An Intelligent Controller designed to improve the Efficiency of Cascade Gama-LC Resonant Converters

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Abstract: In this paper a cascade $\Gamma - LC$ resonant power converter on base of a hybrid controller is introduced. The hybrid controller is composed of an Artificial Neural Network (ANN) and a PID classic controller. The structure of converter and its operation in steady state conditions was explained according to steady state model of converter. The ANN controller changes the switching frequency to maximize the voltage gain and consequently the efficiency of converter in case of large load variations. A classic PID controller regulates the voltage on base of an online PWM process. A prototype was designed and implemented on base of theoretical analysis and was experimentally tested. Comparison between simulation and experimental results shows validity of the hybrid controller and its reliability for expanding to other topologies of DC converters.

Key words: Artificial Neural Networks, Hybrid, PID controller, Cascade Resonant, DC Converter, Simulation

INTRODUCTION

DC-dc converters are interesting equipments from the control point of view, due to their intrinsic non-linearity characteristics. Common control approaches, like Voltage Control and Current Injected Control require a good knowledge of the system and its accurate tuning in order to obtain desired performances. These controllers are simple to implement and easy to design, but their performances generally depend on the working point, so that the presence of parasitic elements, time-Varying loads and variable supply voltages can make difficult selection of the control parameters which ensure a proper behavior in any operating conditions (Arulselvi, S., 2004). The design and analysis of resonant converters is often complex due to the large number of operating states occurring within a pulse period (Cavalcante, F.S. and J.W. Kolar, 2003). Many adaptive controllers for the resonant Converter are suggested during the recent years, such as Fuzzy control (Viswanathan, K., 2002), Fuzzy-PID control (Malekjamshidi, Z., 2009; Isin Erenoglu, 2006), Fuzzy-Neural control (Kuo-Hsiang Cheng, 2007), Sliding Mode control (Siew-Chong Tan, 2008), Sequential State Machine (Aigner, H., 2005), Gain Scheduled control (Astrom, K.J., B. Wittenmark, 1995) and Passivity Based control (Cecati, C.; Ortega, R., 1998). In this a new hybrid controller for resonant converters is introduced. The proposed controller is composed of an Artificial Neural Network (ANN) and an online PID classic controller. The output voltage of converter remains constant in case of any changes in load and line voltage by PID controller. On the other hand the switching frequency was changed by ANN controller to maximize the converter voltage gain and consequently to optimize the converter efficiency via a step by step gradual change. The ANN controller only operates in case of large changes in load value ($\Delta I_L > 5\%$) with a certain time delay, via a step by step gradual change to prevent any interference between two controllers operation. The online PID controller changes the Duty Cycle of switches to regulate the output voltage of converter permanently according to a PWM process. In the next sections, the structure of converter and its operation modes are discussed and the proposed control technique was explained, simulated and experimentally tested.

Structure Of $\Gamma - LC$ Resonant Converter:

The $\Gamma - LC$ resonant converter topology is shown in figure 1. In this topology voltage drop on series capacitors C1 and C2 is Vin/2 and switches Q1 and Q2 conduct on alternate half cycles. The switching process applies an AC square wave to the resonant circuit. The fundamental component of the square wave applied to the resonant network and the resulting sine wave AC current allows us to use classical AC analysis. The AC voltage is rectified by the fast recovery Schottky diodes and filtered. As is illustrated in figure 1, if Q1 and Q2 are "on" simultaneously – even for a short time- there is a short circuit across the supply voltage (Vin) and switches will be destroyed.
To make sure that this doesn't happen, the maximum duty cycle for Q1 and Q2, which occurs at minimum input voltage will be set at %80 of a half period (Malekjamshidi, Z., 2009).

**Steady State Analysis Of Converter:**

In this section, the steady state analysis of $\Gamma - LC$ resonant converter is undertaken. To study the voltage transfer gain and frequency response of converter our study needs some assumptions and simplifications. At the first step the rectifier and output filter are expressed as an equivalent load resistance. The current injected by rectifier into the output filter and the load, is a square wave which its fundamental component was used to achieve the equivalent resistor (Luo, F.L., H. Ye, 2006).

