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Neuro Fuzzy Based Auxilary Switch Control of a Bidirectional DC-D Converter

Manoj Kumar. R[1], Dr. A. Satheesh[2]

1PG scholar, Nandha Engineering College, Erode, Tamil Nadu, India

2Dean /EEE, Nandha Engineering College, Erode, Tamil Nadu, India

Abstract: ***The auxiliary switch control using a neuro fuzzy technique is proposed to enhance the efficiency of bidirectional converter used in electric vehicle which performs soft switching. Continuous current data are difficult to obtain during a resonant operation due to limit of DSP ADC capacity. The auxiliary switch control has a lookup table reference of the turn on time. The ANFIS controller properly controls the auxiliary switch turn on time according to the required load current, this auxiliary switch control brings the more efficient control in generative and regenerative more operation.***

Keywords: Auxiliary switch control, electric vehicle, lookup table (LUT), resonant type of bidirectional converter, soft switching.

1. Introduction

In recent years, the environmental and economical benefits from commercial electric vehicles have stimulated global interest in developing electric vehicles. To improve the efficiency of electric vehicles, the auto industry has financially invested significantly in batteries, various types of charging equipments, inverters and bidirectional dc/dc converters, and traction motors for EVs. Among them, various topologies for the bidirectional dc/dc converter have been proposed for many EVs. The bidirectional dc/dc converter on board electric and hybrid vehicles should boost the low voltage of batteries to the high voltage of the inverter dc-link . It should also be operated in the buck mode to charge the battery bank with regenerative energy during vehicle deceleration and braking.

The importance of a bidirectional dc–dc converter is getting increased. Because the structure of the converter is simple, and its control is comparably easy, it is used as the topology of conventional bidirectional converter. However, the drawbacks of the conventional bidirectional dc–dc converter are the large switching losses and the long reverse recovery time of antiparallel diodes. Particularly, during the reverse recovery time of the diodes, it can be caused of circuit damage and electromagnetic interference problems due to high current spikes. Thus, in order to improve the shortcomings of conventional pulse width modulation (PWM) methods, and increase the efficiency of the system, the study using series resonance, parallel resonance, and quasi-resonance methods have progressed. However, due to the common characteristic of resonant converter, lots of conduction losses occur because of high circulating energy. To overcome the drawbacks of the resonant converter, the zero voltage transition (ZVT) and zero current transition (ZCT) methods are proposed. The ZVT and ZCT methods are that switches turning ON and turning OFF under zero voltage and zero current condition using resonance. The ZVT and ZCT methods can be applied to the conventional bidirectional dc–dc converter through adding auxiliary circuit to the converters. However, since the added auxiliary circuit is operated under hard-switching condition, the other losses occur. Moreover, lots of other circuits are weak in high resonant current and voltage, and the range of load for resonant circuit is limited. The composition of the proposed resonant bidirectional dc/dc converter is an auxiliary circuit added form to the conventional bidirectional buck–boost converter. The fundamental operation equals the conventional bidirectional buck–boost converter. The resonance of the proposed converter is caused by the resonant capacitor and inductor of the auxiliary circuit. The auxiliary switch is operated in boost mode and buck mode. The soft switching is carried out by the main switches, diodes, and auxiliary switches.

