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Family of Isolated Zero Current Transition PWM Converters

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ABSTRACT

In this paper a family of zero current transition PWM converters which employs a simple auxiliary circuit is introduced. This soft switched auxiliary circuit is only composed of a switch and a capacitor. The proposed converters are analyzed and various operating modes of the ZCT flyback converter are discussed. Design considerations are presented and the experimental results of the ZCT flyback converter laboratory prototype are illustrated. The experimental results confirm the validity of theoretical analysis.

Key words: Isolated DC-DC converters, Zero Current Switching (ZCS)

1. Introduction

Isolated converters are vastly used in industry as power supplies. In regular isolated converters, the leakage inductance of transformer causes serious problems at switch turn off instant. In single switch isolated converters, such as forward and flyback, the energy of transformer leakage inductance is absorbed by the switch output capacitance at turn off instant and thus the switching losses are increased and high voltage spikes also appear across the converter switch. However, in full bridge and half bridge converters, the voltage across the switches is limited to input voltage, but the leakage inductance increases the switching losses of these converters too. Therefore, regular isolated converters usually suffer from high switching losses and Electro Magnetic Interference (EMI), which limits their operating power and switching frequency.

Soft switching techniques are proper solutions to decrease switching losses and EMI and to achieve higher power conversion density. Zero Voltage Transition (ZVT), Zero Current Transition (ZCT) and active clamp techniques provide soft switching conditions for regular PWM converters [1-4]. In these converters, an auxiliary circuit composed of an auxiliary switch and resonant elements is added which provides soft switching condition for the main switch at switching instants, and the converter behaves like a regular converter during the rest of period. Therefore, these converters have the advantages of regular PWM converters and also high efficiency and low EMI due to achieved soft switching conditions. In ZVT and active clamp techniques, the leakage inductance energy is absorbed by a snubber capacitor or clamp capacitor [4-7].

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However, in ZCT technique, the leakage inductance current is reduced to zero and then the switches are turned off [8-11].

Several isolated ZCT converters were previously introduced. The ZCT flyback converter introduced in [8] has no additional current stress on the main switch, which is the major advantage of this converter. However, the voltage stress of the converter main switch is much higher than the voltage stress of an ideal basic flyback converter switch. Usually switches with high voltage stress are expensive and also have higher conduction losses. Other ZCT flyback converters are introduced in [9-10], which use an auxiliary circuit connected to an additional winding on the converter transformer. In these converters, the main switch voltage stress is fairly higher than the voltage stress of an ideal basic flyback converter. Furthermore, in this converter, a high current peak is applied to the converter main switch. High current peaks are less important since semiconductor switches usually can tolerate them. The main switch voltage stress of the flyback converter introduced in [11] is also fairly higher than the voltage stress of an ideal basic flyback converter. In this converter, the presented auxiliary circuit requires two resonant inductors. If the converter is used with the simplified version of the auxiliary circuit, only one resonant inductor is needed for the auxiliary circuit but a high current peak is applied to the main switch.

Also, two ZCT full bridge converters are introduced in [12-13] which apply an auxiliary circuit containing two auxiliary switches in the primary side of transformer. In [14-15], ZCT full bridge converters are introduced which apply an auxiliary circuit in the transformer secondary side. By applying the auxiliary circuit in the secondary side of transformer, only one auxiliary switch is required. However, these converters require an additional resonance inductor and the switches current peak is high. In [16], a simple auxiliary circuit is applied to a full bridge converter similar to the proposed auxiliary circuit. However, in this converter, the control strategy is phase shift PWM instead of regular PWM. Also, in this converter, two of the bridge switches are zero voltage switched and the others are zero current switched. However, in the proposed family of converters, all the main switches operate under zero current switching.

In this paper, a family of isolated ZCT converters which employs a simple soft switching auxiliary circuit is introduced. The auxiliary circuit of these converters uses the transformer leakage inductance as the resonant inductor. This can be considered as the main advantage of these converters over previous ones.

