A novel topology for a soft-switching buck dc–dc converter with a coupled inductor is proposed. The soft-switching buck converter has advantages over the traditional hard-switching converters. The most significant advantage is that it offers a lower switching loss. This converter operates under a zero-current switching condition at turn on and a zero-voltage switching condition at turn off. It presents the circuit configuration with a least components for realizing soft switching. Because of soft switching, the proposed converter can attain a high efficiency under heavy load conditions. Likewise, a high efficiency is also attained under light load conditions, which is significantly different from other soft switching buck converters.

Keywords: Buck converter, coupled inductor, soft switching, zero-current switching (ZCS), zero-voltage switching (ZVS).

I. INTRODUCTION

Buck converters are step-down DC-DC converters that are widely being used in different electronic devices like laptops, cell phones and also electric vehicles to obtain different level of voltages. These converters are nothing but, high frequency switching devices operating on PWM principle. The need for a lighter and smaller electronic devices propels the need for reduced size of converters operating at higher load currents. With all these inadvertent conditions the switching frequency has jumped from KH range to MHz range.

The switching devices are made to turn on and turn off the entire load current at high di/dt, and also withstand high voltage stress across them. Due to these two effects there is an increased power losses in these converters and reduces the efficiency significantly. High switching frequency can be used to drop sizes and weights of converters. Still, if converters work under hard-switching conditions, switching losses will rise as switching frequency increases, and the total efficiencies will collapse. Soft switching technologies are the best techniques to diminish switching losses, and improve efficiencies and reliabilities. Thus, the sizes of heat sinks can be reduced. The total weights and sizes of converters will also be reduced. There are many methods to gather soft switching, and the most common is using extra quasi-resonant circuits. By adding auxiliary switches, capacitors and inductors, zero-current-switching (ZCS) conditions or zero-voltage switching (ZVS) conditions can be simply achieved in quasi-resonant converters. But, high current stresses and high voltage stresses for power switches are also created. It is not favorable to select the suitable rank of power switches, because there are additional conduction losses when using higher voltage power switches. Moreover, in some converters, auxiliary switches work under hard-switching conditions. Thus, additional power losses will be produced. Due to auxiliary switches, the control technique is more complicated than that of conventional pulse width modulation converters, and extra measuring circuits of voltage and current are desired. Great amount of research is done to develop soft-switching techniques in dc–dc converters. In these converters, it is desirable to control the output voltage by pulswidth modulation (PWM) because of its simplicity and constant frequency. The switch is turned off under ZVS condition, due to the small leakage inductance of the coupled inductors, a small voltage spike appears across the switch, and then, the switch voltage rises slowly to its final value. Thus, actually, the switch is turned off under almost ZVS condition even though the spike peak is usually much smaller than the switch maximum voltage [1].

The switching loss mechanisms include the current and voltage overlap loss during the switching interval and the capacitance loss during turn on. The diode reverse recovery also causes an additional conduction loss and further contributes to the current and voltage overlap loss. Active or passive soft-switching methods have been reported to reduce these switching losses.
Recently, passive soft switching has received renewed inspection as a better alternative to active methods, because they do not require an extra switch or additional control circuitry. The two necessary components that must be added to the circuit to achieve passive zero-current turn on and zero-voltage turn off are a small inductor and capacitor. The inductor provides zero-current turn on of the active switch and limits the recovery current of the diodes while the capacitor provides zero-voltage turn off of the active switch. Traditionally, the Inductor and capacitor have been placed in series and parallel with the active switch, respectively. However, many other locations are possible and can lower the component count and reduce switch stress.[2]

To create ZC condition for switch turn-on is to have a snubber inductor in series with the switch or diode. However, at turnoff, this inductor will cause a voltage spike on the switch. Therefore, a pulse current source is required to provide the output current, and, thus, the switch can be turned off under ZC condition while preventing the voltage spikes. To reduce the number of circuit elements, the pulse current source path and the required snubber inductor to decrease turn-on losses can be combined for a buck converter. A pulse voltage source can be applied to the snubber inductor and create the required pulse current source at switch turnoff.[3]

The pulsedwidth modulation technique is praised for its high power capability, fast transient response, and ease of control. The pulsedwidth-modulated (PWM) dc–dc converters have also been widely used in industry. For minimization of size and weight, increasing switching frequency in the PWM converter is required. However, increasing switching frequency will result in more switching losses and electromagnetic interference (EMI). Recently, for solving this problem, a number of soft-switching PWM techniques are available, aimed at combining required features of both the conventional PWM and resonant techniques. The zero-voltage-switching (ZVS) methods are necessary for the majority of semiconductor devices such as MOSFETs, since the turn-on loss produced by the output capacitance is large. The zero-current-switching (ZCS) approaches are suitable for the minority of carrier semiconductor devices. [4].

