Voltage Control of Dual Input Step-up SCI Converter using Fuzzy Switching Control Method

Vahid Omrani[1], Mohammad Reza Ershadi[2*], Mohammad Hossein Ershadi[1]
1- Department of Engineering, Khomeinishahr Branch, Islamic Azad University, Isfahan, Iran.
Email: ershadi@iaukhsh.ac.ir
2- Department of Engineering, Majlesi Branch, Islamic Azad University, Isfahan, Iran.
Email: ershadi@iaumajlesi.ac.ir (Corresponding author)

Received: December 2018 Revised: May 2019 Accepted: July 2019

ABSTRACT:
Dual input step-up Switched Capacitor Inductor (SCI) converters have been investigated in this paper. At first, the structure of this converter is reviewed and analyzed carefully. It has shown that besides capacitor and inductor, a small resonant inductor is also used in order to limit the current peak, which is caused by switched capacitor. Therefore, efficiency has been improved. In the proposed solution, fuzzy control method is used for controlling and switching the circuit. Simulation results have revealed that by using this method; the output waveforms are according to idealized ones while achieving a high voltage gained. In addition, by using such method, the output voltage ripple is significantly decreased.

KEYWORDS: Fuzzy Control, Dual Input Converter, Switched Capacitor Converter.

1. INTRODUCTION

With the advent of modern industrial technology and high electrical energy demand, it is essential to increase the electric power generation to fulfill this demand. In this case, distributed generation technologies have gained wide attention [1]. Therefore, high step-up dc-dc converters are getting more attention and have been widely studied [2].

A systematic, technological structure of new convertors was proposed for the first time by makowski et al. Their structure was based on duality between a switching-capacitor cell and a switching-inductor cell, as well as the duality between a voltage driven convertors and a current driven one [3].

Traditional inductor-based converters, including buck converters, have been the basic form of design for nearly most switched-mode voltage regulators. Simply, a buck convertor is formed by only two switches, one inductor and one input capacitor. With regard to the simple structure of this design and control methodology, other basic structures have been proposed such as boost, buck-boost, zeta, cuk and sepic due to their relatively high advantages such as high efficiency, easy design, simple control suit and etc. Hybrid switched capacitor dc-dc buck convertors, also improves defects of traditional buck convertors. Basic Switched-Capacitor (SC) convertors have wide range of application as they can propose high power density. In order to eliminate current peak and attaining soft switching, small resonant inductor has been added in SC converters, which could lead to high efficiency and good performance [4].

With the aim of obtaining high step/down voltage gain, researchers are trying to use advantages of aforementioned converters and achieve high efficiency converter. Zeta, sepic and cuk converters use two step-up SC cells in order to achieve high set up voltage conversion ratio. Other research proposes a family of switched-boost dc-dc convertors for the high step-up voltage conversion applications, constant power supply, and etc. In their proposed method, traditional switched-boost network combines with switched-capacitor/switched-inductor cells. This method would result in a higher output voltage gain, fewer number of passive components, and lower voltage stress across the output diode and power switches [5].

In this paper, in order to gain higher output level and high rate of efficiency, a new switched-mode converter, including capacitor and inductor, is proposed; in which switching operation is controlled by a fuzzy controller. In this method, fuzzy method leads to easy way of switch controlling and overcomes some defects of previous methods.

This paper is organized as follows: in section 2, the detailed design and analysis of the proposed method are introduced and discussed. In section 3, simulation results are proposed, and in section 4 conclusion of this study is withdrawn.

2. ANALYSIS OF DUAL INPUT CONVERTER

In the assumed circuit depicted in Fig. 1, two inductors have been used, in which L_1 function as an energy transfer inductor, while L_r is only used as a limiter of current peak caused by the capacitor C_1 when the switch Q is turned on. When switch Q is turned on, charging or discharging of the capacitor C_1 would occur. If no pre-defined strategy to limit the peak current exist, the charging or discharging current will be soar to a very high peak and circuit will be damaged. To solve this problem, a small inductor (L_r) is connected in series with capacitance to form a resonant tank during switching on period, by resonant frequency of $f_o = 1/2\pi\sqrt{L_r C_1}$. In this case, quantity of current gradually increases from zero to peak value. To ensure of occurrence of this phenomena, the switching time should be more than half of resonant frequency [6].