The equivalent load resistance is used to simplify the AC circuit diagram of converter as presented in figure 3.

$$I_{rms} = \frac{2\sqrt{2}}{\pi} I_L$$  \hspace{1cm} (1)

$$V_{rms} = \frac{\pi}{2\sqrt{2}} V_o$$  \hspace{1cm} (2)

$$R_{eq} = \frac{V_{rms}}{I_{rms}} = \frac{\pi^2 V_o}{8 I_L} = \frac{\pi^2}{8} R_L$$  \hspace{1cm} (3)

The voltage transfer gain of converter according to this model can be calculated as:
The resonant components \((L_1, L_2, C_1, C_4)\) are selected as follows to prevent complex mathematical analysis.

\[
L_1 = L_2 = L, \quad C_1 = C_4 = C, \quad \omega_0 = \sqrt{1/LC}
\]

The quality factor \(Q\) is defined as:

\[
Q = \frac{\omega_0}{R_{eq}} = \frac{1}{\omega_0 C R_{eq}} = \frac{Z_0}{R_{eq}}
\]

Where \(Z_0\) is selected as characteristic impedance. The relative switching frequency can be obtained by (8).

In this equation \(\omega\) is switching frequency and \(\omega_0\) is the natural resonant frequency of resonant network.

\[
\omega_i = \frac{\omega}{\omega_0}, \quad \omega_0 = \frac{1}{\sqrt{L/C}}
\]

The voltage gain \(G(\omega_i)\) can be simplified as (10) and phase of \(G(\omega_i)\) also can be obtained by equation (11) (Luo, F.L., H. Ye, 2006).

\[
A(\omega_i) = R_{eq}[1 - 3\omega_i^2 + \omega_i^4 + j(2 - \omega_i^2)\omega_0 Q]
\]

\[
|G(\omega_i)| = \left[1 - 3\omega_i^2 + \omega_i^4 + (2 - \omega_i^2)^2 \cdot \omega_0^2 Q^2\right]^{1/2}
\]

\[
\varphi = \angle G(\omega_i) = -\tan^{-1} \left(\frac{2 - \omega_i^2 \cdot \omega_0 Q}{1 - 3\omega_i^2 + \omega_i^4}\right)
\]

Figure 4 shows the characteristics of both voltage transfer gain \(G(S)\) and the phase angle \(\varphi\) versus relative frequency \(\omega_i\) and changes in quality factor \(Q\).
As is clear from figure 4, the voltage transfer gain $G(s)$ is higher than unity for some switching frequencies. It means that the resonant circuit in this converter enlarges the input energy for switching frequencies higher than resonant frequency $\omega_r$ (Luo, F.L., H. Ye, 2006). The maximum voltage transfer gain can be calculated from equations (12) and (13).

$$\left. \frac{d}{d(\omega_r^2)} G(\omega_r) \right| = 0$$

$$4\omega_r^6 + (3Q^2 - 18)\omega_r^4 +$$

$$(22 - 8Q^2)\omega_r^2 + 4Q^2 - 6 = 0$$  \hspace{1cm} (13)

The equation 13, give us the frequency which maximum voltage transfer gain can be achieved for certain values of Q. for example for Q=1 the relative switching frequencies for maximum gain are $\omega_r = 1.53$ and $\omega_r = 0.42$. As is clear from equations (3, 7, 9, 10) and (13), the maximum voltage transfer gain $G(s)$ depends on quality factor of converter and the load value $(R_L)$ for certain values of $L_1, L_2, C_1, C_2$. Therefor the maximum value of voltage transfer gain is a function of changes in output load and consequently, the equation 13 can be written as below.

$$4\omega_r^6 + \left[ \frac{0.65L}{C.R_L^2} - 18 \right] \omega_r^4 +$$

$$\left[ 22 - 8 \left( \frac{0.65L}{C.R_L^2} \right) \right] \omega_r^2 + 4 \left( \frac{0.65L}{C.R_L^2} \right) - 6 = 0$$  \hspace{1cm} (14)

To maximize the $G(s)$, the relative switching frequency of converter should be changed according to changes in load value. The changes in output load can be received by changes in load current $I_o(S)$ for a set value of output voltage $V_o(S)$. Changes in $I_o$ and $V_o$ applied to the ANN controller as input variables. The output signal of ANN controller resulted changes in switching frequency $\Delta \omega$ to maximize the voltage transfer gain in any operating point.