2. Operation Mode Analysis

A. Configuration

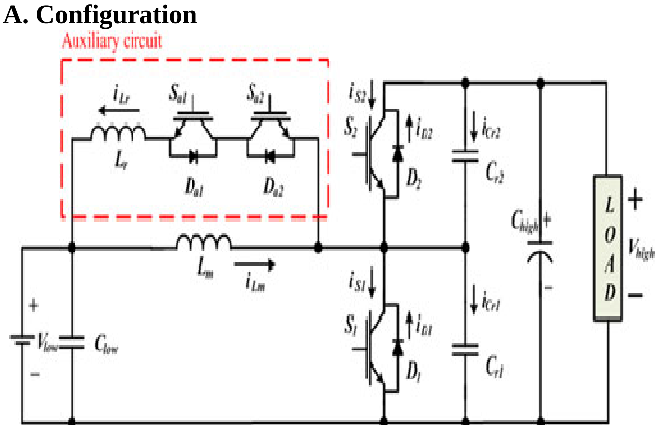

Figure 1: Proposed bidirectional soft-switching dc/dc converter

Fig. 1 shows the proposed bidirectional soft-switching dc–dc converter, which is formed by adding one resonant inductor, two resonant capacitors, and two switches to the conventional bidirectional converter circuit. The soft-switching operation occurred by energizing Lrin the auxiliary circuit with the voltage difference $V_{high}-V_{low}$ just before turning ON the main switch. In order to maintain the voltage across Lrwith $V_{high}-V_{low}$ before the main switch is turned ON; theupper converter should be operated in continuous conduction mode. The boost mode operation of the proposed system is depicted in the next section, and has seven operational modes. The description of boost mode is provided, as well as the mathematical equations that represent boost mode. The mathematical equations can be derived from an equivalent circuit of mode.

B. Operation Mode

MODE 1 ($t_0 \leq t < t_1$): At $t=t_0$, both switches S_1 and S_{a1} are in turn-off state. When the S_{a1} is turned ON, mode 1 is started. Since the resonance of L_r , any current is not flowing through S_{a1} , and the switch is turned ON under the ZCT condition. During this mode, i_{Lr} is increased by the current flowing through Lm and the antiparallel diode of S_{a2}, and it can be described as (1)–(5). When the same amount of current is flowing though Lm and L_r , this mode is finished.

$i_{Lm}(t_0) = I_{Lm\_0}$, $i_{Lr}(t_0) = I_{Lr\_0} = 0$ (1)
$V_{Cr1}(t_0) = V_{high}$, $V_{Cr2}(t_0) = 0$ (2)
$i_{Lm}(t) = 1/L_m(V_{low} - V_{high})(t - t_0) + I_{Lm\_0}$ (3)
$i_{Lr}(t) = 1/L_r(V_{high} - V_{low})(t - t_0) + I_{Lr\_0}$ (4)
$i_{Lm}(t_1) = I_{Lm\_1}$, $i_{Lr}(t_1) = I_{Lr\_1} = I_{Lm\_1}$ (5)

MODE 2 ($t_1 \leq t < t_2$): When i_{Lr} is larger than i_{Lm}, mode 2begins. Due to the continuity of i_{Lr}, the resonance between $S_1$and the output capacitor of S_2 is started. Two switches S_1 andS_2 are in turn-off state, and as the capacitor C_{r1} is charged anddischarged, i_{Lm} and resonant capacitor current flow throughL_r . As a result, the voltage across S_1 and S_2 is decreased and increased complementary due to the resonance. It can be described through (7). When the voltage across S_1 becomes 0 V, and that of S_2 is equal to V_{high}, the resonance between C_{r1} and$L_r$is finished. Moreover, i_{Lr} is getting decreased.

$i_{Lr}(t_1) = I_{Lr\_1} = I_{Lm\_1}$ (6)
$i_{Lm}(t_1) = I_{Lm\_1} = I_{Lm\_2}$ (7)
$i_{Lr}(t) = ((V_{high} - V_{low})/Z_r)\sin\omega_r(t - t_1) + I_{Lr\_1}$ (8)
$V_{Cr1}(t) = V_{low} + (V_{high} - V_{low})\cos(\omega_r(t - t_1))$ (9)
$V_{Cr2}(t) = V_{high} - V_{Cr1}(t)$ (10)
$C_r = C_{r1} + C_{r2}$ (11)
$\omega_r = 1/\sqrt{L_r C_r}$, $Z_r = \sqrt{L_r C_r}$ (12)

MODE 3 ($t_2 \leq t < t_3$): Even though the i_{Lr} is getting decreased from mode 2, since the amount of i_{Lr} is still larger than that of L_m, the continuity of current is maintained. Thus, the surplus i_{Lr} is flowing through the antiparallel diode of S_1. Since the surplus current is flowing through the antiparallel diode of S_1 , the voltage across S_1 is equal to zero, and the switch can be turned ON under the ZVT condition. In this mode, i_{Lr} and i_{Lm} are depicted with following equations, and when the same amount of current is flowing through those two inductors, L_m and L_r, mode 3 is finished.

