The paper introduced a new zero voltage transition (ZVT) interleaved flyback converter which has two similar flyback converters. Two flyback converters are in parallel connection and auxiliary circuit in this converter provides ZVT condition for all of the main switches and also provides zero current switching and zero voltage zero current switching (ZVZCS) conditions for the auxiliary switch. Also, ZCS conditions are created for diodes turning off, so reverse recovery problem is solved. The auxiliary circuit in the suggested converter is modular, and by adding parallel branches to the flyback circuit, this circuit can provide soft switching conditions for all switches without significantly change. A complete analysis of the converter is provided and its operating intervals are explained. A 180 W laboratory prototype of the converter is made to approve the theoretical calculations. The experimental results show 7.7% increase in efficiency.
diodes are reduced, but the switch voltage is higher than 2Vin. A zero-voltage interleaved buck converter is offered in [21] in which there is an active switch in its auxiliary circuit structure. In suggested converter, each the semiconductor devices achieve soft switching operation but the converter has numerous auxiliary elements and the auxiliary switch has high voltage and current stresses. With two transformers in a ZVS interleaved flyback converter, the over-size problem of the transformer is eliminated and the converter efficiency is prospered. The major demerit of this converter is the dependency of soft switching condition to the load. In such a way that ZVS condition in light load is eliminated [22].

A new interleaved half-bridge flyback converter with ZCT technique in [23] is presented and the efficiency prospered and also the switching-off losses reduced. Parameter variations lead to a power imbalance problem in the proposed ZCS interleaved converter. A ZVS parallel interleaved current-double converter which reduces the current stress and the current ripple is recommended in [24]. Furthermore, on account of the coupling of the output inductors, the number of the output inductors and the output current ripple are decreased. Many numbers of magnetizing components, high conduction losses and duty cycle losses are the disadvantages of the converter. Types of non-isolated converters like as boost, buck, and buck–boost are illustrated in [25], [26] in which a conventional auxiliary circuit has applied. The ZVT auxiliary circuit only uses an auxiliary switch which creates soft switching conditions for two main switches of interleaved structure. The most important problem in the suggested circuit [25] is the intense voltage stress in its auxiliary switch, which increases the RDS (on) of the auxiliary switch and as a result increases its conduction losses and converter [26] problems are that the number of auxiliary circuit components is numerous and the voltage stress on the auxiliary switch is measured also intensive.

In this study, a new auxiliary circuit for an interleaved flyback converter has presented so that it can be extended to more parallel branches and because of the low number of elements, soft switching of elements and low circulating current of the auxiliary circuit, this circuit does not inflict considerable losses on the converter. Since all converter diodes also turn off under ZCS conditions, there is no problem of reverse recovery in this converter. For this reason, the efficiency compared to previous converters has increased significantly. In part 2, the ZVT interleaved flyback converter operating analysis is provided. Design technique of the converter is proposed in part 3 and the control circuit of this converter is proposed in part 4. Experimental results of the suggested proposed ZVT interleaved flyback converter have exhibited in part 5. Part 6 compares the efficiency of the ZVT interleaved flyback converter with a conventional interleaved flyback converter.

2. CIRCUIT DESCRIPTION AND OPERATION

2.1. Circuit structure

The introduced converter has exhibited in Figure 1 which is composed of the main switches M1 and M2, the output diodes D01 and D02, output filter capacitor Co, two isolating transformers which consist of primary windings Lp1 and Lp2, leakage inductances Lk1 and Lk2, and secondary windings Ls1 and Ls2. The auxiliary circuit has an auxiliary switch Ma, auxiliary inductor La, auxiliary diodes Da and Db, and auxiliary winding Lb coupled to the main winding, a capacitor Cs, snubber diodes Ds1 and Ds2, and snubber capacitor Cs. The first isolating transformer includes the primary winding Lp1, the secondary winding Ls1 and the auxiliary winding Lb. The second isolating transformer includes the primary winding Lp2 and the secondary winding Ls2. The turn ratio of Lp1/Ls1 is n/s1 and the turn ratio of Lp2/Ls2 is n/s2.