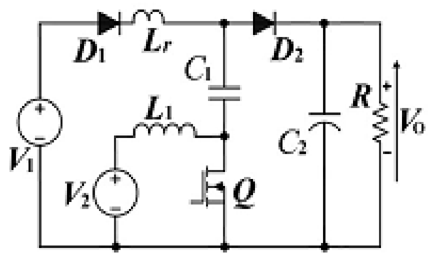

Fig. 1. Dual input step-up convertor.

There are three working states for each SCI convertors in one period of switching cycle. The circuits of these three states are illustrated in Fig. 2. In addition, their idealized waveforms are shown in Fig. 3. All simulations presented in this research are based on following assumptions: 1- all components are ideal without any voltage drop or inherit resistance. 2- Output capacitor is very large, therefore, the output voltage ripple could be ignored and assumed as a constant value. 3- The inductor L1 operates in permanent current mode [6].

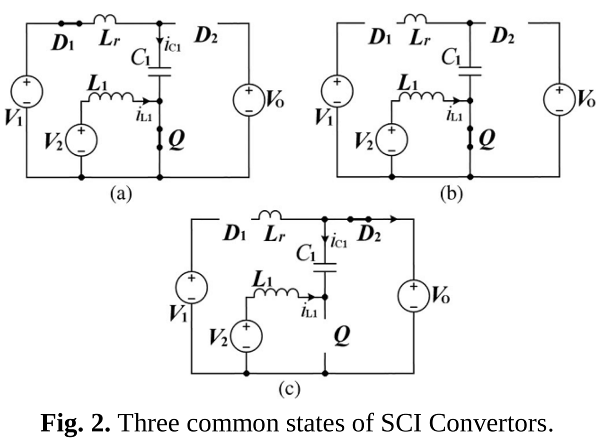

Fig. 2. Three common states of SCI Convertors.

In state 1, between time intervals of t_0-t_1, when switch Q is on, diode D_2 is biased reversely. Diode D_1 is forward biased and resonant inductor L_r forms a resonant tank as it has been explained previously. By applying input voltage (equal to V_1) across the resonant tank; i_{c1} would be induced and begins to gradually increase from zero in sinusoidal manner. Following this phenomenon, C_1 is charged and its voltage increases gently. Beside this, another input voltage V_2 is developed across inductor L_1 and current i_{L1} increases linearly. These procedures could be formulated as follow:

$$i_{C_1} = I_{C_1} sin\omega_0(t - t_0) \tag{1}$$

$$V_{C_1} = V_1 - \frac{\Delta V_{C_1}}{2} cos\omega_0(t - t_0) \tag{2}$$

$$i_{L_1} = I_{L1-min} + \frac{V_2}{L_1}(t - t_0) \tag{3}$$

Where, ω_0 equals to $1/\sqrt{L_r C_1}$ and named resonant angular frequency. In addition, I_{C1} and ΔV_{C1} which are related to the output current, are oscillation amplitudes of the current and voltage of capacitor C1, respectively. Finally, $I_{L_{1-min}}$ is the minimum value of the current flowing through L_1. [6]

