Proceedings of the International Conference on Renewable, Applied and New Energy Technologies
ICRANET-2018, 19-22 November 2018, Air University, Islamabad, Pakistan
ICRANET2018-180410

# SLIDING MODE CONTROL OF LLC (INDUCTANCE INDUCTANCE & CAPACITANCE) DC-DC RESONANT CONVERTER

Hafiz Harun Jamil*
Department of Electrical Engineering
Air University Islamabad, Pakistan
harunjamil@hotmail.com

Muhammad Adil khan*
Department of Electrical Engineering
Air University Islamabad, Pakistan
adil.khan@mail.au.edu.pk

Muhammad Waleed Shujha*
Department of Electrical Engineering
Air University Islamabad, Pakistan
Wali.shuja90@gmail.com

Aftab Hussain*
Department of Electrical Engineering
Air University Islamabad, Pakistan
Aftab536@yahoo.com

Muhammad Insaf Butt*
Department of Electrical Engineering
Air University Islamabad, Pakistan
Insafbutt78@gmail.com

*Abstract*—As the technology is increasing day by day, the DC-DC converters are gaining popularity as well. Since, it is desired to reduce the size of power supplies and switching losses, the zero-voltage switching is of great importance. The LLC (Inductor Inductor Capacitor) resonant converter has high power density, improved efficiency and less EMI (Electro Magnetic Interference) emission. The main function of these converters is to reduce the switching losses of the functional devices. Due to the natural characteristics the current through these devices fall to zero. The small signal variations of LLC resonant converters keep on changing at every instant, so it is very problematic to design parameters of closed loop control. The sliding surface is designed using the output voltage error and the current through the output capacitor. Using the “Extended Describing Function” (EDF) the large signal model is formed. The circuit being discussed here works at fixed switching frequencies with the implementation of sliding mode control strategy. The extended describing function topology is used to determine large signal model and the characteristics of the steady state response. All the parameters and sliding mode control are explored on the phase plane. Using the MATLAB Simulink the model was developed and tested with the required parameters. It is realized that the given sliding mode controller gives fast transient response due to its strong robustness. This thesis provides a detailed study of LLC Resonant DC-DC converters using the Sliding Mode Control. *Index Terms*—LLC, EMI, EDF, DC-DC converters

## I. INTRODUCTION

DC-DC converters are being widely used in a large number of applications where there is a need of power consumption and power conversion. They have the capability to boost the power from micro to megavolts. The main parts in the circuit of these converters consist of capacitors, inductors, resistors, switches, diodes and transformer. In order to keep up with the required demand, these circuits are tested continuously to improve their performance and power levels. As the demand for power supplies is increasing because of the larger number of applications, so DC-DC converters are being used intensively. In order to decrease the size of the power supplies, the frequency of operation is raised [1]. When the operating frequency is raised, the switching losses are also increased, so resonant power converters are used to cater this problem. The most common amongst the resonant converters are the Series Resonant Converters (SRC), Parallel Resonant Converters (PRC), Series Parallel Resonant Converters (SPRC), LLC Resonant Converters and the Capacitor Inductor and Capacitor CLLC Resonant Converters [2]. The main problem of SRC is that they reduce the voltage regulation capability at no load condition. If we increase the input voltage, it starts operating away from the resonant frequency which needs more power in the resonant network. The third category namely SPRC combines the advantages of the two series and parallel resonant converters and removes their drawbacks. These LLC resonant converters are the subtype of SPRC and are gaining popularity in industrial electronics and other multiple applications. When compared with other converters, these LLC converters have higher efficiency, lower harmonics and provide less electromagnetic interference. If handled properly, they can control the output voltage over large input range and most importantly at different load ranges while maintaining increased efficiency.