Figure 1. The suggested ZVT Interleaved flyback converter
2.2. Operating of the suggested converter

The checking of the suggested converter can be simplified, therefore the following assumptions have presented: i) All elements design ideal; ii) The capacitor \( C_b \) has a large value, in order that the output voltage can be fixed; iii) The Capacitor \( C_b \) has a large value, in order that its voltage can be fixed and identical to \( V_{cb} \); and iv) Magnetizing inductances \( L_m1 \) and \( L_m2 \) are same and large, thus the current \( I_{Lm} \) is considered fixed:

\[
L_m1 = L_m2 = L_m.
\]

To evaluate the suggested converter, the first 9 intervals of the converter are fully analyzed. The equivalent circuit of each of the 9 intervals has exhibited in Figure 2. Figure 3 indicates the key waveforms of the operating intervals. Before the interval 1: It can be presumed that the main switches \( M_1 \) and \( M_2 \) are off and diodes \( D_{o1}, D_{o2} \) and \( D_b \) are on and transmit current, and so the snubber capacitor voltage \( V_{Cs} \) is identical to \( V_{in} + V_o/n \) and the capacitor voltage \( V_{Cb} \) is identical to \( mV_o \).

![Figure 2. Equivalent circuit of the operation intervals](image-url)
Interval 1 \([t_0-t_1]\): At the beginning, the auxiliary switch \(M_a\) turns on under ZCS condition, because an auxiliary inductor \(L_a\) with the auxiliary switch \(M_a\) are in series. Because of the output diodes \(D_{o1}\) and \(D_{o2}\) conduct, the constant voltage \(mV_o+V_c/n\) is placed across \(L_{k1}\) and \(L_a\) and also across \(L_{k2}\) and \(L_a\). Therefore, the snubber circuit diodes \(D_{s1}\) and \(D_{s2}\) start to conduct and the auxiliary switch current \(I_{Ma}\) increases linearly. Since the values of \(L_{k1}\) and \(L_{k2}\) are small, in this interval snubber capacitor voltage \(V_{Cs}\) has considered constant and identical to \(V_o+V_c/n\), therefore the auxiliary switch current \(I_{Ma}\) is calculated from (1).

\[
I_{Ma}(t) = \frac{V_o(m+1)}{L_a} (t - t_0)
\]

(1)

\[
n = \sqrt{\frac{t_{p1}}{t_{p2}}} = \sqrt{\frac{t_{s1}}{t_{s2}}}
\]

(2)

\[
m = \sqrt{\frac{i_c}{i_a}}
\]

(3)

By increasing the auxiliary switch current \(I_{Ma}\), current in output diodes \(D_{o1}\) and \(D_{o2}\) is reduced and when the auxiliary switch current \(I_{Ma}\) achieves \(I_{lm1}+I_{lm2}\), the output diodes \(D_{o1}\) and \(D_{o2}\) turn off with ZCS and current mode finishes. Duration of this mode is:

\[
\Delta t_1 = t_1 - t_0 = \frac{2L_m i_{la}}{V_o(m+1)}
\]

(4)

Figure 3. Key waveforms of the suggested ZVT interleaved flyback converter

Interval 2 \([t_1-t_2]\): The output diodes \(D_{o1}\) and \(D_{o2}\) turn off under ZCS condition as soon as the interval starts and then the snubber capacitor \(C_s\) begins to resonate with \(L_a\) and its energy has transferred to capacitor \(C_b\). Important equations of this interval are:

\[
I_{Ma}(t) = \frac{V_o(m+1)}{Z_o} \sin(w_o(t - t_1)) + 2I_{lm}
\]

(5)
\[ V_{Cs}(t) = V_o \left( m + \frac{1}{n} \right) \cos(\omega_o(t - t_3)) + (V_{in} - mV_o) \]  

(6)

where:

\[ Z_o = \frac{L_o}{C_s} \]  

(7)

\[ \omega_o = \frac{1}{\sqrt{L_o C_s}} \]  

(8)

Because the anode voltage of \( D_b \) is less than \((V_{in} + V_o/n)/2\), the resonance stops after half a cycle and at the finale of this interval the capacitor \( C_s \) has fully discharged and this mode ends. Then, the duration of current interval can be derived:

\[ \Delta t_2 = t_2 - t_1 = \pi \sqrt{L_o C_s} \]  