Therefore, the converter does not require any additional resonant inductor and the auxiliary circuit is only composed of an auxiliary switch and an auxiliary capacitor. Another important advantage of the proposed flyback converter is the switch voltage stress, which is equal to the voltage stress of an ideal basic flyback converter. Moreover, the auxiliary circuit boosts the effective duty cycle. However, the main switch current peak is still high, but this can be usually tolerated by semiconductor switches. In the second section of this paper, the proposed flyback converter is analyzed and design considerations are discussed. The ZCT forward, half bridge and full bridge converters are introduced in the third section. A prototype of the ZCT flyback converter is implemented and the converter experimental results are presented in the fourth section.

2. Circuit Description and Operation

The proposed ZCT flyback converter is shown in Fig. 1. The main converter is composed of the main switch S, main diode D, output voltage capacitor C, and transformer T which is modeled by magnetizing inductance L_m, leakage inductance L_{Lk} and an ideal transformer with primary to secondary turns ratio of n:1. The auxiliary circuit is composed of the auxiliary switch S_a and auxiliary capacitor C_a. In order to simplify the converter analysis, it is assumed that converter output and input voltages are constant in a switching cycle and equal to V_0 and V_{in} respectively. It is also assumed that L_m current is almost constant and equal to I_{Lm} and all semiconductor devices are ideal. The converter has seven different operating intervals in a switching cycle. Main theoretical waveforms of the converter are shown in Fig. 2 and the equivalent circuit for each operating interval is shown in Fig. 3. Before the first interval, it is assumed that D is conducting, C_a is charged to V_0 and all other semiconductor devices are off.

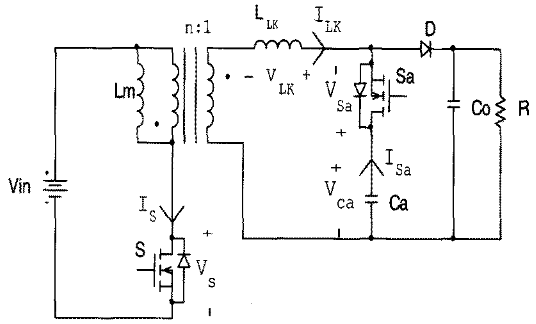


Fig. 1 Proposed ZCT PWM flyback converter

Interval 1 [t_0-t_1]: This interval starts by turning the main switch on. By turning this switch on, the input voltage is placed across the primary side of transformer and therefore the voltage across the leakage inductance (V_{Lk}) is V_0+V_{in}/n. Thus, L_{Lk} current (I_{Lk}) decreases linearly from n.I_{Lm} to zero and the main switch current increases from zero to I_{Lm} consequently. Due to the existence of L_{LK}, the main switch is turned on under almost zero current (ZC) condition and at the end of this interval, diode D turns off under almost ZC condition. L_{LK} current equation during this interval is:

$$I_{Lk} = n.I_{Lm} - \frac{(V_0 + V_{in}/n)(t - t_0)}{L_{LK}} \tag{1}$$

Duration of this interval is:

$$t_1 - t_0 = \frac{n.I_{Lm}.L_{LK}}{V_0 + V_{in}/n} \tag{2}$$

Interval 2 [t_1-t_2]: In this interval the main switch is conducting and the converter operates like a regular PWM flyback converter. During this interval the energy is stored in L_m, but since L_m is large, its current can be assumed almost constant.

Interval 3 [t_2-t_3]: This interval starts by turning the auxiliary switch on and thus, a resonance begins between C_a and L_{Lk}. Therefore, the auxiliary switch turns on under ZC condition. Since the main switch is conducting, the transformer secondary side voltage is -V_{in}/n and thus C_a voltage decreases in a resonance fashion from V_0 to -V_0-2V_{in}/n. Therefore, the equations for C_a voltage, L_{Lk} current and the main switch current during this interval are:

$$V_{Ca} = (V_0 + V_{in}/n)\cos(\omega_0(t - t_2)) - V_{in}/n \tag{3}$$

$$I_L = -\frac{V_0 + V_{in}/n}{Z_0}\sin(\omega_0(t - t_2)) \tag{4}$$

$$I_S = I_{Lm} + \frac{V_0 + V_{in}/n}{nZ_0}\sin(\omega_0(t - t_2)) \tag{5}$$

where:

$$\omega_0 = \sqrt{\frac{1}{L_{Lk}.C_a}} \tag{6}$$

$$Z_0 = \sqrt{\frac{L_{Lk}}{C_a}} \tag{7}$$

Duration of this interval is:

$$t_3 - t_2 = \frac{\pi}{\omega_0} \tag{8}$$

Interval 4 [t_3-t_4]: In this interval the auxiliary switch body diode starts to conduct and the resonance between L_{LK} and C_a continues. In this interval the L_{Lk} current increases in its positive direction and therefore, the main switch current decreases accordingly. The equations for C_a voltage, L_{Lk} current and the main switch current during this interval are:

$$V_{Ca} = -(V_0 + V_{in}/n)\cos(\omega_0(t - t_3)) - V_{in}/n \tag{9}$$

$$I_L = \frac{V_0 + V_{in}/n}{Z_0}\sin(\omega_0(t - t_3)) \tag{10}$$

$$I_S = I_{Lm} - \frac{(V_0 + V_{in}/n)}{nZ_0}\sin(\omega_0(t - t_3)) \tag{11}$$

According to (11), the main switch current becomes zero if (V_0+V_{in}/n)/nZ_0 is greater than I_{Lm}. This interval ends when the main switch current reaches zero. The C_a voltage at the end of this interval is defined as V_1 which is less than –V_{in}/n. Duration of this interval is less than $\pi/2\omega_0$

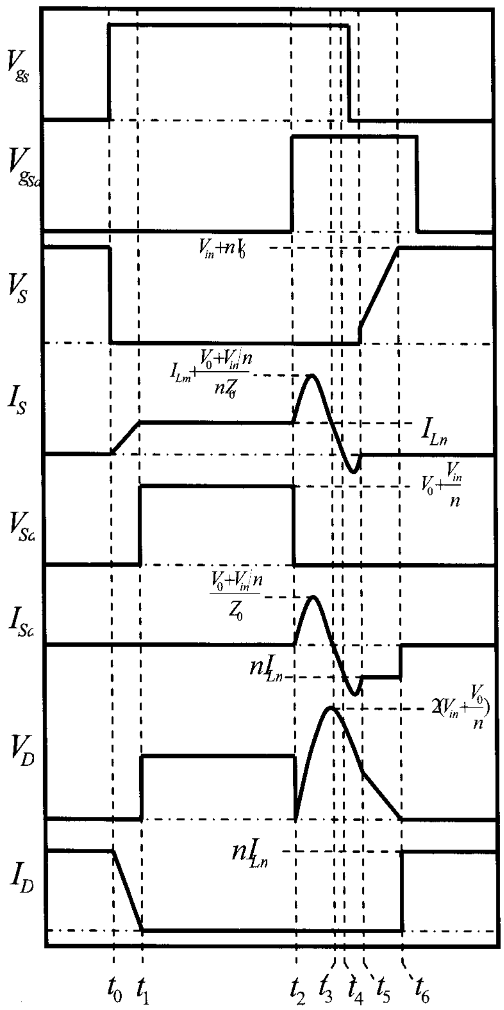


Fig. 2 Main theoretical waveforms of the proposed converter

Interval 5 [t_4-t_5]: The main switch body diode starts to conduct and the main switch can be turned off under zero current zero voltage (ZCZV) condition. The important equations of this interval are:

$$V_{Ca} = (V_1 + V_{in}/n)\cos(\omega_0(t-t_4)) - V_{in}/n \quad (12)$$

$$I_L = nI_{Lm} + \frac{-V_1 - V_{in}/n}{Z_0}\sin(\omega_0(t-t_4)) \quad (13)$$

$$I_S = \frac{V_1 + V_{in}/n}{nZ_0}\sin(\omega_0(t-t_4)) \quad (14)$$

This interval ends when the main switch body diode turns off. C_a voltage at the end of this interval is defined as V_2 which is greater than $-V_{in}/n$.

Interval 6 [t_5-t_6]: In this interval the L_{Lk} current is constant and equal $n.I_{Lm}$ and C_a charges with constant current until its voltage reaches V_0 and then, diode D is forward biased. C_a voltage during this interval is:

$$V_{Ca} = V_2 + \frac{nI_{Lm}(t-t_5)}{C_a} \quad (15)$$

At the end of this interval, the auxiliary switch body diode turns off under true ZV condition. Thus, its reverse recovery time is not important and the body diode of regular power switches can be used in this position even at high frequencies. This is another advantage of this converter over previous ZCT flyback converters [9]-[11]. In these converters the auxiliary switch body diode turns off under non-zero voltage condition and thus the body diode of power switch is not a proper element to be used at high frequencies.