$i_{Lm}(t) = 1/L_m(V_{low}.(t - t_2)) + I_{Lm\_2}$ (13)
$i_{Lr}(t) = -1/L_r(V_{low}.(t - t_2)) + I_{Lr2}$ (14)
$i_{Lr}(t_3) = I_{Lr\_3} = I_{Lm\_3}$ (15)

MODE4 ($t_3 \leq t < t_4$): At the beginning of this mode, the main switch S_1 is turned ON under the ZVT condition. As the main inductor current is increased linearly, the main switch current is increased as well. At the end of this mode, the resonant inductor is discharged completely and the current of the auxiliary switch becomes 0 A.

$i_{Lm}(t) = 1/L_m(V_{low}.(t - t_3)) + I_{Lm\_3}$ (16)
$i_{Lr}(t) = -1/L_r(V_{low}.(t - t_3)) + I_{Lr\_3}$ (17)

MODE5 ($t_4 \leq t < t_5$): Since any current is not flowing through S_{a1} , the current loop is exactly same as that of the conventional bidirectional dc–dc converter in boost mode. That is, the main inductor current is flowing through S_1 , and the main inductor current is increased. When $t=t_5$, S_1 is turned OFF under the ZVT condition due to the resonance of C_{r1} , and the auxiliary switch S_{a1} is turned OFF under the ZCT condition. When the two switches are turned OFF, this mode is finished.

$i_{Lr}(t_4) = 0$ (18)
$i_{Lm}(t) = 1/L_m(V_{low}.(t - t_4)) + I_{Lm\_4}$ (19)

MODE6 ($t_5 \leq t < t_6$): In mode 6, the main inductor current is flowing through S_1, C_{r1} consistently. The voltage across S_1 is increased meanwhile the voltage across S_2 is decreased, and the equations are given. When the voltage across S_1 is equal to output voltage, S_2 is turned ON under the ZVT condition. Note that C_r means $C_{r1}+C_{r2}$ as (11), and the parameter of these two capacitors should be almost same for correct ZVT condition

$i_{Lm}(t) = I_{Lm5} = I_{Lm6}$ (20)
$i_{Lr}(t) = 0$ (21)

MODE 7 ($t_6 \leq t < t_7$): When the antiparallel diode of S_2 is conducted, mode 7 is started. The main inductor current is decreased until S_{a1} is turned ON, and it can be described as (24). When current is flowing through the antiparallel diode of S2, the ZVT turning-on and ZVT turning-off conditions are qualified. Moreover, since the current flows through the antiparallel diode of S2, the current path is secured, and loss is reduced. That is, the turning-on loss of the diode is larger than that of RDS (ON) conduction loss. This method is called the synchronous rectifying method, and the method can be applied to the topologyoperating in boost mode and buck mode as well

$i_{Lm}(t) = 1/L_m((V_{low} - V_{high})(t - t_6) + I_{Lm\_6}$ (22)
$i_{Lm}(t_7) = I_{Lm\_7} = I_{Lm\_0}$ (23)

Fig.2 shows the key waveforms of each component in the boost mode, and each waveform depicts the operational characteristic of each component in the ideal condition.