This will be very helpful when we are dealing with renewable energy resources such as the batteries, wind turbines or other energy storage systems [1]. These converters are used in many applications such as Industrial DC-DC power supplies, Military Power Supplies and Battery Charging. Some of the short comings in these converters have enabled the researchers to discover some new operational methods, especially when high input to output ratio is required for better dynamics, stability and reliability. Also further improvements have been made to minimize (PSRR) power supply rejection ratio, voltage ripples, electromagnetic interference and most importantly the cost of these designs [3].

## II. SYSTEM DESCRIPTION

The main objective of the LLC resonant DC/DC converter is to provide a higher efficiency, lower harmonics and provide

Identify applicable funding agency here. If none, delete this.

less electromagnetic interference with better dynamic response and robustness [4]. A typical LLC resonant DC/DC converters have a switching unit which is interfaced with a resonant tank circuit. A Fixed switching frequency makes the LLC resonant converter work. To make the sliding surface possible and maintain high efficiency, the frequencies must meet the following condition:

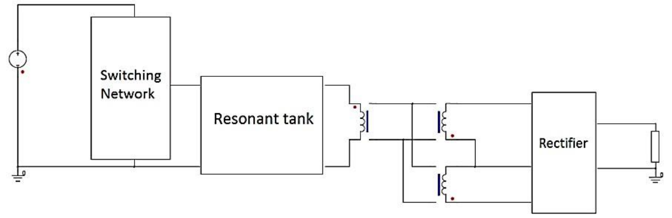


Fig. 1. LLC Resonant Converter Block Diagram .

- The output voltage must be in range with the load series as well as input voltage.
- The converter should meet the Zero Voltage Switching condition.

A simpler form of LLC Resonant inverter is shown in Figure 10. LLC Resonant converters are used as a voltage divider, so the gain is lower than unity [2]. Zero voltage switching has advantages, as it reduces the energy needed to operate switches, low loss of switching, less generation of EMI and noise. The highest gain is attained at resonant frequency as the impedance of resonant tank will be inferior at this rate of recurrence. High frequency deviation is not required for the maintenance of regulated output-voltage [3]. Light load is not a problem for regulation in LLC resonant converter as it's in SRC. In addition, the operation region is slighter and current in the electric devices declines as the load declines and that is how high load efficiency is conserved [5].

## III. CONTROL DESIGN

The detailed description of the overall system with proposed control approach is shown in Figure ?? . A square wave will be given to the LLC resonant tank converter. For developing the model, the series resistance of resonant tank is taken into account. By applying Kirchhoff's law to the Figure ??, ?? – ?? can be achieved easily [6].

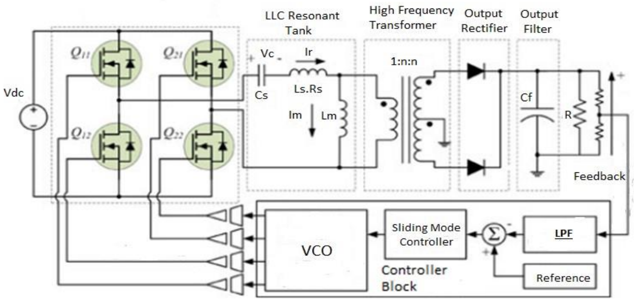


Fig. 2. Resonant DC-DC Converter Control Description.

$$\frac{di_r}{dt} = \frac{vin}{L} - \frac{r_s i_r}{L_s} - \frac{V_c}{L_s} - \frac{n}{L_s} Sign(i_r - i_m)V_{cf} \quad (1)$$

$$\frac{dv_c}{dt} = \frac{i_r}{C_s} \quad (2)$$

$$\frac{di_m}{dt} = \frac{n}{L_m} V_{cf}\, sign(i_r - i_m) \quad (3)$$

$$\frac{dv_{cf}}{dt} = \frac{n}{C_f}|i_r - i_m| - \frac{V_{cf}}{R} \quad (4)$$

The AC state variable Ir, Vc and Im can be broken down into their Sine and Cosine components, using the sinusoidal approximation. To get steady state values their derivatives are set to zero. By applying this decomposition, it gives birth to two states for each variable.