(9)

Interval 3 \([t_2-t_3]\): With complete discharge of \( C_s \), the body diodes of the main switches \( M_1 \) and \( M_2 \) (\( D_{b1} \) and \( D_{b2} \)) start to conduct under ZV. Therefore, the constant voltage \( V_{in} - mV_o \) is reversed across the auxiliary inductor \( L_a \) and the auxiliary switch current \( I_{Ma} \) reduces linearly. The main switch \( M_1 \) can turn on with zero-voltage. This interval ends by turning the body diodes of the main switches \( M_1 \) and \( M_2 \) (\( D_{b1} \) and \( D_{b2} \)) off. Whenever the auxiliary inductor current \( I_a \) is identical to \( I_{Ma} + I_{Ma} \), the body diodes of the main switches \( M_1 \) and \( M_2 \) (\( D_{b1} \) and \( D_{b2} \)) have turned off. The following \( 10 \)-\( 11 \) obtain the auxiliary switch current \( I_{Ma} \) and the duration of this interval:

\[ I_{Ma}(t) = I_{Ma}(t_2) - \frac{V_{in} - mV_o}{L_a}(t - t_2) \]  

(10)

\[ \Delta t_3 = t_3 - t_2 = \frac{I_{Ma}(t_2)}{V_{in} - mV_o} \]  

(11)

Interval 4 \([t_3-t_4]\): Current transmission from the body diode of the main switch \( M_1 \) to the main switch \( M_1 \) occurs and increases linearly with the same slope and the body diodes of the main switches \( M_1 \) and \( M_2 \) (\( D_{b1} \) and \( D_{b2} \)) turn off with ZCS. While the current of the main switch \( M_1 \) achieves \( I_{lm1} \), finally the snubber diode \( D_{s1} \) turns off with ZCS. The main switch current \( I_{M1} \) and the time of this interval are derived from \( 12 \)-\( 13 \).

\[ I_{M1}(t) = \frac{V_{in} - mV_o}{L_a}(t - t_3) \]  

(12)

\[ \Delta t_4 = t_4 - t_3 = \frac{I_{lm1}}{V_{in} - mV_o} \]  

(13)

Interval 5 \([t_4-t_5]\): This interval starts as soon as the snubber diode \( D_{s1} \) turns off and the \( I_{lm1} \) current charges the capacitor \( C_s \) linearly. Also, current of the auxiliary switch \( M_3 \) charges the auxiliary switch \( M_3 \) turns off under ZVZC condition on account of the presence of capacitor \( C_s \) and the auxiliary circuit entirely exits from the converter. Also the current of the main switch \( M_1 \) is fixed and identical to \( I_{lm1} \).

Interval 6 \([t_5-t_6]\): In this mode, while the \( C_s \) capacitor voltage achieves to \( V_{in} + V_o/n \), the snubber diode \( D_{s2} \) turns off and the diode \( D_{o2} \) conducts, and the magnetizing inductance \( L_{m2} \) starts discharging to the output. Interval 7 \([t_6-t_7]\): Interval 7 occurs simultaneously as the main switch \( M_1 \) is turned off, and the magnetizing inductance \( I_{lm1} \) charges the snubber capacitor \( C_s \) and the output diode \( D_{o1} \) has also turned on under ZCS condition. The equation of duration is expressed as:

\[ V_{Cs}(t) = \frac{I_{lm1}}{C_s}(t - t_5) + (V_{in} - mV_o) \]  

(14)

\[ \Delta t_6 = t_6 - t_5 = \frac{V_o(m + 1/2)}{L_m} \]  

(15)