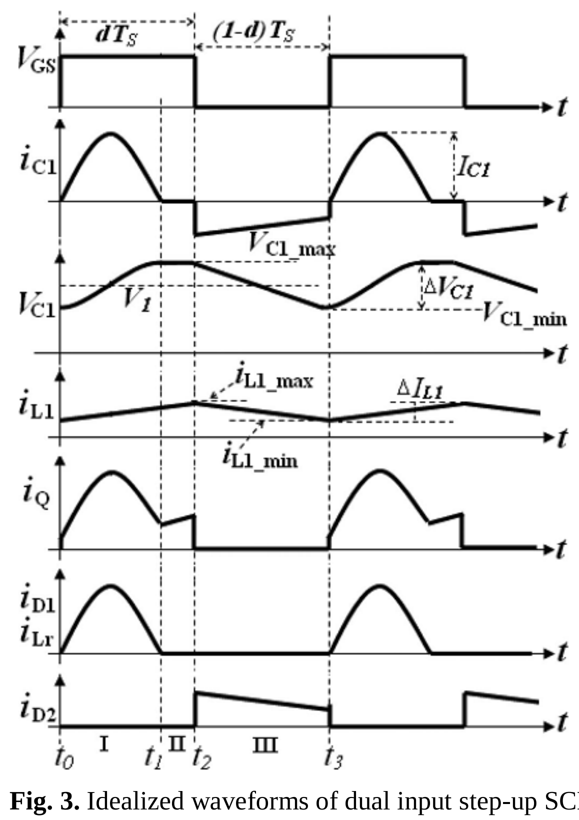

Fig. 3. Idealized waveforms of dual input step-up SCI Convertors.

It could be deduced from Fig. 3 that the resonant current i_{C1} is set to zero after L_r and C_1 resonate for half of a cycle and after this, diode D_1 is biased reversely. Simultaneously, the capacitor voltage sets at its maximum level. This could be formulated as follow:

$$V_{C1-max} = V_1 + \frac{\Delta V_{C1}}{2} \tag{4}$$

In state 2, between time interval of t_1-t_2, the resonance has been stopped, switch Q is going to ON and i_{L1} increases linearly as it has shown in (3). At this time, no current flows through capacitor C_1 and therefore, its voltage maintained the maximum value. This state continues to happen till the switch is turned OFF, and after that, the inductor current i_{L1}rises to its maximum value.i.e.,[6]

$$I_{L1-max} = I_{L1-min} + \frac{V_2}{L_1} dTs \tag{5}$$

Finally, in state 3 between time interval of t_2-t_3, switch Q will be OFF and diode D_1 biased forwardly, while D_2 is reversely biased. As it is obvious, in this case, C1, L1 and input source V2 are connected in series and thus the flowing current through C1 and L1 are same and can be expressed by:

$$i_{L1} = -i_{C1} = I_{L1-max} - \frac{V_O - V_2 - V_{C1}}{L_1}(t - t_2) \tag{6}$$

As it is assumed that switching frequency is large enough so that ($T_s \ll 2\pi\sqrt{L_1 C_1}$), thus capacitor voltage V_{C1} and inductance current i_{L1} changed linearly. At the end of this state, i_{L1} and V_{C1} both decrease to their minimum values. After this, the switch Q will be turned on and all these 3 states repeat again.

Based on previous studies of dual-input step-up convertors; it has shown that oscillation amplitudes of resonant current and voltage could be determined by C_1 and L_r. In addition, the value of L_1 can be determined by the design requirements of its current ripple.

Therefore, the design steps can be divided as follows:

1- At the first level of design process, the minimum and maximum values of the duty ratio and switching frequency should be determined and then calculate the resonant frequency according to this rule that says: switch condition time should be longer than half of a period of resonant frequency:

$$f_0 = \frac{1}{2\pi\sqrt{L_1 C_1}} > \frac{1}{2 d_{min} T_S} \tag{7}$$

Where, d_{min} is defined as the minimum value of the duty ratio and T_S equals to switching cycle.

2- Value of L_1 can be formulated as follows:

$$L_1 = \frac{V_2}{\Delta I_{L1}} d_{max} T_s \tag{8}$$

In which, d_{max} equals to maximum value of the duty ratio and ΔI_{L1} is the design requirements of the current ripple flowing through L_1.

3- Value of capacitor C1 can be determined by:

$$C_1 = \frac{I_{O-max} T_S}{\Delta V_{C1}} \tag{9}$$

Where, I_{O-max} is the maximum output current and ΔV_{C1} is the design requirement of voltage oscillation amplitude.