$$i_r(t) = i_{rs}(t)sin(w_s t) - i_{rc}(t)cos(w_s t) \quad (5)$$

$$\frac{di_r}{dt} = (\frac{di_{rs}}{dt} + w_s i_{rc})sin(w_s t) - (\frac{di_{rc}}{dt} - w_s i_{rs})cos(w_s t) \quad (6)$$

The "Extended Describing Function" is a strong concept for demonstrating these resonant converters so that we can analyze their behavior [7], [8]. It combines the frequency and time domain analysis and separates the modulated waveform into the cosine as well as sine waves. So the non-linear terms in [1]–[4] can be estimated as essential harmonic terms.

$$F_1(d, V_{in}) = \frac{4V_{dc}}{\pi} sin(\pi d) = \frac{4V_{dc}}{\pi} \quad (7)$$

$$F_2(i_s, i_p, v_{cf}) = \frac{4}{\pi}\frac{i_s}{i_p} V_{cf} \quad (8)$$

$$F_3(i_s, i_p, v_{cf}) = \frac{4}{\pi}\frac{i_c}{i_p} V_{cf} \quad (9)$$

$$F_4(i_s, i_c) = \frac{2}{\pi} i_p \quad (10)$$

The non-linear terms are approximated as follows:

$$V_{in}(t) = F_1(d, V_{in})sin(W_s t) \quad (11)$$

$$sign(i_r - i_m)V_{cf} = F_2(i_s, i_p, v_{cf})$$

$$sin(w_s t) - F_3(i_s, i_p, v_{cf})cos(w_s t) \quad (12)$$

$$|i_r - i_m| = F_4(i_s, i_c) \quad (13)$$

By making use of equations 7, the sine and cosine terms are separated out and are given below.

$$\frac{di_{rs}}{dt} = \frac{4V_{dc}}{\pi L_s} - W_s i_{rc} - \frac{r_s}{L_s} i_{rs} - \frac{v_{cs}}{L_s} - \frac{4n}{\pi L_s} \frac{i_{rs} - i_{ms}}{ip} V_{cf} \tag{14}$$

$$\frac{di_{rc}}{dt} = W_s V_{cc} - \frac{r_s}{L_s} V_{cc} - \frac{4n}{\pi L_s} \frac{i_{rs} - i_{ms}}{i_p} V_{cf} \tag{15}$$

$$\frac{dv_{cs}}{dt} = W_s V_{cc} - \frac{1}{C_s} i_{rs} \tag{16}$$

$$\frac{dv_{cc}}{dt} = -W_s V_{cc} - \frac{1}{C_s} i_{rc} \tag{17}$$

$$\frac{di_{ms}}{dt} = -W_s i_{mc} - \frac{4n}{\pi L_m} \frac{i_{rs} - i_{ms}}{i_p} V_c f \tag{18}$$

$$\frac{di_{mc}}{dt} = W_s i_{ms} - \frac{4n}{\pi L_m} \frac{i_{rc} - i_{mc}}{i_p} V_c f \tag{19}$$

$$\frac{dV_{cf}}{dt} = \frac{2n}{\pi C_f} i_p - \frac{n}{RC_f} V_{cf} \tag{20}$$

### *A. SLIDING MODE CONTROL*

The direct grouping of variables is the best widely used sliding surface. In order to decrease the chattering phenomena, the discontinuous terms are transferred to their derivative terms by converting of the function of tedious sliding mode [9]. Random sample of the output voltage and the capacitor current gives the switching function a gain and is given by

$$S(X,t) = K_v x(t) + K_i i_c(t) \tag{21}$$

Where output voltage error is represented by $x(t)$, $X(t) = V_o(t) - V_{ref}$. $Ki$ and $Kv$ are the gain factors so, as a result the Surface of Sliding can be obtained by

$$(X,t) = Kx(t) + \frac{dv^0(t)}{dt} = 0 \tag{22}$$

When applied the attainment condition, the control law is found by$ss < 0$ [10].