There is also a second control loop, included an online PID controller which regulates the output voltage of converter on base of PWM strategy. The output signal of PID controller make changes in the duty cycle $(\Delta D)$ of converter switches (Q1 and Q2). In the next sections, details of both ANN and PID controllers are discussed.

**Analysis Of Control Strategy:**

**A. Design of ANN Controller:**

In this section the design procedures for Artificial Neural Network (ANN) based controller will be described in brief. In this research, a multi-layer feed-forward artificial neural network is employed to achieve real-time control. The input variables of ANN are, output current variation $(i_o)$ and the changes in output DC voltage $(V_o)$ which are calculated according to equations (15) to (16). Since the changes in switching frequency is a nonlinear function of load changes, therefore it was chosen to be the output of the neural network controller as is shown in figure 5.

$$\Delta I_o(K) = I_o(K) - I_o(K-1)$$  \hspace{1cm} (15)

$$\Delta V_o(K) = V_o(K) - V_o(ref)$$  \hspace{1cm} (16)

$$\Delta \omega(K) = \omega(K) - \omega(K-1)$$  \hspace{1cm} (17)

To compensate the output voltage variation and maintain a constant output voltage, the duty cycle of the converter switches $(\Delta D)$, should change inversely proportional to $(V_o)$. 

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The training data of ANN controller was produced using a wide range pairs of Req and respected Q and \( \omega \), according to the equation (13). The resulted trained ANN was tested on an ideal simulated model of the converter which is illustrated in figure 6. The ideal model is simulated using MATLAB software and the waveforms of simulated converter are shown in figures 8(A,B).

![Diagram: The overall structure of designed controller.](image)

**Fig. 5:** The overall structure of designed controller.

In order to satisfy this requirements, a multi-layer feed-forward ANN, was selected to be trained. It is clear that a multi-layer feed-forward ANN can approximate any nonlinear function. The nonlinear sigmoid function is chosen as the activation function (Xiao-Hua Yu,; Kamran, F., 1998; Quero, J.M., 2002; Li, W., X.H. Yu, 2007).

\[
f(x) = \frac{1}{1 + e^{-ax}}
\]  

(18)

After simulation of converter, a sensitivity based neural network pruning approach is employed to determine an optimal neural network controller configuration (Karnin, E., 1990). In this approach, the contribution of each individual weight to the overall neural network performance is indicated by a sensitivity factor \( f(w_j) \).

The sensitivity of a global error function, with respect to each weight, \( S_{ij} \) can be defined as the following.

\[
S_{ij} = J(w_j = 0) - J(w_j = w_j^f) \\
S_{ij} = J(\text{without } w_j) - J(\text{with } w_j)
\]  

(19)

In these equations, \( w_j \) is the weight of the neural network and \( w_j^f \) is the final value of weight after training. The equation (19) can be approximated by (20) for the back-propagation algorithm (Xiao-Hua Yu,; Kamran, F., 1998).

\[
S_{ij} \approx \sum_{n=1}^{N} \Delta w_j(n) \frac{w_j^f}{\eta (w_j^f - w_j^i)}
\]  

(20)
Where \( N \) is the number of training patterns for each ANN weight update, \( \eta \) is the learning rate which is chosen to be 0.43 and \( \Delta W_{ij} \) is the weight update. The sensitivity calculations were done based on Equation (20). The weights that are insignificant can be deleted if their sensitivity factor was smaller than a defined threshold and also a neuron can be removed when the sensitivities of all the weights related with this neuron are below the threshold (Kamran, F., 1998). This process reduced the number of active weights and neurons and was effective in development of ANN controller speed. The three layer feed-forward neural network which has one hidden layer with 10 neurons was selected and the network weights are selected randomly with uniform distribution over the interval \([-1, 1]\).