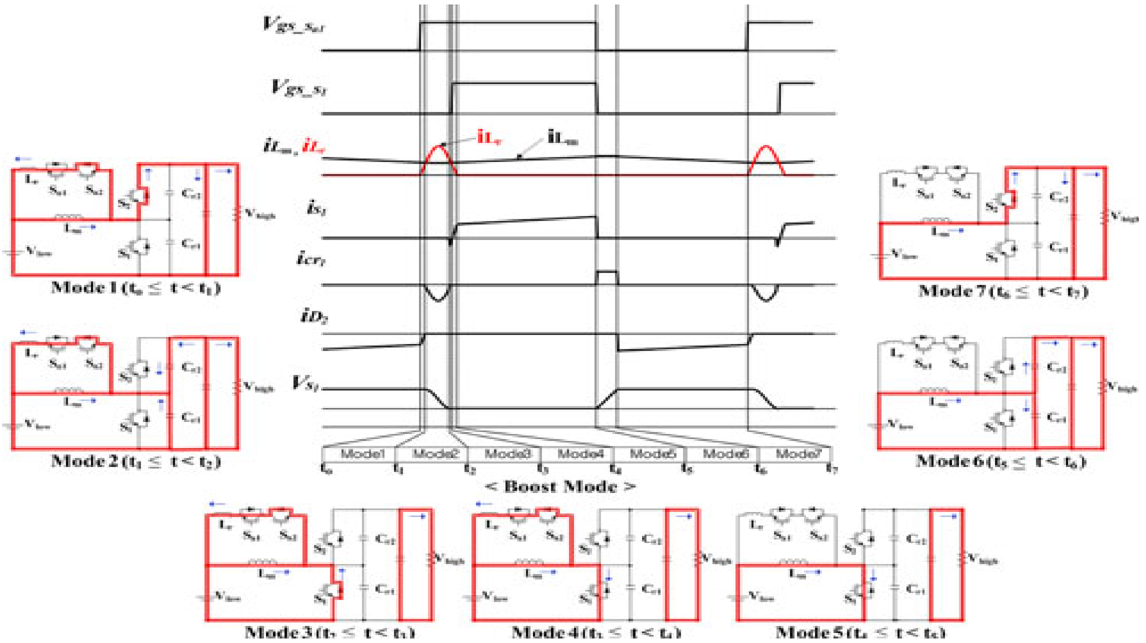

Figure 2: Operation mode and key waveforms of the proposed converter in boostmode