$$u = \begin{cases} 0 & for \quad S > 0 \\ 1 & for \quad S < 0 \end{cases} \tag{23}$$

In the real system a comparator is designed to make sure that the sliding control mode works properly. Thus, rule can be improved as

$$\begin{cases} 0 & for \quad S > \rho \quad or \quad (|S|) < \rho \quad S < 0 \\ 1 & for \quad S < -\rho \quad or \quad (|S|) < \rho \quad S < 0 \end{cases} \tag{24}$$

The following argument is on the phase plane, where $\rho$ is the delay on the phase plane where $x(t)$ is the representation of output voltage error and $\frac{dv^0(t)}{dt}$ is the differential term taken on y-axis [11]. The sliding surface is always a straight line (0,0) on the plane, and is prolonged to give bounded sliding region

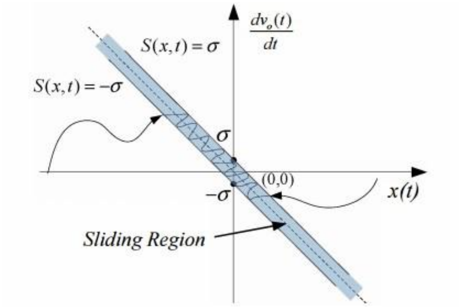


Fig. 3. Sliding Region on the Phase Plane

### *B. SLIDING MODE CONTROL GAIN PARAMETERS*

It has mainly three control parameters $Kv$, $Ki$ and the hysteresis breadth. They can be cut down into two, bestowing to the association between them,

$$K = \frac{K_v}{K_{i^o C^o}} \tag{25}$$

$$\rho = \frac{\varepsilon}{K_{i^o C^o}} \tag{26}$$

As discussed earlier K is the sliding control mode gain and sigma is the periodic delay [12]. The ?? shows the trajectory of cycle on the platform with the parameter K. With the increase in the value of K the gradient of region of sliding rises while the route is compacted.

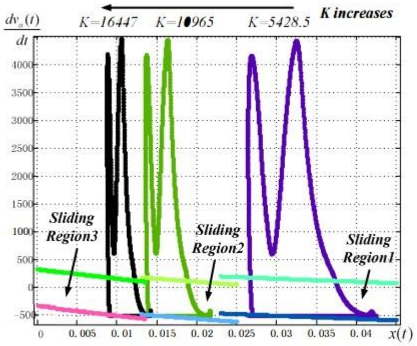


Fig. 4. Steady state trajectory of control cycle.

#### *1) SYSTEM PARAMETERS:*

## IV. SIMULATIONS AND RESULTS

*A. SMC Controller Diagram* by making use of the equation obtained in 21, the controller diagram was implemented.

| Parameter | Description | Value |
|---|---|---|
| V-dc | Nominal input & Voltage(v) | 90 |
| C-out | Nominal output & Voltage(v) | 200 |
| I-out(max) | Maximum output Current(A) | 7.5 |
| Ls | Resonant Conductance(uH) | 13.1 |
| Cs | Resonant Tank Capacitor(nF) | 170 |
| Lm | Magnetizing Conductance(uH) | 47 |
| N | Transfer Ratio | 1.875 |
| Fr | Resonant Frequency(kHz) | 106.7 |
| Kv | Voltage Gain | 2.59 |
| Ki | Current Gain | 38090 |

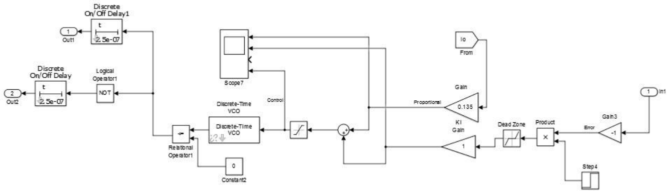


Fig. 5. Sliding Mode Controller

*1) SMC OUTPUT:* The steady state simulation waveform is shown in the figure below. The resonant current, output voltage and the sliding control mode signal $^0u^0$ is presented in the output. The result shows that current is regulated and the output voltage by varying the control signal $^0u^0$.

