Step-Down DC-DC Converter Using Coupled-Inductors and Passive Clamped Circuit

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Abstract. A novel step-down DC-DC converter configuration is adopted in this paper. The new converter makes use the closed inversely coupled inductors topology. The proposed technique targeting the suppression of high content of switching noise that commonly accompanies the stepping-down converter circuits. This can be achieved by restraining the induced back electromotive force in the prime inductor. The induced back electromotive force is a result of discontinuous flow of line current in the prime inductor. The proposed technique preserves an uninterrupted stream of line current through-out the prime inductor which results in a considerable depression in the induced back electromotive force and consequently minimises the switching noise and enhancing the power conversion efficiency. A unique design of passive clamped circuit using coupled inductors is also proposed in this converter architecture. The leakage energies of the prime and the coupled-inductors can be recycled using the new passive clamped circuit and the captured energy can be then transferred to the load side alongside with the source or input energy. As a result, an efficiency improvement of the new converter can be achieved and the voltage stress on the power switches and diodes can be reduced. Circuit configuration, principles of operation and the transfer function of the new converter are figured out. The proposed concept of the new conversion technique is verified by the experimental and the simulated results of a range of case studies.

1. Introduction

Step-down dc-dc convertors are widely used as the front-end stage for many applications such as switching mode power supplies, distributed generation systems and power factor correction techniques. Meanwhile, the operation of traditional step-down DC-DC converter circuits is typically accompanied a considerable rate of noise with high voltage stress on the power switches of the converter circuit. However, low noise rate, high power conversion efficiency, large scale currents, and smooth stepping-down performance with reduced injected harmonics content to the mains are the main concerns for designing a new technique for step-down conversion in direct current circuits.

The switching noise is the outcome of the induced back electromotive force in the prime inductor of the converter circuit. This induced electromotive force is a consequence of the choppy currents in the prime inductor throughout the switching transient. The induced back electromotive force is a role of abundant aspects. Rated or demand current, size of the inductor, and the frequency of the applied switching scheme are the main of these aspects [1]-[2]. The coupled inductors configuration is proposed to minimize the
voltage stress, ripple current and switching losses on the power switches of the converter circuit. The coupled inductors architecture can be realised as a kind of distinctive objectives transformers. Several types of coupled inductors could be investigated in further based on the inductor’s ordination. The possible ordination could be either inversely or directly coupled; interleaved or loosely and if they are carried out on multiple magnetic cores or composite on a mutual magnetic core. Moreover, the coupled inductors structure is an attractive solution for higher power densities applications with reduced weight, size and minimised losses of the electrical and magnetic components. Therefore, this kind of topology is very attractive for different purposes such as electric railway traction, electric vehicles and range of industrial applications. Passive clamped circuit is defined as a collection of passive components (inductor, capacitor, and diodes) are coordinated in specific arranging. The passive clamped circuit is substantial to abolish unwanted resonance due to the leakage inductance of inductors and the parasitic capacitor of power diodes in the converter circuit. Passive clamp circuit also used to regain the restricted energy by the leakage inductances \([3]-[7]\). The stored energy by the leakage inductance is recaptured using passive clamped circuit and diverted to the load alongside with the supply (source) energy \([8]\). An active clamped circuit might be also used to recapture the stored energy by the leakage inductance with a ZVS to avert an extra switching loss \([9]-[10]\). Zero-voltage switching techniques can be carried out to turn on and off the power switch of the step-down converter that employs the coupled-inductor configurations \([11]-[14]\).

2. Circuit Configuration

The circuit layout of the proposed step-down DC-DC converter is illustrated in figure 1. The power switch \(S_1\) at the source side, the inversely coupled inductors \(L_{p1}\) and \(L_{s1}\), the input capacitor \(C_i\) are all connected to end side of the power switch \(S_1\). The input capacitor \(C_i\) and the power diode \(D_1\) are configuring the passive clamped circuit while the inversely coupled inductors \(L_{p1}\) and \(L_{s1}\) which they are integrated on a monocular toroid core are configuring the primary and the secondary windings of the transformer \(T_1\). The closed end of the inversely coupled inductors \(L_{p1}\) and \(L_{s1}\) is connected to the input side of the prime inductor \(L_2\). The cathode side of Schottky diode \(D_2\) is also connected to the input side of the prime inductor to complete the circuit for discharging current at the off-time interval of power switch \(S_1\). The end side of the prime inductor \(L_2\) is connected to the output capacitor filter \(C_o\) and to the load side.