Interval 7 [t_6-t_0+T]: Diode D turns on under ZV condition and L_{LK} current runs through this diode. The converter behaves like a regular flyback converter during this interval and energy is transferred to the output capacitor.

In the proposed converter, there is an additional current stress on the main switch with respect to regular flyback converter. Since the main switch is in series with the input voltage source, the proposed converter absorbs more power than a regular flyback converter with the same duty cycle due to the existence of auxiliary circuit. Therefore, the auxiliary circuit boosts the effective converter duty cycle. However, at light loads a part of this energy is returned to input source while the body diode of main switch starts to conduct.

The main converter is designed like a regular PWM flyback converter. In order to design the auxiliary circuit, only C_a value should be selected.

It can be observed from (11) that zero current switching for the main switch turn off is achieved if $(V_0+V_{in}/n)/nZ_0$ is greater than I_{Lm}. Therefore, Z_0 can be calculated as follows:

$$Z_0 \le \frac{V_0 + V_{in}/n}{n.I_{Lm}} \quad (16)$$

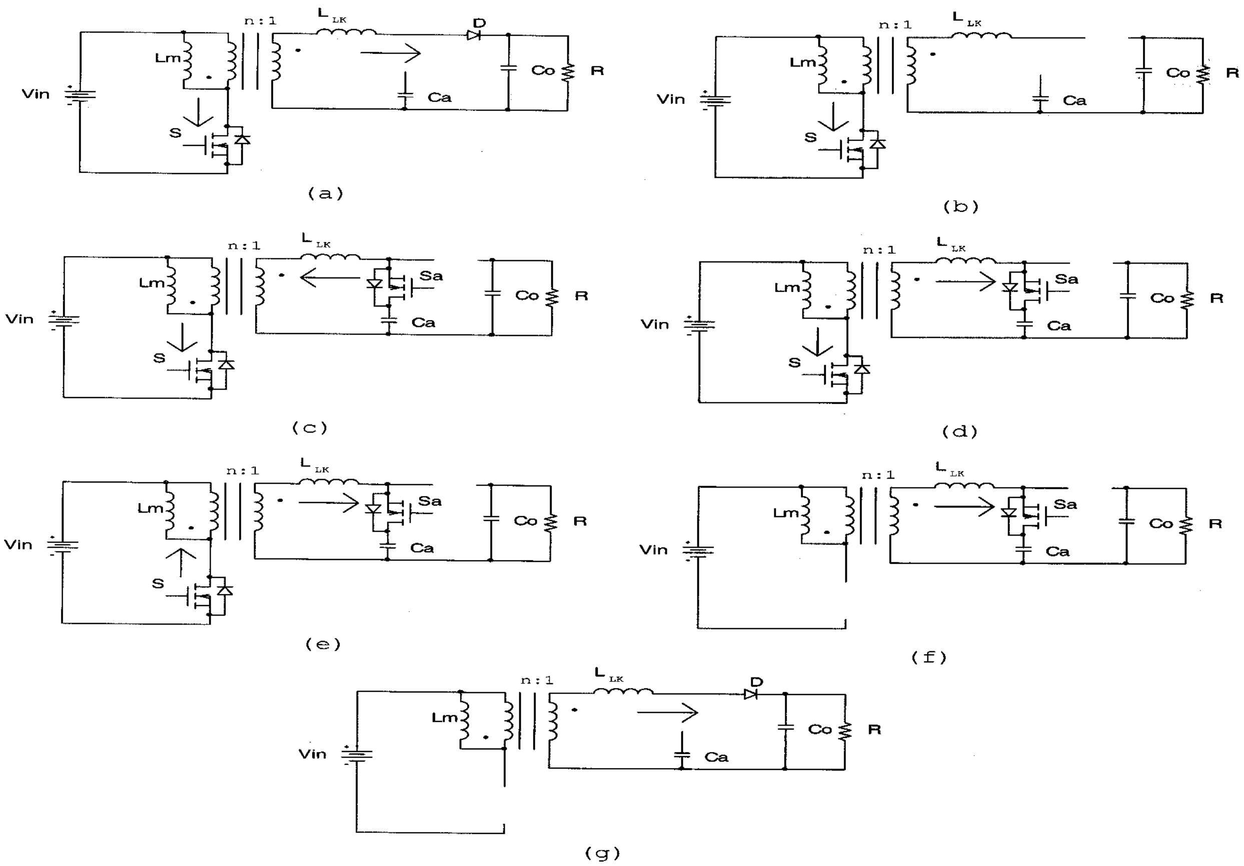


Fig. 3 Equivalent circuit of each operating interval at (a) $[t_0\text{-}t_1]$ (b) $[t_1\text{-}t_2]$ (c) $[t_2\text{-}t_3]$ (d) $[t_3\text{-}t_4]$ (e) $[t_4\text{-}t_5]$ (f) $[t_5\text{-}t_6]$ (g) $[t_6\text{-}t_0+T]$

In practice, at least 20% overdesign is necessary for selecting Z_0. Therefore, by measuring L_{Lk}, C_a can be calculated as follows:

$$C_a \geq \frac{1.44.n^2 L_{LK} I_{Lm}^2}{(V_0 + V_{in}/n)^2} \tag{17}$$

3. Other Isolated ZCT Converters

The proposed auxiliary circuit can be applied to other isolated converters such as forward, half bridge and full bridge converters as shown in Fig. 4. The operation of the auxiliary circuit with buck type ZCT converters is different from its operation with the flyback converter. Considering the forward converter of Fig. 4(a) and assuming its output inductor (L) current constant and equal to I_0, the converter operating modes is as follows:

1- The main switch turns on under ZC condition similar to the ZCT flyback converter due to transformer leakage inductance.

2- Once the main switch current reaches I_0/n, diode D_2 turns off and the transformer leakage inductance will resonate with C_a through the auxiliary switch body diode and C_a is charged up to $2V_{in}/n$.

3- The auxiliary switch body diode turns off and the converter operates like a regular PWM forward converter.

4- Just before turning off the main switch, the auxiliary switch is turned on and a resonance starts between L_L and C_a. During this resonance, L_L current and main switch current reduces to zero. In order to achieve ZC condition for the main switch turn off, V_{in}/nZ_0 should be greater than I_0, where Z_0 is defined by (7).

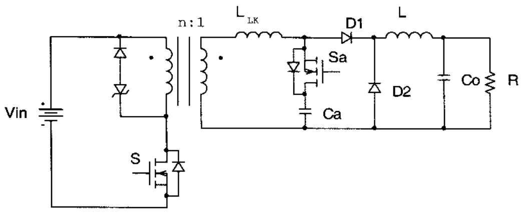
5- The main switch body diode conducts and this switch can be turned off under ZC condition.

6- C_a is discharged by L current through the auxiliary switch. When C_a voltage reaches zero, D_2 starts to conduct and the converter operates like any regular forward converter. In this condition, transformer core reset is achieved.

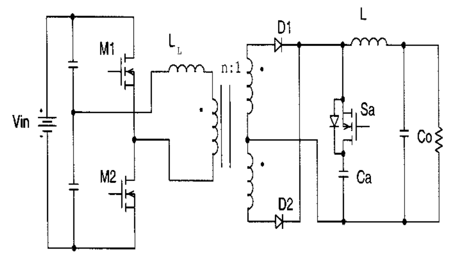
The operation of ZCT full bridge and half bridge converters is similar to ZCT forward converter.

4. Experimental Results

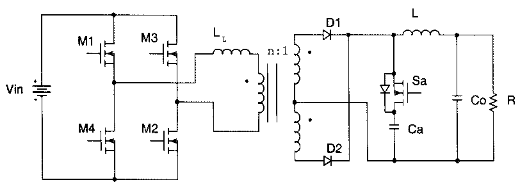
An 80W prototype of the proposed flyback converter operating at 100KHz is implemented. The converter input voltage is 150V and its output voltage is 45V. The transformer magnetizing inductance in the primary side is 1mH and the leakage inductance in the secondary side is 2uH. The transformer turns ratio n is 3. An 18Nf capacitor is used for C_a, IRF840 is used for S, IRF640 is used for S_a and MUR860 is used for D. Experimental results are shown in Fig. 5. In order to verify the achieved soft switching condition, the switching instances are shown in Fig. 6. The current swings which have appeared on the main switch current at turn-on instance are due to the main diode reverse recovery time. The converter efficiency curve is shown in Fig. 7.