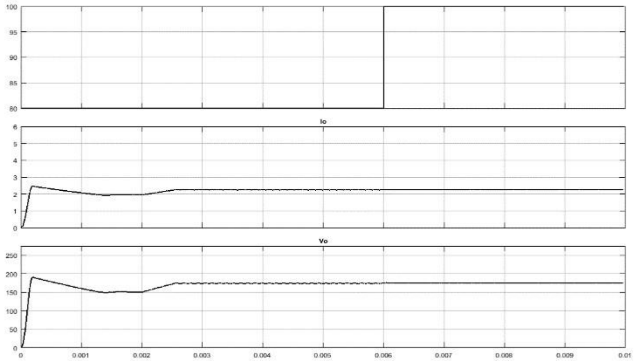
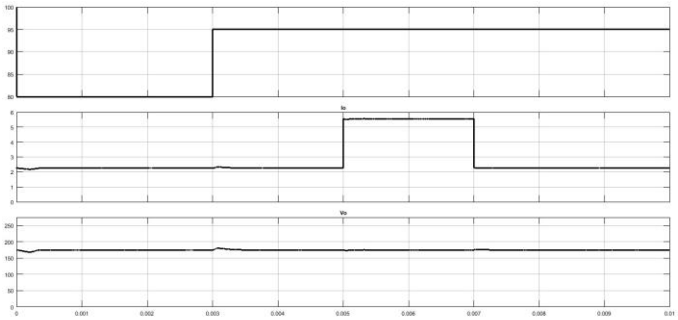


Fig. 6. SMC Output



### *B. PID Controller Diagram*

A PID controller was also design to provide a comparison between two controls. The values of the gain were calculated using hit and trial method. The integral and derivative gains are settled to zero and $K_p$ was amplified [13]. When the voltage of output starts to fluctuate, then the values were set to look at the response.

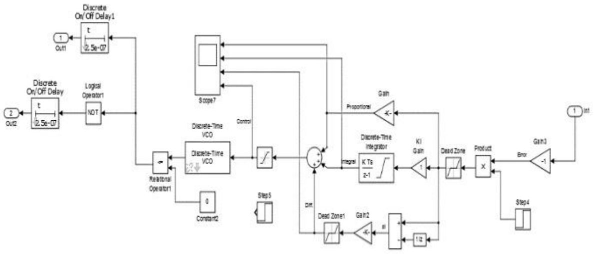


Fig. 7. SMC Output

Fig. 8. SMC Output

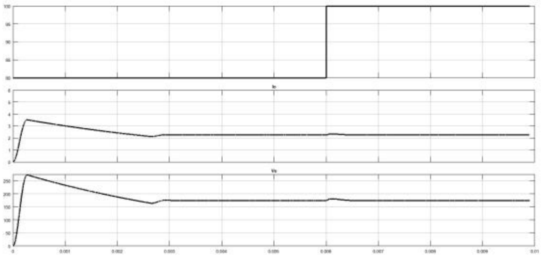


Fig. 9. PID Output(a)

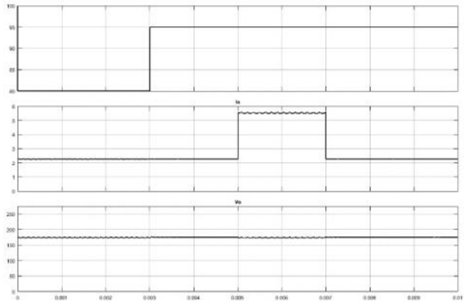


Fig. 10. PID Output (b)

### *1) PID Output:*

| Transient Response | PID Controller | Sliding Mode Controller |
|---|---|---|
| Convergence Time | 0.003s | 0.0025s |
| Overshoot | 25% | 5% |
| Settling Time | 0.007s | 0.005s |

## V. CONCLUSION

This comprehensive study poses a detailed study of LLC resonant DC-DC converters. The EDF (Extended Describing Function) method is applied to obtain the dynamic signal model and the solution of steady state. All the constraints are conferred on the phase plane. Mathematical model is presented in detail with the discussion on sliding mode control. A PID controller was also implemented and the results were compared. The sliding mode control because of its strong robustness, gives fast transient response as compared to PID.