Interval 8 \([t_7-t_8]\): The auxiliary diode \( D_b \) turning on occurs at the beginning of this interval. Because both of the main switches \( M_1 \) and \( M_2 \) are off, the magnetizing inductances are discharged to the output. In this mode, the resonance occurs between the leakage inductance of the transformer \( L_{l1} \) and the snubber capacitor \( C_s \) and the voltage of the main switch \( M_1 \) is increased resonating. This interval ends with the complete discharge of the leakage inductance \( L_{l1} \). Finally, the main switch voltage \( (V_{M1}) \) and transformer leakage inductance current \( (I_{l1}) \) expressions for this interval are as follows:
\[ V_{M1}(t) = V_{in} + V_0/n + Z_1 I_{Lm} \sin(\omega_1(t - t_6)) \]  
(16)

\[ Z_1 = \frac{l_{k1}}{c_s} \]  
(17)

\[ I_{Lk1}(t) = I_{Lm} \cos(\omega_1(t - t_6)) \]  
(18)

Where:

\[ \omega_1 = \frac{1}{\sqrt{l_{k1} c_s}} \]  
(19)

Duration of this interval is:

\[ \Delta t_7 = t_7 - t_6 = \frac{\pi}{2} \]  
(20)

Interval 9 [t_8-t_9]: by fully discharging the energy of the transformer leakage inductance \( L_{k1} \) and turning snubber circuit diode \( D_{s1} \) off under ZCS condition, this interval begins and therefore voltage across the main switch \( M_1 \) decreases to a fixed amount and identical to \( V_{in} + V_0/n \), and similar to a regular flyback converter in off switch mode, both magnetizing inductances are discharged to the output.

3. DESIGN METHOD

In this part, the design of the converter is discussed. The converter has prepared for 300V input voltage, 40V output voltage, and 180W output power. Switching frequency can be selected at 100kHz. The turn ratio of \( L_{b}/L_{s1} \) should be selected in such a way that the anode voltage of \( D_{b} \) is less than \((V_{in} + V_0)/2\). If \( L_b \) turns is defined as \( n_b \) and \( L_{s1} \) turns as \( n_{s1} \) and \( L_{s2} \) turns as \( n_{s2} \), then:

\[ V_{A}(D_{D}) = V_{in} - V_{cD} = V_{in} - mV_0 \]  
(21)

The snubber capacitor \( C_s \) is selected like a turn-off snubber capacitor according to (22)-(23) [27].

\[ C_s > C_{Smin} = \frac{l_{sw} \cdot t_f}{2 \cdot V_{sw}} \]  
(22)

\[ C_b = \frac{100 I_{Lm} D_{Mmax}}{m V_{of}} \]  
(23)

It can be presumed that the switch current fall time is indicated by abbreviation \( t_f \). \( I_{sw} \) is the switch current before the switch is turned off and \( V_{sw} \) is the switch voltage after the switch is turned off. To prove soft switching in practice, the snubber capacitor \( C_s \) should be much greater than \( C_{Smin} \). To prove the snubber capacitor \( C_s \) discharge, the amount of \( C_b \) should be greater than \( C_s \). \( D_a \) is designed like a turn-on snubber. For appropriate selection of \( D_a \), there is a relationship between \( M_a \) maximum current and \( D_{max} \) which can be indicated by:

\[ D_{max} = \frac{T - \frac{2 l_{Lm} I_a}{V_0(m + \frac{1}{n})} - \pi \sqrt{l_{Lm} c_s}}{T} \]  
(24)

\( L_b \) should be much greater than \( L_a \). The maximum current and voltage of auxiliary switch \( M_a \) are obtained as follows:

\[ I_{Ma max} = \frac{V_0(m + \frac{1}{n})}{Z_0} + I_{Lm} \]  
(25)

\[ V_{Ma max} = \frac{V_0(m + \frac{1}{n})}{Z_0} + \sqrt{\frac{l_{Lm}}{C_s} I_{Lm}} \]  
(26)

4. CONTROL CIRCUIT

The closed loop system digital control circuit of the suggested converter is exhibited in Figure 4. A SPARTAN-6 FPGA is selected as the PI digital controller hardware. The output voltage feedback is directed to the analog-to-digital converter (ADC), and then the output of the ADC converter is appraised with the reference voltage (\( V_{ref} \)). The error voltage (\( V_{error} \)) is directed to the PI digital controller which produces the
necessary control signal. Then this signal is entered to the digital pulse width modulation (DPWM) generator to create the switching gate signals necessary for the three converter switches.