![Figure 1: Circuit layout of the proposed step-down DC-DC converter.](image)

3. The Principle of Operation

The principles of operation for the step-down mode in steady state conditions and continuous conduction mode are debated in this part. In order to clarify the operational principles of the new converter, the next presumptions have been made:

a) The parasitical capacitance and resistance of the switch and diodes have been neglected.
b) Zero forward voltage drop for all diodes.
c) A unity turn ratio (\(n = 1\)) of the transformer \(T_1\).
d) The mutual inductance of the windings of transformer \(T_1\) is integrated to the primary winding \(L_{p1}\).
e) The magnetic field of the prime inductor \(L_2\) would not saturate.

The operation of proposed system can be illustrated by representing the function of the whole converter circuit as two operating conditions or two statuses, On status and Off status.
3.1 On status, \([S_1 \text{ On, } D_1, D_2 \text{ Off}]\):
While the power switch \(S_1\) is switched On, line current starts streaming into the primary inductor \(L_{p1}\), in the meantime the input capacitor \(C_i\) delivers another route for current to stream into the secondary inductor \(L_{s1}\). Both current routes are jointly with each other in the combined point of the closed inversely coupled inductors at the input side of the prime inductor \(L_2\). The source voltage now is applied on the cathode side of both diodes \(D_1\) and \(D_2\), which results in being both Off. Due to the leakage inductance of the coupled inductors, an amount of energy has been stored in the primary and the secondary windings of the transformer \(T_1\) (leakage energy) and the input side capacitor \(C_i\). The circuit layout of the proposed converter at On status with entire currents routes is illustrated in figure 2. The line current in the prime inductor \(L_2\) is the aggregate of currents in the two sides of the unity turn-ratio transformer.

![Figure 2](image)

**Figure 2.** On status equivalent circuit of the proposed converter.

3.2 Off status, \([S_1 \text{ Off, } D_1, D_2 \text{ On}]\):
At the end of the On time interval that controlled by the applied duty cycle for the power switch \(S_1\), the switch is turned Off. All passive components of the closed coupled inductors circuit start releasing their stored energies during the Off-time interval of the power switch \(S_1\). The capacitor \(C_i\), primary winding \(L_{p1}\), and the secondary winding \(L_{s1}\) start discharging their storage energies instantaneously in circular path and some of the released energy goes to the prime inductor \(L_2\) to keep a continuous flow of current in the prime inductor during the Off-time interval of power switch \(S_1\). The time constant of the input capacitor \(C_i\) is pivotal to avert any disconnectedness in the stream of the line current passing by the prime inductor \(L_2\). The capacitor \(C_i\) is much faster than any other devices or diodes to get over the lateness in conduction due to the wanted conduction time for any specific diode. After diode \(D_1\) being forward biased, an auxiliary track for current to circulate is provided beside the current track of the freewheeling Schottky diode \(D_2\). The circuit layout of the proposed converter at Off status with entire currents routes is illustrated in figure 3. The line current in the prime inductor \(L_2\) is the aggregate of both currents in diodes \(D_1\) and \(D_2\). This arrangement is preserving an uninterrupted stream of current in both sides of the transformer \(T_1\) and the prime inductor \(L_2\) even with Off status interval of switch \(S_1\).

![Figure 3](image)

**Figure 3.** Off status equivalent circuit of the proposed converter.

Consequently, there is a slight influence of the induced back electromotive force in the prime inductor of the new converter circuit, while the generated magnetic flux in the coupled inductors will cancel each other because they are opposite orientation. The transfer function of proposed converter is the typical transfer function of the step-down (buck) converter with a typical duty cycle as expressed in (1), where \(D\) is the duty cycle of the power switch \(S_1\).
\[ D = \frac{V_{\text{out}}}{V_{\text{in}}} \] (1)

4. Experimental Set-Up
The prototype of the new step-down converter has been designed, feigned and tested. The closed inversely coupled inductors is separately fabricated and integrated on a monocular toroid core. A single N-channel type MOSFET is used as the power switch \( S_1 \) with a single high-side MOSFET driver circuit. A separate control scheme is used to generate the control command that used to fire the MOSFET driver circuit. The role of the control scheme is to create a wide range of duty cycles \( D \) that used as a trigger for the power switch \( S_1 \). The range of generated duty cycles is started from 5% and end up with 90% step-up by 5%. This is to assure an extensive realization to the performance analysis of the proposed system. The experimental set-up of the new converter circuit utilized the below parameters values as in table 1.

