HIGH EFFICIENCY AND HIGH GAIN NON-ISOLATED BIDIRECTIONAL DC-DC CONVERTER WITH SOFT SWITCHING CAPABILITY

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To my beloved parents and my wife,
for their endless love, motivation and support.

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ABSTRACT

The non-isolated dc-dc power converters are considered as a unique option for flexible voltage control and adaptation in the modern energy conversion systems due to their simple and light configurations. To this date, these converters are primarily investigated to generate high efficiency and high gain with a sustained soft switching capability and a smaller footprint. On that account, this work proposes two effective solutions to address the aforementioned issues. First, a high-efficiency soft switching non-isolated bidirectional dc-dc converter with a simple configuration is proposed. The converter executes the zero voltage zero current switching (ZVZCS) over a wide operating region to ensure high efficiency. For verification, a 150 W experimental prototype is built and tested for soft switching performance by varying the input voltage, switching frequency and the loading. It is observed that the efficiency remains consistently high and has a full-load maximum of 98.2% in the boost mode and 97.5% in the buck mode. The analysis of the Electromagnetic Interference (EMI) performance of the converter also shows the improvement in the noise signature. Second, an improved high gain zero voltage switching (ZVS) non-isolated bidirectional dc-dc converter is proposed. The high gain is realized by using an intermediate energy storage cell with reduced size. Besides, the ZVS is implemented by two integrated auxiliary resonant networks. These networks ensure sustained ZVS operation over the entire duty ratio. A 200 W prototype is built to verify the concept. As a result, a full load efficiency of 97.5% (in boost mode) and 95.5% (in buck mode) is recorded at f_s= 30 kHz. Also, these efficiencies are recorded as 97% (boost mode) and 94.5% (buck mode) at f_s= 100 kHz. Moreover, it is observed that the efficiency (and so the soft switching) is consistent over the entire gain profile. However, there is a slight additional drop of 1.5% (boost mode) and 1% (buck mode) at extreme duty ratios. Both converters also implement soft switching for auxiliary switches and eliminate the reverse recovery loss.

ABSTRAK

Penukar kuasa dc-dc tidak terasing dianggap sebagai pilihan unik untuk pengawal voltan yang fleksibel dan penyesuaian dalam sistem penukaran tenaga moden disebabkan konfigurasinya yang mudah dan ringan. Sehingga kini, penukar ini menjadi keutamaan untuk menjana kecekapan tinggi dan gandaan voltan tinggi dengan keupayaan beralih lembut yang berterusan dan tapak yang lebih kecil. Sehubungan itu, kerja ini mencadangkan penyelesaian yang berkesan untuk menangani isu tersebut. Pertama, penukar dc-dc pensuisan lembut tidak terasing dwiarah berkecekapan tinggi dengan konfigurasi mudah dicadangkan. Penukar melaksanakan mod pensuisan voltan sifar dan arus sifar (ZVZCS) untuk memberikan kecekapan tinggi dalam julat operasi yang luas. Untuk pengesahan, prototaip eksperimen 150 W dibina dan diuji untuk prestasi pensuisan lembut dengan mengubah voltan masukan, frekuensi pensuisan dan bebanan. Diperhatikan bahawa kecekapan secara konsisten tinggi dan mempunyai kecekapan beban penuh 98.2% dalam mod *boost* dan 97.5% dalam mod *buck*. Analisis prestasi gangguan elektromagnetik (EMI) penukar jelas menunjukkan penambahbaikan terhadap pengurangan hingar. Kedua, penambahbaikan penukar dc-dc gandaan tinggi pensuisan voltan sifar (ZVS) tidak terasing dwiarah dicadangkan. Pensuisan lembut dilakukan oleh dua rangkaian bersepadu resonan pembantu. Ciri penting bagi penukar ini adalah ZVS dapat dikekalkan dalam keseluruhan kitar tugas (nisbah gandaan). Ini memastikan gandaan voltan tinggi dengan kecekapan operasi yang tinggi. Prototaip 200 W diuji untuk mengesahkan operasi penukar. Hasilnya, kecekapan beban penuh 97.5% (dalam mod *boost*) dan 95.5% (dalam mod *buck*) dicatatkan pada f_s = 30 kHz. Begitu juga, kecekapan adalah 97% (mod *boost*) dan 94.5% (mod *buck*) pada f_s = 100 kHz. Tambahan lagi, diperhatikan bahawa kecekapan (dan pensuisan lembut) konsisten di seluruh kawasan operasi. Walau bagaimanapun sedikit penurunan sebanyak 1.5% (mod *boost*) dan 1% (mod *buck*) pada nisbah kitaran tugas yang melampau. Kedua-dua penukar memastikan pensuisan lembut bagi suis-suis pembantu dan menghapuskan kehilangan pemulihan terbalik.