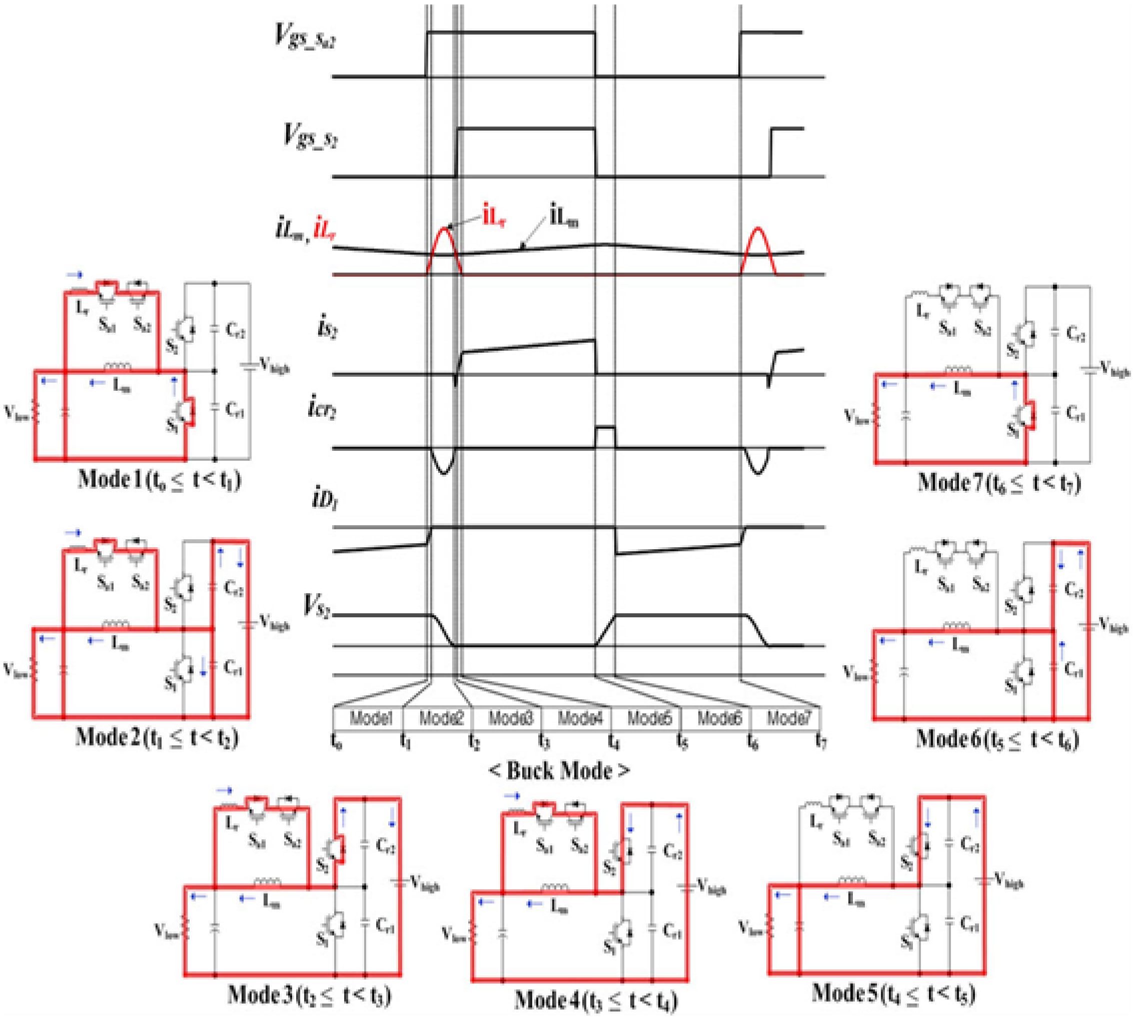

Figure 3: Operation mode and key waveforms of the proposed converter in buck mode

Similar to the boost mode, the buck mode can be classified into seven modes. The operational characteristic is almost the same as that of the boost mode since the buck mode operates in complement with the boost mode. However, the two switches *S2* and *Sa2* are activated in the buck mode operation.

C. Control Configuration

In a vehicle application, the bidirectional dc/dc converter is operated in either the buck or the boost mode depending on the driving condition. The buck–boost control method using only a single voltage controller has advantage of a soft mode change according to the flow of the dc-link energy. But when the mode is changed, the discontinuous period occurs due to the addition of the auxiliary circuit. If the voltage control is only applied in this system, the soft-switching condition is not operated. Therefore, it is operated with the buck and boost mode control independently for the soft switching. Fig.2.6 shows the overall control diagram of the proposed bidirectional dc/dc converter. In the boost mode, the output of the voltage controller is compared with a triangle wave and this duty signal controls the main switch $S1$. Contrast to the boost mode, the buck mode controller is for current control of the main inductor. In the buck mode, $S2$ switch is on–off switching for the current regulation of the main inductor. As same as the main switches, auxiliary switches are also controlled with the buck mode and boost mode operation. Auxiliary switch $Sa1$ is for soft-switching operation of boost mode and $Sa2$ is for the same operation of buck mode. The signals of the auxiliary switches $Sa1$ and $Sa2$ are generated by each LUT.