| Parameter  | Value |
|------------|-------|
| \( L_{p1}, L_{s1} \) | 98 \( \mu \)H |
| \( L_2 \) | 1.54 mH |
| \( C_i \) | 4.8 \( \mu \)F |
| \( C_o \) | 112 \( \mu \)F |

5. Experiment Results of Selected Case Study
The transfer function of the converter circuit has been determined and the performance of the proposed converter circuit has been exercised with a range of undertaken case studies. The results verified the derived transfer function and they were in accordance with the theoretical analysis. A single case study has been selected to demonstrate in this section. The experimental set-up of the prototype of the proposed converter utilized for this case study are given in table 1. while the applied source voltage, the applied load, and the duty cycle of power switch \( S_1 \) are presented in table 2. The experimental waveforms of currents for this case study are illustrated in figures 4, 5 respectively. The examined efficiency of this case study was 96.6%.

| Parameter | Value |
|-----------|-------|
| \( V_{\text{in}} \) | 14V |
| \( D \) | 50% |
| \( R_{\text{load}} \) | 11\( \Omega \) |
Figure 4. Experimental Waveforms of Currents of Selected Case Study.

a) Converter line current \(i_{in}\)  
b) Primary inductor current \(L_{p1}\)  
c) Secondary inductor current \(L_{s1}\)

Figure 5. Experimental Waveforms of Currents of Selected Case Study.

a) Transformer windings currents \(L_{p1}\), \(L_{s1}\)  
b) Prime inductor current \(i_{L2}\)  
c) Signal of switch \(S_1\)

6. A Case Study with Simulated Results

A simulation model for the proposed step-down DC-DC converter is performed using an electronic circuits simulator for Linear Technology version IV 4.22. The design parameters of the prototype of the proposed converter mentioned in table I, have been also used in the setting of the simulation model. The simulation model of this converter is examined with the same testing conditions mentioned in table II of the case study presented in 5. This is to ensure a fair comparison between the prototype circuit and the simulation model for this case study. The only difference between the practical and the simulation models is the absence of current sensors. The current sensing elements are required in the practical circuit to captivate the real time current waveforms. This results in a tenuous footnote between the actual and the simulated outputs. The simulated current waveforms of the above case study are shown in figures 6, 7 respectively. The simulated outcomes are verified and in accordance with the practical results.

7. Experimental Results

In order to demonstrate the performance of the new converter, the proposed system must be tested under wide range of duty cycles with various values of input voltage and loading conditions. This is to assure an inclusive analysis to the performance of the proposed system. The experimental outcomes of a domain of case studies applying (7 V supply and 22 \(\Omega\) load, 14 V supply and 44 \(\Omega\) load, 20 V supply and 66 \(\Omega\) load) with a full range of applied duty cycles of power switch \(S_1\) for each case study at 120 kHz frequency is illustrated in figure 8.

Figure 8 showed the linearity performance of the new converter and the response behaviour of the system when working at vast assortments of case studies and loading statuses.
8. CONCLUSIONS
The proposed converter employs the closed inversely coupled inductors topology with a new design of passive clamped circuit. The proposed converter architecture is well designed to maintain an uninterrupted stream of current in the prime inductor delivered to the load side. This can be achieved by releasing the captured energy in the passive clamped circuit during the Off-time intervals of the power switch in the converter circuit. Preserving an uninterrupted outflow of current in the converter circuit
leads to considerable depression in the induced back electromotive force of the prime inductor and consequently minimises the switching noise and switching losses. Switching noise is a result of the choppy currents in the prime inductor of the converter circuit. Choppy currents are consequences of switching transient that normally occurs during the On and Off switching status of the power switch in the converter circuits. Consequently, enhancing the power conversion efficiency and minimising the rate of switching noise and voltage fatigue on the power switching devices. The prototype of the new step-down converter has been designed, feigned and tested. The performance of the new converter has been demonstrated by testing the proposed system under wide range of duty cycles with various values of input voltage and loading conditions. A simulation model for the proposed step-down DC-DC converter has been also done using an electronic circuits simulator to validate the operation of the converter circuit. The proposed concept of the new conversion technique is verified the analytical and the experimental results and widely compatible.

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