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LIST OF ABBREVIATIONS

DSP	-	Digital Signal Processor
EV	-	Electric Vehicle
ESU	-	Energy Storage Unit
HS	-	Hard Switching
PV	-	Photovoltaic
PID	-	Proportional-Integral-Derivative
RE	-	Renewable Energy
RES	-	Renewable Energy Sources
ZVS	-	Zero Voltage Switching
ZCS	-	Zero Current Switching
ZVZCS	-	Zero Voltage Zero Current Switching
ZVT	-	Zero Voltage Transition
ZCT	-	Zero Current Transition
ZVZCT	-	Zero Voltage Zero Current Transition

LIST OF SYMBOLS

C - Capacitor

D - Diode

$G_{step\text{-}up}$ - Step up gain

$G_{step\text{-}down}$ - Step down gain

I - Current

i_H - High side current

i_L - Low side current

i_{Sr1} - Current through switch $\mathrm{S}_{\mathrm{r}1}$

i_{Sr2} - Current through switch $\mathrm{S}_{\mathrm{r}2}$

i_{S1} - Current through switch S_1

i_{S2} - Current through switch S_2

i_{S3} - Current through switch S_3

i_{S4} - Current through switch S_4

i_{S5} - Current through switch S_5

K_P - PID controller proportional coefficient

K_I - PID controller integral coefficient

K_D - PID controller derivative coefficient

L - Inductor

P - Power

R_{Lr1} - Parasitic resistance of inductor L_{r1}

R_{Lr2} - Parasitic resistance of inductor L_{r2}

R_{Lr3} - Parasitic resistance of inductor L_{r3}

V - Voltage

v_L - Low side voltage

v_H - High side voltage

v_{Sr1}	-	Voltage across switch S_{r1}
v_{Sr2}	-	Voltage across switch S_{r2}
v_{S1}	-	Voltage across switch S_1
v_{S2}	-	Voltage across switch S_2
v_{S3}	-	Voltage across switch S_3
v_{S4}	-	Voltage across switch S_4
v_H	-	High side voltage
v_L	-	Low side voltage
ΔE	-	Change in efficiency
ΔV	-	Change in voltage

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CHAPTER 1

INTRODUCTION

1.1 Application Overview of the dc-dc Converter

The sharp increase in the power requirements for modern computers, mobile devices, automotive/spacecraft and renewable energy system (RES) demand more efficient and reliable dc-dc power converters. Notably, as the applications are becoming more complex and diverse, the demand for high-performance, cost-effective converter topologies continue to grow. Consequently, there is an impetus to develop dc-dc converters with higher efficiency, higher gain and a smaller footprint that can function under flexible operating conditions. From this viewpoint, the non-isolated dc-dc power converters are considered as a preferable option, compared to its bulkier and expensive isolated counterparts.

In the communication and computer sector, the power supply can be either an isolated or non-isolated type of dc-dc converter. Regardless of the type, it is required to be efficient, inexpensive and lightweight with low ripple noise to protect the delicate electronics. Besides, it is expected to support a wide range of input voltage, but should not be limited by certain load constraints. For the renewable energy system (RES), these converters are primarily used to convert the dc voltage from one level to another, i.e. from photovoltaic [1], wind [2], fuel cell [3, 4], wave, ocean thermal and thermoelectric systems [5, 6]. In the microgrid environment, it also provides seamless integration of the RES to the internal grid by allowing the voltage and current from the RES to be precisely controlled. Additionally, an increasing number of RES deploy energy storage units (ESU) to store and manage the power flow more efficiently. The ESU requires non-isolated dc-dc power converters to interface with, for example, PV arrays or dc loads, such as electric vehicles. Such application illustrates the necessity of a dc conversion system with bidirectional power flow capability.