(a)

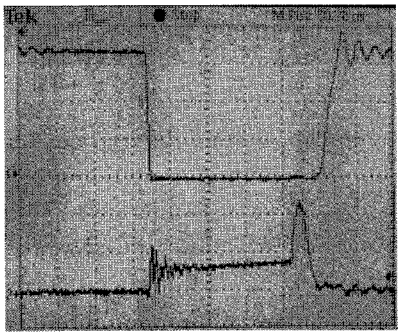


(b)

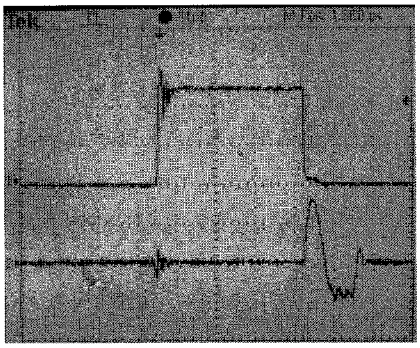


(c)

Fig. 4 Isolated ZCT converters (a) forward (b) half bridge (c) full bridge

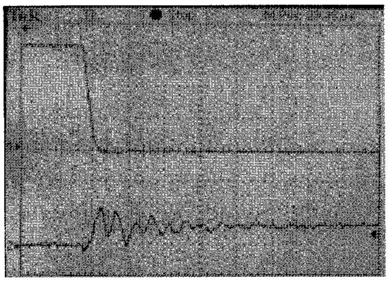


(a)

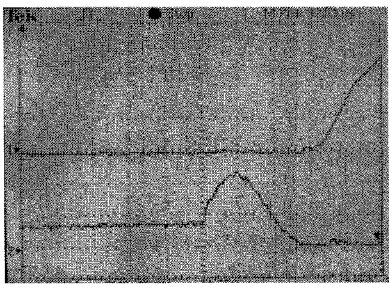


(b)

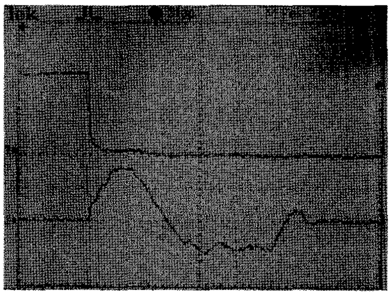
Fig. 5 In all waveforms, voltage is the top waveform and the current is the bottom waveform (a) main switch (vertical scale is 85V/div or 2A/div and time scale is 1us/div) (b) auxiliary switch (vertical scale is 35V/div or 6A/div and time scale is 1us/div)



(a)



(b)



(c)

Fig. 6 In all waveforms, the voltage is the top waveform and the current is the bottom waveform. (a) Main switch turn-on instant (vertical scale is 85V/div or 2A/div and time scale is 250ns/div) (b) Main switch turn-off instance (vertical scale is 85V/div or 2A/div and time scale is 250ns/div) (c) Auxiliary switch (vertical scale is 35V/div or 6A/div and time scale is 250ns/div).

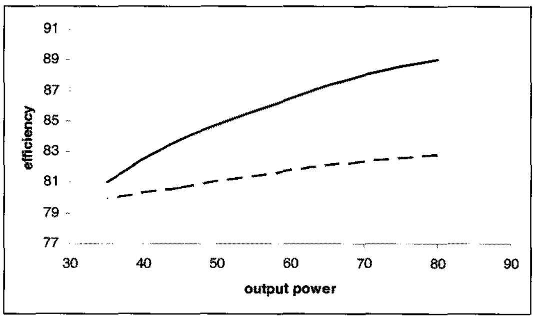


Fig. 7 Efficiency of ZCT flyback converter (continues line) and regular flyback converter (broken line)

5. Conclusions

In this paper a family of zero current transition PWM flyback converters with a simple soft switching auxiliary circuit is introduced. The auxiliary circuit is composed of only a switch and a capacitor. The proposed converter is analyzed and design considerations are discussed. Experimental results from a prototype converter are presented which confirm the validity of the theoretical analysis.

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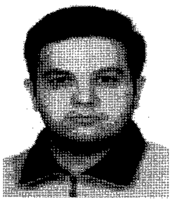

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