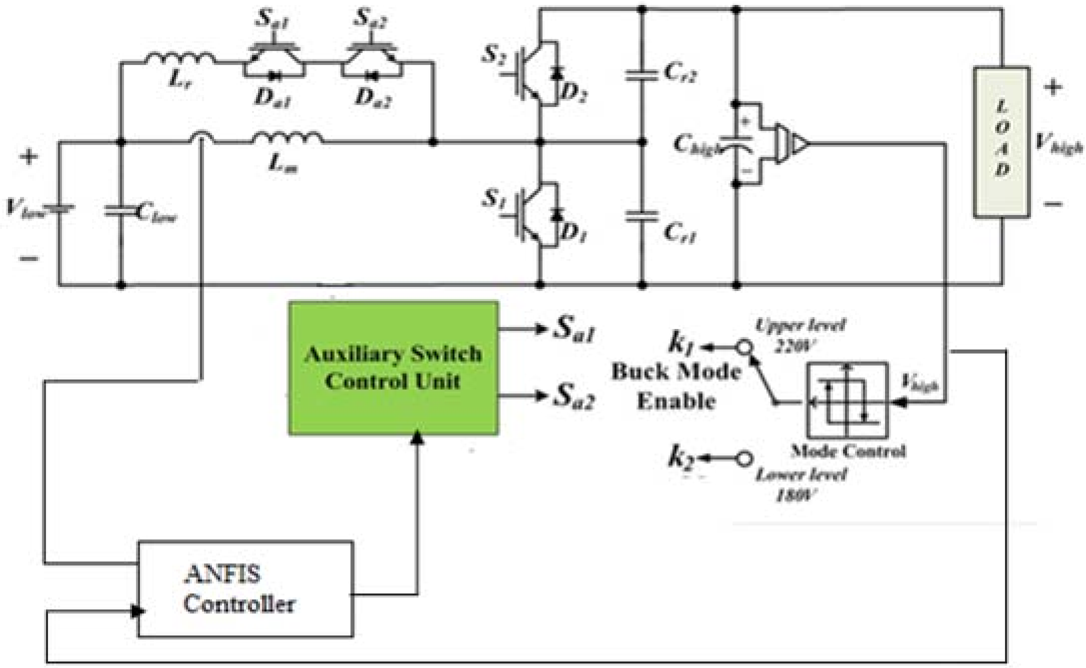

Figure 4: Control diagram of the applied bidirectional dc/dc converter

3. Neuro-Fuzzy Controller

Fuzzy systems and neural networks have attracted the interest of researchers in various scientific and engineering areas. The number and variety of applications of fuzzy logic and neural networks have been increasing, ranging from consumer products and industrial process control to medical instrumentation, information systems and decision analysis.

The main idea of fuzzy logic control (FLC) is to build a model of a human control expert who is capable of controlling the plant without thinking in terms of a mathematical model. The control expert specifies his control actions in the form of linguistic rules. These control rules are translated into the framework of fuzzy set theory providing a calculus which can simulate the behavior of the control expert. The specification of good linguistic rules depends on the knowledge of the control expert, but the translation of these rules into fuzzy set theory framework is not formalized and arbitrary choices concerning, for example, the shape of membership functions have to be made. The quality of fuzzy logic controller can be drastically affected by the choice of membership functions. Thus, methods for tuning fuzzy logic controllers are necessary. Neural networks offer the possibility of solving the problem of tuning. Although a neural network is able to learn from the given data, the trained neural network is generally understood as a black box. Neither it is possible to extract structural information from the trained neural network nor can we integrate special information into the neural network in order to simplify the learning procedure. On the other hand, a fuzzy logic controller is designed to work with the structured knowledge in the form of rules and nearly everything in the fuzzy system remains highly transparent and easily interpretable. However, there exists no formal framework for the choice of various design parameters and optimization of these parameters generally is done by trial and error.

A combination of neural networks and fuzzy logic offers the possibility of solving tuning problems and design difficulties of fuzzy logic. The resulting network will be more transparent and can be easily recognized in the form of fuzzy logic control rules or semantics. This new approach combines the well established advantages of both the methods and avoids the drawbacks of both. In this paper, a neuro-fuzzy controller architecture is proposed, which is an improvement over the existing neuro fuzzy controllers. It overcomes the major drawbacks of the existing neuro-fuzzy approaches; of either keeping neural networks and fuzzy logic as separate entities (co-operative models) working towards a common goal or in most of the existing neurofuzzy approaches, the trained controller no longer can be interpreted as fuzzy logic controller. The novelty of this scheme is that the fuzzy controller itself is interpreted as a neural network. So, an error in the resulting control value can be distributed back among the control rules, instead of the integrating neural networks in certain parts of the controller, acting as black boxes to optimize the weights. One of the objectives of this paper is to understand adaptation of the membership functions as a reverse mechanism deduced from the forwarding inference machinery of the fuzzy logic controller.

4. Simulation Results

The simulation of the DC-DC converter with ANFIS controller is shown in figures. The simulation consists of two sub system which has also shown in the figure.