In most soft-switching converters, efficiencies can be improved significantly under heavy load conditions, but as in [5] effects are not good under light load conditions. It is generally because of additional power dissipations of auxiliary circuit. To solve the low-efficiency problem at a light load, based on a ZVS converter, an improved soft-switching buck converter with coupled inductor is proposed.
is freewheeling through the D2. Because L3 is very small, the current of L3 drops quicker than that of L1, and also reduces to zero before S1 turns ON. It offers the ZCS condition for S1. Due to snubber capacitor Cr1, S1 can turn OFF under a ZVS condition. Cpi is the parasitic capacitance of the MOSFET S1. Associated on the waveforms of the inductor currents, one switching period is allocated into five intervals, as shown in Fig.2. Equivalent circuits for each interval are established. In Fig.2, kij shows a slope of inductor currents at a different mode, where i denotes the number of the inductor and j represents the number of the different operating mode. The detailed theoretical analyses for each mode will be given as follows.

A. Mode 1 \([t_0 \rightarrow t_1]\):
At \(t_0\), S1 is triggered to conduct. Due to \(L_3\), \(i_{s1}\) will increase slowly, so S1 can turn ON under a ZCS condition. Resonance occurs between \(L_3\) and \(C_{r1}\). Then, \(i_3\) and \(i_1\) will increase, and \(i_2\) will go down. Since \(L_3\) is very small, the current-rising level of \(L_3\) is larger than \(L_1\). At \(t_1\), \(i_3\) and \(i_1\) are equal. It means that \(D_2\) turns OFF automatically, and this mode ends. Fig 3(a) shows Equivalent Circuit of Mode 1.

B. Mode 2 \([t_1 \rightarrow t_2]\):
At \(t_1\), \(i_3\) and \(i_1\) are identical, and both increase linearly and \(i_2\) is zero. In this mode, \(D_2\) is always OFF, and the branch of \(L_2\) does not work. At \(t_2\), S1 turns OFF, and this mode ends. It is similar to a conventional buck converter. Fig 3(b) shows Equivalent Circuit of Mode 2.

C. Mode 3 \([t_2 \rightarrow t_3]\):
This begins with turn-off of S1, and then a resonance occurs between inductors \((L_1, L_3)\), parasitic capacitor \(C_{pi1}\), and snubber capacitors \(C_{r1}\). \(C_{pi1}\) is charged, and \(C_{r1}\) is discharged at the equal time. When the voltage across \(C_{r1}\) diminishes to zero, \(D_1\) will conduct. Because \(C_{pi1}\) is very small, it can be neglected. Fig 3(c) shows Equivalent Circuit of Mode 3.

D. Mode 4 \([t_3 \rightarrow t_4]\):
At \(t_3\) D1 conducts, then \(D_2\) will conduct. When D1 conducts, voltage across output inductor changes polarity. Because inductors L1 and L2 are tightly coupled, the voltage \(V_{d2}\) becomes negative. Then D2 begins to conduct. Fig 3(d) shows Equivalent Circuit of Mode 4.

E. Mode 5 \([t_4 \rightarrow t_5]\):
In this mode S1 and D1 are OFF, then a small resonance between \(L_3\) and \(C_{r1}\) occurs, in which \(i_3\) oscillates around zero and the amplitude is pretty small, so \(i_3\) is supposed to zero in this mode. As shown in Fig. 2, the current just flows through \(L_1\) and \(L_2\), i.e., \(i_1\) is equal to \(i_2\)
Indeed, some converters are purposely designed to operate in DCM for all loads.

III. SIMULATION

A. Simulation Circuit Diagram

The SIMULINK model of the buck converter is shown in the Fig.4 and PWM generation via Matlab is shown in figure 6. The design parameters are listed as follows: input voltage=24V, output voltage=12V, switching frequency=20 kHz.

When the ideal switches of a dc-dc converter are implemented using current unidirectional and/or voltage-unidirectional semiconductor switches, one or more new modes of operation known as discontinuous conduction modes (DCM) can occur. The discontinuous conduction mode arises when the switching ripple in an inductor current or capacitor voltage is large to cause the polarity of the applied switch current or voltage to reverse, the current- or voltage-unidirectional assumptions made in gathering the switch with semiconductor devices are violated. The DCM is commonly witnessed in dc-dc converters and rectifiers, and can also sometimes happen in inverters or in other converters containing two-quadrant switches. The discontinuous conduction mode typically occurs with large inductor current ripple in a converter operating at light load and containing current-unidirectional switches. Since it is usually required that converters operate with their loads removed, DCM is frequently encountered.
The inductor ripple current does not depend on the load current. When the output current reduces below the ripple level, the inductor current can go negative. This negative current discharges the output capacitor and causes additional losses.

CONCLUSION

A soft-switching buck converter with coupled inductor has been proposed. By making inductor L3 to work under DCM, ZCS turn on and ZVS turn off for S1 are achieved. The detailed theoretical studies of the operating principle at steady state have also given. Moreover, no auxiliary MOSFET is added in this topology, so the control method is as simple as that of a conventional buck converter.

REFERENCES