In the automotive industry—one of the main user of dc conversion systems, the non-isolated dc-dc converter is primarily used for internal electronics and vehicle control [7]. There is a wide range of dc voltage levels to be derived from the main battery for various vehicle instrumentation needs. Looking into the future, the electric vehicle (EV) sector is paving the way for the widespread application of high voltage, high power dc-dc converters. The on-board chargers of the EV are required to be bidirectional and lightweight. On the other hand, the off-board chargers must be capable of providing a flexible output voltage range to adapt to a different type of vehicles. With the expected high penetration of EV, the integration of RES into the charging system is foreseen as a viable solution to reduce the burden on the electrical grid [7-11]. Particularly, for the high power dc (fast) charging, the charging efficiency has become a critical issue. From these perspectives, the overall performance of future the power systems is largely determined by these converters.

On a more extreme outlook, the possible replacement of ac distribution system by dc is being widely debated [8-10]. Correspondingly, within the smart grid infrastructure, the dc-dc converter will be the main component that interfaces the dc distribution voltages with the consumer appliances.

1.2 Challenges for High-Performance dc-dc Converter Operation

In all applications, the efficiency of the dc-dc converters is of utmost concern. Thus, the conduction and switching losses must be reduced. Conventionally, the hard switching PWM converters induce substantial switching losses, particularly at high switching frequency. Nevertheless, the high-frequency operation is highly desirable to reduce the size of the converter. On that account, the soft switching technique is sought to reduce the switching losses and thus to improve the efficiency. The existing soft switching converters apply zero voltage switching (ZVS), zero current switching (ZCS) or zero voltage zero current switching (ZVZCS) techniques to suppress these losses. Evidently, the ZVZCS provides improved loss reduction capability as compared to the former due to manipulation of both the voltage and current waveforms simultaneously.

However, the ZVZCS can only be achieved either at the cost of increased component count (and the conduction losses) and more complex controller. Furthermore, most converters with ZVZCS can only provide unidirectional power flow capability [12] [13] [14-16]. Operational-wise, the change in the input voltage, switching frequency or the loading of the converter disrupts the function of ZVZCS [17-28]. Consequently, the efficiency of the converter is often compromised to allow the converter to work in wider operating range.

Another issue of interest for the non-isolated dc-dc converter is the voltage gain ratio. Unlike its isolated counterpart, which utilizes transformer that can be concurrently used as a step-up mechanism, the nonisolated dc-dc converter has to employ other means to increase its gain. The popular method is to utilize the multilevel configuration, switched capacitor or coupled inductors. However, these topologies cannot provide a competitive gain without significantly increasing their component count and magnetic footprint. In addition, high gain converter comes with a substantial trade-off in terms of efficiency [26, 29-31]. For example, the multilevel topology cascades multiple converters units in series formation. As a result, the overall efficiency, which is the multiplication of the efficiency of each converter unit, is reduced. Furthermore, this configuration requires a large number of active and passive components that result in higher conduction losses.

On the other hand, the coupled inductor based topology attains high gain by manipulating the turn's ratio of the coupled inductors. On that account, the increase in the turns ratio, requires more conductor, thus increases the I^2R losses. In addition, at high power, bigger magnetic circuit is required to accommodate the magnetic flux, in order to achieve the same gain ratio. Thus, the core losses are increased proportionally. As for the switched capacitor designs, multiple switched capacitor cells are required to boost the gain ratio. Besides additional device losses, the residual charges contribute to lower the efficiency.

In general, due to large number of switches in the above-mentioned topologies, it is extremely difficult to integrate the soft switching cells into the circuit. Since they could not exploit the advantages of the soft switching, most of these high gain converters exhibit higher switching losses [25, 32]. Notwithstanding, a small number of converters that integrate the soft switching fail to maintain it consistently over the entire gain profile. This is primarily due to the extreme duty ratio in which high gain converter operates [26, 29-31, 33].