**Figure 4.** The suggested interleaved flyback converter with implemented digital control circuit

### 5. EXPERIMENTAL RESULTS

A new ZVT interleaved flyback converter has demonstrated. The picture of the tested converter has exhibited in Figure 5. The design values and components of the converter are exhibited in Table 1. In the Figure 6(a), gating signals waveforms of main switches and auxiliary switch is displayed. The ZV conditions for the main switches are illustrated in Figures 6(b) and 6(c). At the turn on instant of the main switches, their currents are negative and the body diodes are conducting, therefore the main switches can turn on under ZV. The ZCS condition for the auxiliary switch is illustrated in Figure 6(d). The auxiliary switch current increases with the slope, thus the auxiliary switch can turn on with ZCS. The auxiliary switch current decreases with the slope and also the voltage has identical value to zero, therefore the auxiliary switch can turn off with ZVZCS technique. The output diodes are also soft switched as shown in Figures 6(e) and 6(f). The output diodes can turn on and off with ZCS. The operation of this converter is justified by the experimental results.

**Figure 5.** Picture of the implemented ZVT interleaved flyback converter

| Parameter             | Value          |
|-----------------------|----------------|
| Output power ($P_o$) | 180W           |
| Input voltage ($V_{in}$) | 300V          |
| Output voltage ($V_o$) | 40V           |
| Main switches switching frequency ($f_m$) | 100kHz        |
| Load resistance ($R_o$) | 10Ω           |
| MOSFET power switches (M) | IRFP460B    |
| Power diodes           | MUR860        |

| Parameter             | Value          |
|-----------------------|----------------|
| Leakage inductances ($L_1$ and $L_2$) | 4 μH         |
| Auxiliary inductor ($L_a$) | 5μH           |
| Output filter capacitor ($C_o$) | 100μF        |
| Filter capacitor ($C_b$) | 10μF          |
| Snubber capacitor ($C_s$) | 2.7 nF       |
| Turn ratio (n) | 0.4           |
| Turn ratio (m) | 4             |
Figure 6. Experimental waveforms (a) The measured gaiting signals of the switches $M_1$ (top), $M_2$ (middle), $M_a$ (bottom) (voltage: 10 V/div; time: 2.5 μs/div), (b) The measured current (top) and voltage (bottom) of the main switch $M_1$ (voltage: 200 V/div; current: 2 A/div; time: 1 μs/div), (c) The measured current (top) and voltage (bottom) of the main switch $M_2$ (voltage: 400 V/div; current: 2 A/div; time: 1 μs/div), (d) The measured current (top) and voltage (bottom) of the auxiliary switch $M_a$ (voltage: 400 V/div; current: 4 A/div; time: 1 μs/div), (e) The measured current (top) and voltage (bottom) of the diode $D_{o1}$ (voltage: 80 V/div; current: 2 A/div; time: 1 μs/div), (f) The measured current (top) and voltage (bottom) of the diode $D_{o2}$ (voltage: 100 V/div; current: 5 A/div; time: 1 μs/div).
6. **EFFICIENCY**

Figure 7 shows the suggested ZVT interleaved flyback converter efficiency diagram and as well as the hard switching interleaved converter efficiency diagram. According to Figure 7, both efficiencies are designed for 180 W. The efficiency has measured at 5 various loads and when compared to the hard switching interleaved converter, the efficiency has increased by 7.7%. In Table 2, the losses of the suggested ZVT interleaved flyback converter with a hard switching interleaved flyback sample have compared. In the presented Table, the rise and fall times of the converter switches currents are indicated by abbreviations $t_r$ and $t_f$, respectively. Also, $t_{ov}$ can be considered as reverse recovery time of the diodes. In addition, $C_{out}$ can be defined as the switches output capacitance, $R_{ds}$ is supposed equivalent to the switches on state resistance, $V_f$ can be considered as a forward voltage of diodes, and $f_{sw}$ is switching frequency. Furthermore, all semiconductor elements can turn on and off with soft switching technique, accordingly switching losses have significantly declined.