4- The value of resonant inductor Lr can be determined by:

$$L_r = \frac{1}{4\pi^2 f_0^2 C_1} \tag{10}$$

3. FUZZY SWITCHING CONTROL METHOD

In this paper, fuzzy method has been used for controlling the switching function of a circuit. In next section, simulation results have shown the efficiency of the proposed method. In this section, the focus is on the details of the proposed method.

In order to design a fuzzy controller, in the first step; input membership functions should be determined. Accordingly, fuzzy rules should be expressed. Afterwards, the normalization procedure should be done. At the end, the output membership functions as well as results of each rule would be excluded. The structure of fuzzy control system in the proposed method is illustrated in Fig. 4.

In the proposed model, fuzzy control circuit has two inputs, including error and its derivative. The input membership functions of the fuzzy controller are illustrated in Fig. 5. In addition, the implemented fuzzy rules are illustrated in Fig. 6.

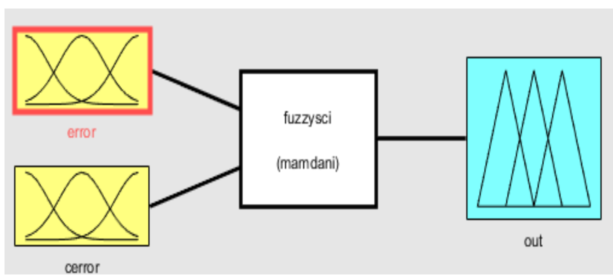

Fig. 4. Fuzzy control structure of the method.

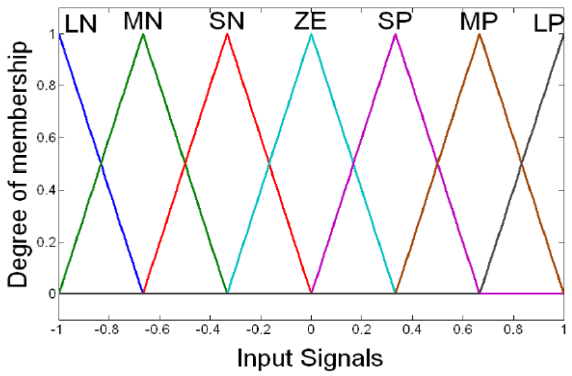

Fig. 5. Input membership functions of fuzzy controller.

e \ ce	LN	MN	SN	ZE	SP	MP	LP
LN	LN	LN	MN	LN	MN	LN	MN
MN	MN	MN	LN	MN	MN	LN	MN
SN	LN	MP	SN	ZE	SP	MN	LN
ZE	MN	MN	SN	ZE	SP	MP	LN
SP	MP	MP	SN	ZE	SP	LP	MN
MP	LP	LP	LP	MP	MP	MP	MP
LP	MP	MP	MP	LP	MP	LP	LP

Fig. 6. Fuzzy rules of the proposed method.

4. RESULTS

Based on experimental parameters [6], a simulation circuit of dual input step-up convertor has been built and results of the simulation are provided in this section. Table. 1 illustrates the parameters and component's value of the circuit [6].

Table. 1. Parameters and component's value of dual input step-up SCI converter.

Input voltages (V1,V2)	30 V-20V
Out Power Max	250w
Switching Frequency	102 KHz
C1	4.7 μF
C2	100 μF
L1	95 μH
Lr	0.3 μH
D1 and D2	MBR10100
Q(N channel MOSFET)	IRFI540N

The simulation results are shown in Fig. 7. By comparing simulated waveforms by idealized waveforms, based on section 2, it can be concluded that, i_{c1} increases gradually in a sinusoidal manner when V_1 is developed across resonant tank and then decreases to zero, because there is not any current flowing through C_1. After that, based on (6), i_{c1} increases linearly by time.

