3

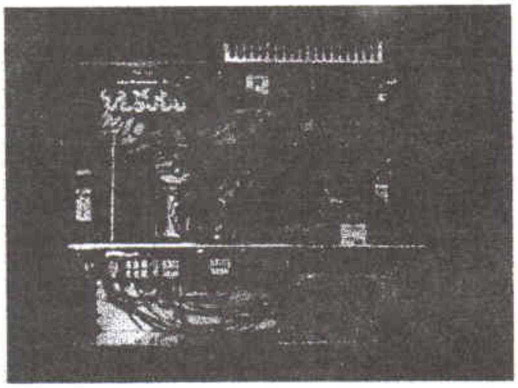
Single Phase:

Input Voltage: 220 VAC (+ %10, - %10)
Input Frequency: 50Hz-60Hz
Input Power Factor: 0.85
Output Power: 3.4 kW
Output Voltage: 57 VDC
Voltage Stability: < %1

Three Phase:

Input Voltage: 380 VAC (+ %10, - %10)
Input Frequency: 50Hz-60Hz
Input Power Factor: 0.95
Output Power: 7.8 kW
Output Voltage: 130 VDC
Voltage Stability: < %1





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