![Figure 7. Evaluated efficiency of the suggested ZVT interleaved flyback converter versus conventional hard switching interleaved flyback converter](image)

**Table 2. Calculation of losses in hard switching interleaved flyback converter and the suggested ZVT interleaved flyback converter**

| Kinds of loss                              | Formula                                                                 | Hard switching interleaved flyback converter | Suggested converter |
|-------------------------------------------|-------------------------------------------------------------------------|---------------------------------------------|---------------------|
| Switching loss in $M_1$                   | $1/2 V_{out} I_{out} f_{sw}(t_r + t_f + t_{ov})$                         | $1/2 \times 400 \times 2.1 \times 400 \times 10^3 (31 + 56 + 437) \times 10^{-4}$ | N.A                 |
| Parasitic capacitance loss in $M_1$       | $1/2 C_{out} V_{out}^2 f_{sw}$                                          | $1/2 \times 131 \times 10^{-12} \times 400 \times 10^3$ | N.A                 |
| Conduction loss in $M_1$                  | $R_{ds} f_{sw} I_{out}$                                                 | $0.25 \times (1.65)^2$                      | $0.25 \times (1.6)^2$ |
| Switching loss in $M_2$                   | $1/2 V_{out} I_{out} f_{sw}(t_r + t_f + t_{ov})$                         | $1/2 \times 400 \times 2.1 \times 400 \times 10^3 (31 + 56 + 437) \times 10^{-4}$ | N.A                 |
| Parasitic capacitance loss in $M_2$       | $1/2 C_{out} V_{out}^2 f_{sw}$                                          | $0.25 \times (1.5)^2$                      | $0.25 \times (1.12)^2$ |
| Conduction loss in $M_2$                  | $R_{ds} f_{sw} I_{out}$                                                 | $0.25 \times (2.6)^2$                      | N.A                 |
| Switching loss in $M_s$                   | $1/2 V_{out} I_{out} f_{sw}(t_r + t_f + t_{ov})$                         | $0.25 \times (1.5)^2$                      | N.A                 |
| Parasitic capacitance loss in $M_s$       | $1/2 C_{out} V_{out}^2 f_{sw}$                                          | $0.25 \times (1.5)^2$                      | N.A                 |
| Conduction loss in $D_{o1}$               | $V_f L_{on} \times t_o$                                                 | $1.5 \times 2.3$                           | $1.5 \times 0.8$    |
| Conduction loss in diode $D_{o2}$         | $V_f L_{on} \times t_o$                                                 | $1.5 \times 2.3$                           | $1.5 \times 1$      |
| Conduction loss in diode $D_{o1}$         | $V_f L_{on} \times t_o$                                                 | $1.5 \times 2.3$                           | $1.5 \times 0.4$    |
| Conduction loss in diode $D_{o2}$         | $V_f L_{on} \times t_o$                                                 | $1.5 \times 2.3$                           | $1.5 \times 0.3$    |
| Conduction loss in diode $D_s$             | $V_f L_{on} \times t_o$                                                 | $1.5 \times 2.3$                           | $1.5 \times 0.8$    |
| Conduction loss in diode $D_o$             | $V_f L_{on} \times t_o$                                                 | $1.5 \times 2.3$                           | $1.5 \times 0.8$    |
| Conduction losses of magnetizing inductance $L_{on}$ | $R_{on} f_{sw}$            | $23.68 \times 10^3 \times (0.6)^2$       | $23.68 \times 10^3 \times (0.8)^2$   |
| Conduction losses of magnetizing inductance $L_{on}$ | $R_{on} f_{sw}$            | $23.68 \times 10^3 \times (0.6)^2$       | $23.68 \times 10^3 \times (0.66)^2$   |
| Total loss                                | 26.59 W                                                                 | 12.71 W                                    |                     |

7. **CONCLUSION**

This paper presents a new interleaved flyback converter with a modular auxiliary circuit to produce soft switching conditions for all semiconductor devices. The main switches of the converter operate under ZVT and the auxiliary switch turns off under ZVVC conditions. On the other hand, the input current ripple of the
converter is much less than the regular flyback converter due to its interleaved structure. Because of the few numbers of components, and low circulating current in the auxiliary circuit, this circuit does not inflict considerable losses on the converter. The practical results of the suggested converter exhibit a 7.7% increment in efficiency at full load versus the hard switching counterpart.

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