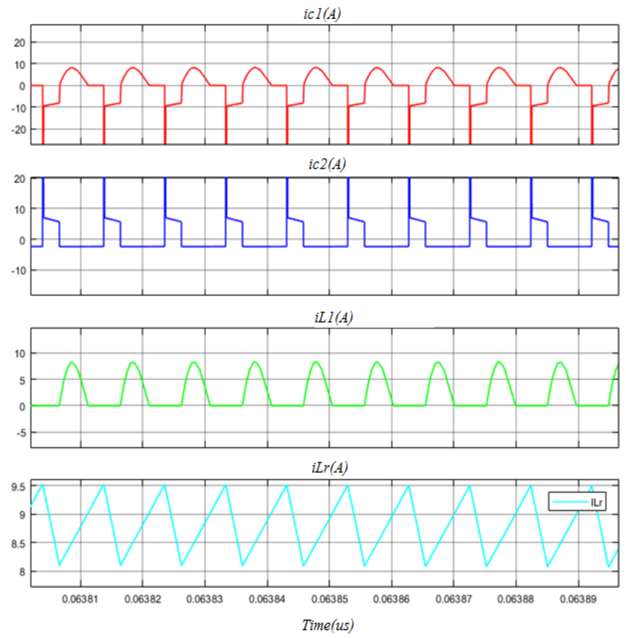

Fig. 7. Ic1 value, ic2 value, iLr value and iL1 value respectively.

Albeit, i_{c2} is set to zero during states 1 and 2, while decreasing linearly in state 3. In addition, when V_2 is developed across L_1; i_{L1} increases linearly based on (3) and then decreases linearly by time in next states according to (6). As it is illustrated in Fig. 8, the ripple of output voltage has been removed, thus, a high gain of output voltage has been achieved. These results are in accordance with previous researches and confirm the efficiency of the proposed method.

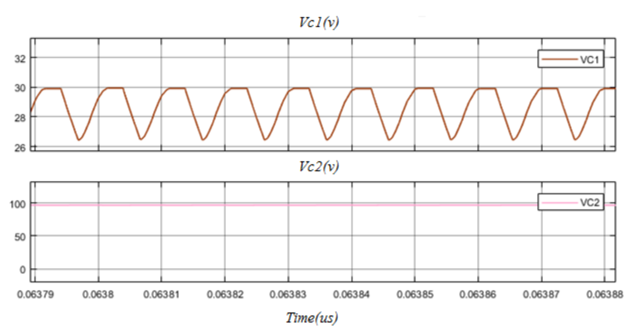

Fig. 8. Vc1 and Vc2 (Vo) values of assumed circuit.

5. CONCLUSION

The aim of this study was to simulate the dual input step-up SCI convertor by using fuzzy logic for switching control. The results of the simulation have shown that the outputs of proposed method are similar to previously performed studies. The results are also in agreement with theory (Fig.3). By using the proposed method, the output voltage ripple has been significantly decreased and high voltage gain has been achieved.

REFERENCES

[1] Y. Yuanmao and K. W. E. Cheng "**Level-Shifting Multiple-Input Switched-Capacitor Voltage-Copier**," *IEEE Trans. Power Electron*. , Vol. 27, nNo. 2, pp. 828–837.2012

[2] K. W. E. Cheng, "**Zero-Current-Switching Switched-Capacitor Converters**," *IEE Proc.-Electr. Power Appl.*, Vol. 148, No. 5, pp. 403–409.2001

[3] Cheng, K. W. E. and Y. Ye . "**Duality Approach to the Study of Switched-Inductor Power Converters and Its Higher-Order Variations**." *IET Power Electronics*, Vol. 8(4), pp. 489-496. 2015

[4] M. Delshad, "**A New Zero Voltage Switching Buck Boost Type DC-DC Converter"** *Majlesi Journal of Electrical Engineering*, Vol. 4(1), 2010

[5] N.Vahidfar and M.H. Ershadi, "**Sliding Mode Controller Design of DC-DC Quasi Z-Source Converter**" *Signal Processing and Renewable Energy*, Vol. 2, pp. 21-26, 2018

[6] Y, Ye. and K. W. E. Cheng . "**A Family of Single-Stage Switched-Capacitor Inductor PWM Converters**." *IEEE Transactions on Power Electronics*, Vol. 28, No.11, pp. 5196-5205.2013.