## REFERENCES

[1] Yang, Bo, Fred C. Lee, A. J. Zhang, and Guisong Huang. ”LLC resonant converter for front end DC/DC conversion.” In Applied Power Electronics Conference and Exposition, 2002. APEC 2002. Seventeenth Annual IEEE, vol. 2, pp. 1108-1112. IEEE, 2002.

[2] Castilla, Miguel, Luis Garc´ıa de Vicuna, Josep Mar˜ ´ıa Guerrero, Jose´ Matas, and Jaume Miret. ”Sliding-mode control of quantum seriesparallel resonant converters via input-output linearization.” IEEE Transactions on Industrial Electronics 52, no. 2 (2005): 566-575.

[3] Galek, Marek, and Gopal Mondal. ”Modular DC/DC converter with improved efficiency for electric vehicles applications.” In Applied Power Electronics Conference and Exposition (APEC), 2014 Twenty-Ninth Annual IEEE, pp. 1958-1965. IEEE, 2014.

[4] Ivensky, Gregory, Svetlana Bronshtein, and Alexander Abramovitz. ”Approximate analysis of resonant LLC DC-DC converter.” IEEE Transactions on power electronics 26, no. 11 (2011): 3274-3284.

[5] Kurokawa, Fujio, and Koji Murata. ”A new fast digital PID control LLC resonant converter.” In Electrical Machines and Systems (ICEMS), 2011 International Conference on, pp. 1-5. IEEE, 2011.

[6] Buccella, Concettina, Carlo Cecati, and Hamed Latafat. ”Digital control of power converters—A survey.” IEEE Transactions on Industrial Informatics 8, no. 3 (2012): 437-447.

[7] Buccella, Concettina, Carlo Cecati, Hamed Latafat, Pierdomenico Pepe, and Kaveh Razi. ”Observer-based control of LLC DC/DC resonant converter using extended describing functions.” IEEE Transactions on Power Electronics 30, no. 10 (2015): 5881-5891.

[8] Ayachit, Agasthya, Dakshina Murthy-Bellur, and Marian K. Kazimierczuk. ”Steady-state analysis of series resonant converter using extended describing function method.” In Circuits and Systems (MWSCAS), 2012 IEEE 55th International Midwest Symposium on, pp. 1160-1163. IEEE, 2012.

[9] Kazimierczuk, Marian K., and Dariusz Czarkowski. Resonant power converters. John Wiley & Sons, 2012.

[10] Sabanovic, Asif. ”Variable structure systems with sliding modes in motion control—a survey.” IEEE Transactions on Industrial Informatics 7, no. 2 (2011): 212-223.

[11] Musavi, Fariborz, Marian Craciun, Deepak S. Gautam, Wilson Eberle, and William G. Dunford. ”An LLC resonant DC–DC converter for wide output voltage range battery charging applications.” IEEE Transactions on Power Electronics 28, no. 12 (2013): 5437-5445.

[12] Hu, Haibing, Xiang Fang, Frank Chen, Z. John Shen, and Issa Batarseh. ”A modified high-efficiency LLC converter with two transformers for wide input-voltage range applications.” IEEE Transactions on Power Electronics 28, no. 4 (2013): 1946-1960.

[13] Hirakawa, M., M. Nagano, Y. Watanabe, K. Andoh, S. Nakatomi, and S. Hashino. ”High power density DC/DC converter using the close-coupled inductors.” In Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE, pp. 1760-1767. IEEE, 2009.