1.3 Problem Statements

From the brief overview above, it can be inferred that the primary challenges that the non-isolated dc-dc power converters are required to address are: 1) High-efficiency operation in a wide operating range, 2) High step-up/step-down gain with sustained soft switching capability, and 3) Simple configuration with lower component count. In the recent literature, the nonisolated dc-dc converters are widely investigated to maintain low switching losses and to achieve high-efficiency operation. However, the high efficiency operation is achieved at the expense of larger component count, higher control complexity or limited operational range. The latter is formulated in the form of soft switching that is limited by the input voltage, switching frequency or loading. In other cases, the converter only allows unidirectional power flow, thus limiting the scope of their applications. On the other hand, in many circumstances (EV, spacecraft), the high gain is required with substantial constraint imposed on the size and weight of the converter. From this viewpoint, the gain heightening in a (low-weight) transformer-less topology is a big challenge by itself. By surveying the relevant literature, it is observed that the existing group of high gain non-isolated dc-dc power converters cannot sustain a high-efficiency operation over the entire operating range of gain ratio and power. Also, most of these converters are not equipped with the soft switching feature so that the switching losses could be suppressed consistently.

1.4 Objectives of Research

Given these drawbacks of the current state-of the art of non-isolated bidirectional dc-dc converter argued in Section 1.2, this work sets two primary objectives. They are summarized as follows.

(i) To design a high-efficiency non-isolated bidirectional dc-dc power converter with soft switching (ZVZCS) capability. The latter is to be implemented by an auxiliary network to reduce the switching losses in the main switches. Most importantly, the ZVZCS must operate in a wide range of input voltage, switching frequencyand loading, while maintaining high efficiency. Besides, the converter is expected to be built using low number of components.

(ii) To design a soft switching non-isolated bidirectional dc-dc power converter that can provide high gain with high efficiency. The high gain is realized by using an intermediate energy storage cell, with reduced size and weight. In addition, the soft switching (ZVS) is to be implemented over the entire operational duty cycle ratios.

Objectives (i) and (ii) are realized using two different circuits.

1.5 Scope of Research

To achieve the objectives of the research, this work is limited by the following scopes:

(i) The topologies of non-isolated soft switching dc-dc converters that are covered in the literature review in Chapter 2 are not exhaustive. However, it provides a comprehensive classification so that the existing circuits should fall under any of these categories.

(ii) The test results of the experimental prototype of the high-efficiency converter in Chapter 3 are recorded at 150 W. Mainly, the low power region allows analyzing the switching losses more effectively. This is because the latter loss is more dominating than the conduction losses in this region.

1.6 Organization of Thesis

This thesis is organized into five chapters. Their contents are outlined as follows:

(i) Chapter 2 provides an extensive review of the soft switching techniques, the soft switching converters and the gain boosting techniques employed in non-isolated bidirectional dc-dc converters. The soft switching techniques are divided into the ZVS, the ZCS, the ZVZCS and the *true* ZVZCS. On the other hand, the soft switching converters are categorized into the active and passive snubber, the series and shunt resonant and the pulse width modulated converters. The merits and drawbacks of these soft switching configurations are highlighted. Besides, the gain boosting techniques are discussed along with their advantages and disadvantages.

(ii) Chapter 3 introduces the proposed non-isolated bidirectional dc-dc converter family. The proposed converter employs a ZVZCS network to improve the efficiency. Despite having a low component count and a simple configuration, it is capable of maintaining the soft switching condition for a wide operating range. Furthermore, it can be integrated to other basic converter platforms to improve the efficiency and extend the soft switching range.

(iii) Chapter 4 presents the proposed high gain and high efficiency non-isolated bidirectional dc-dc converter. The converter is integrated with the soft switching capability implemented by two identical auxiliary resonant networks. The dedicated networks ensure the soft switching over the whole operating condition. Resultantly, the high gain ratio is achievable with high operating efficiency. Besides, the reverse recovery loss is also eliminated.

(iv) Chapter 5 concludes the works undertaken and highlights the contributions of this research. Several suggestions are provided for possible directions of future work.

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