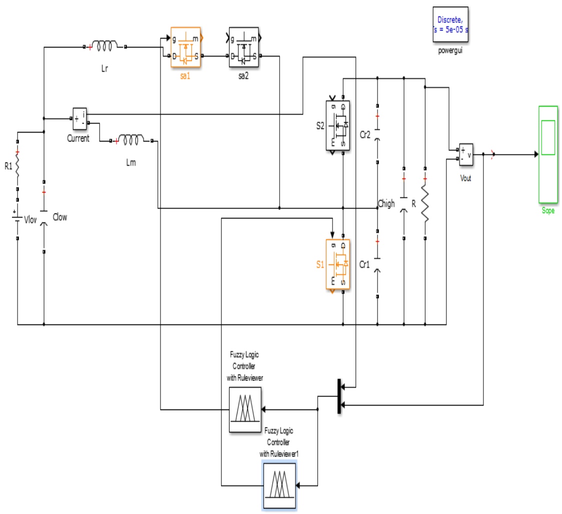

Figure 5: Simulation diagram for the boost mode

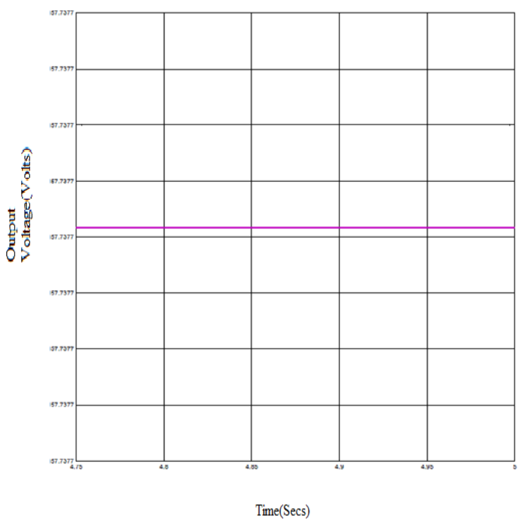

Figure 6: Output for the boost mode

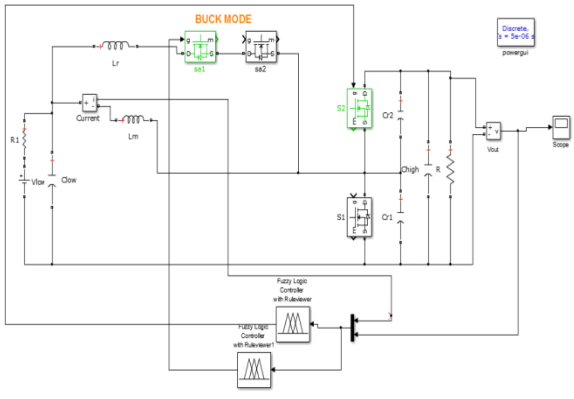

Figure 7: Simulation diagram for the buck mode

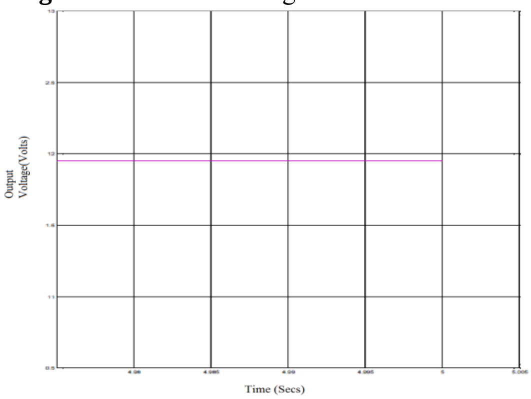

Figure 8: Output for the buck mode

5. Conclusion

In this paper, the auxiliary switch control method for a new bidirectional ZVZCT converter is proposed. Two unidirectional ZVZCT dc/dc converter topologies are combined by auxiliary circuit switches; ZVZCT bidirectional power flow is achieved by the proposed dc/dc converter. To control this bidirectional dc/dc converter with ZVZCT condition, buck and boost mode operation for a discrete voltage controller is illustrated in this paper. Moreover, to achieve more efficiency from a conventional ZVZCT converter, an auxiliary switch control method corresponding to the load condition is illustrated. Because of the resonant current sensing problem, the conventional control method cannot adapt this auxiliary switch control method. However, with the LUT for auxiliary switch control angle data, the proposed converter has more efficiency than the conventional control method especially under the rated load condition. The proposed control method and topology are verified by the mathematical analysis and simulation for experiment. From these results, the proposed bidirectional converter with the auxiliary control method achieves more efficiency than the conventional control method.

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