**B. Structure of PID Controller:**

The ideal continuous PID controller is presented according to equation below:

\[
\Delta D = K_p \left( e_n + \frac{1}{T_i} \int_0^t e * dt + T_d \frac{de}{dt} \right)
\]

(21)

where \( K_p, T_i, T_d \) are the proportional, integral, and derivative gains, respectively, and \( e(t) \) is the error signal.

As we are concerned with digital control, and for small sampling periods the equation may be approximated by a discrete approximation. The derivative term was replaced by a backward difference and the integral by a sum using rectangular integration. The approximation is:

\[
\Delta D = K_p \left( \Delta V_O(K) + \frac{1}{T_s} \sum_{j=1}^{K} \Delta V_O(j)T_s + T_d \frac{\Delta V_O(K) - \Delta V_O(K-1)}{T_s} \right)
\]

(22)

Index \( K \) refers to the time instant (Malekjamshidi, Z., 2009). We have used Ziegler-Nichols method to adjust the \( K_p, T_i, T_d \) parameters which is a well-known method.

**Experimental Results:**

An experimental model of \( \Gamma-LC \) resonant converter is designed and implemented on base of the topology presented in figure 1. Table 1 shows the converter characteristics and parameters in brief.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input voltage(DC)</th>
<th>Output voltage(DC)</th>
<th>Output max current</th>
<th>Rated Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>20 V</td>
<td>5 – 50V</td>
<td>6 A</td>
<td>300 W</td>
</tr>
<tr>
<td>Parameter</td>
<td>Switching frequency</td>
<td>Switching devices</td>
<td>Rectifying devices</td>
<td>Processing device</td>
</tr>
<tr>
<td>Value</td>
<td>40-80 KHz</td>
<td>IRF840</td>
<td>FR107</td>
<td>80C196KB</td>
</tr>
</tbody>
</table>

The input voltage selected 20 volts (+5%10) and inductors are made of ferrite core (L1=L2=100 \( \mu \)H) and the capacitors are made of plain polyester (C1=C2=0.16 \( \mu \)F). Power MOSFETs IRF840 are used as active switches and fast recovery Schottky diodes FR107 as rectifiers. The software programming of ANN and PID controllers were developed in C language and the signals \( \Delta D \) and \( \Delta W \) were calculated as a nonlinear function of the input variables by microcontroller (80C196KB). The input variables were analogue signals which connected to internal analog-to-digital (ADC) converters of microcontroller. The converter was implemented in electrical laboratory of Islamic Azad University (Fasa branch) and experimentally tested (figure 6). It takes an average of 400 instruction cycles for the 80C196 processor to execute a complete cycle of program and provide the gate pulses with new duty cycle for the main switches. The experimental waveforms of resonant network current and voltage, voltage of capacitor(C2) and changes in output voltage of implemented converter are shown in figure 7 (A, B, C and D). It can be seen that simulation and experimental waveforms confirmed each other.

Experimental results show that the ANN controller in case of any changes more than 5% of maximum converter rated current provides an appropriate \( \Delta W \) signal to maximize the converter voltage gain and increase the converter efficiency. The \( \Delta W \) signal changes gradually to provide enough time for online PID controller to compensate the changes in Vo. The online PID controller regulates the output voltage of converter in each set point for all variation ranges of load current and line voltage. As is clear from figure 7 (D), settling time, Overshoot and Rise time in output voltage waveforms remain in an acceptable range in case of any step changes.
The signals of input current and voltage were quite noisy due to high frequency switching elements. The negligible difference between simulation and experimental results is due to off-line training of ANN controller on base of ideal MATLAB/SIMULINK model. To fine-tune the weights of ANN and reduce the difference an online fine-tuning train can be useful (Li, W., X.H. Yu, 2007; Karnin, E., 1990). Experimental results show good agreement with simulations which approve the reliability of small signal model and ANN controller.
Conclusion:
The ANN controller proposed in this paper can be a reliable alternative to classic controllers for DC-DC converters. In general the ANN controller provides good characteristics in terms of overshoot, rise-time and settling time. Comparison between simulated and experimental results showed good agreement which approved reliability of proposed controller.

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