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Soft-Switching Current-FED Flyback Converter with Natural Clamping for Low Voltage Battery Energy Storage Applications

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Abstract. This paper introduces a new galvanically isolated current-fed step-up dc-dc converter intended for high voltage gain applications. The converter has a fully-controllable voltage doubler rectifier, with control signals synchronous to that of the inverter switches. The proposed converter can regulate output voltage within a wide range of the power and input voltage variations. The proposed converter does not require snubbers or resonant switches and with the proposed control sequence ensures switch operation under soft-switching conditions in all transient states. Soft-switching in semiconductors allows achieving high efficiency. Moreover, the input side current is continuous. The operating principle for the energy transfer from the current-fed to voltage-fed side is described, design guidelines along with experimental verification of the proposed converter are shown in this paper. The converter proposed can be used as a front-end converter for grid-connected battery storage.

Keywords: current-fed converter; soft-switching; flyback converter; ZVS; ZCS; switching sequence; clamping; energy storage.

1 Introduction

New trends in European Union green energy policy encourage use of distributed power generation sources [1]. For more efficient use of alternative energy sources in residential applications it is preferable to include battery energy storage (BES) to those systems [2]-[5]. Battery energy storage systems (BESS) are used as a buffer to store excess energy so that later it can help to suppress grid shortages or even inject power to the grid in case of high electric energy demand. This helps to minimize the impact of renewable power generation sources on electric grid stability [6].

BESSs in residential installations have a power rating up to 8 kW. Battery chemistry for battery energy storage also varies significantly. In recent years lithium iron phosphate (LiFePO₄) batteries are preferable for residential usage as they have one of the highest safety and reliability characteristics among lithium batteries. Another important feature is that they can preserve nominal capacity even after few thousands of discharge-charge cycles [7]-[9].

For connecting the BESS to the AC-grid the additional inverter stage is used. The intermediate DC-link of the system is traditionally formed by different voltage-fed (VF) DC-DC converters [10], [11]. One of the most reliable and widely used solution is dual active bridge (DAB) converter as they have soft switching capability and thus high operational performance [12]. Soft-switched current-fed (CF) converters with soft-switching capability is a topic of interest in recent years. Among them there are converters with additional clamping circuits [13],[14], with resonant-assisted transition [15], and others additional circuits [16],[17]. Additional advantage of current-source converters is continuous input current. This places them as preferable choice for battery powered applications [10],[11].

Fully-controllable switches at the rectifier side of isolated CF converters brings new challenges and benefits [18]-[26]. This paper introduces CF flyback DC-DC converter with novel regulation algorithm. This algorithm has duration of transient switching intervals that is constant in a whole operation range and so ensures soft switching across that range. High efficiency can be achieved due to minimizer dynamic losses even at relatively high operational frequencies.

2 Relationship to Smart Systems

Nowadays smart systems are used in all major sectors of human life such as healthcare, safety, automotive and environment. Typical smart system consist of diverse components that are usually physically organized in different physical nodes. And with the rapidly increasing interest in the concept of the Internet of things all those nodes and even entire systems have to be operating and connected to each-other all the time without any interruptions. To ensure this the most critical smart-systems accommodates backup battery-based power supplies. Battery energy storage in household is used to accumulate energy from renewable energy sources when it is not used or from the grid when it has a lowest price. After battery is charged it can be used when it is required by user or when grid is under heavy load and requires additional power. This means that battery energy storage together with smart learning system with energy demand tracking as a part of smart house can increase stability of local power supply system and decrease yearly average grid power usage. So a major research direction of power electronics in smart systems is the development of high-efficiency robust power converters for battery-storage.

3 General Description

Topology of the discussed converter is shown in Fig. 1. It can be considered as derivation of the CF dual-inductor push-pull topology [25] proposed earlier. It consists of the CF inverter with four-quadrant (4Q) switches at the input side and the controllable rectifier at the output VF side. Isolating transformer introduces additional step-up needed to interface low-voltage sources to the high voltage DC-link. Converter provides low level of ripple CF terminal that is faced to battery. By

controlling the duration of the reactive energy circulation interval regulation of output voltage is achieved.

Full soft-switching CF flyback converter topology can be used as interface power converter for connecting battery to the DC-grid or as the first conversion stage in AC-grid connected battery storage. In such applications the proposed topology and proposed control algorithm have the following distinguish features:

- High voltage gain that allows to use transformers with lower turns ratio to connect low voltage 12V and 24V batteries to a standard 400V DC-grid.
- Current-fed terminal that ensures that the battery is operating with continuous input current. This allows increasing battery elements lifetime.
- Natural clamping of input inductor is achieved with the special control algorithm without any additional active or passive elements.
- Soft-switching is achieved in all switching elements through the wide operation range in both energy transfer directions.
- Reduced number of semiconductor devices as compared to the full-bridge boost converter (FSS-IFBBC) [24], and the same number of switches that in the dual inductor push-pull converter [25] and CF push-pull converter [26] that are using same control algorithm.
- High transformer utilization factor due to the double-ended operation with one part of the switching period (t_0 - t_7) proposed topology operates similar to the flyback converter and during the other part (t_7 - t_{12}) it operates similar to the forward converter.
- Transformer flux runaway protection capability without use of RCD snubbers or additional transformer windings.

During operation the transistors S1.2 and S2.2 are controlled synchronously to S1.1 and S2.1 and are turned off (acting like diodes) for transient intervals.

4 Converter Operation

This section describes converter operation with power flow from V_{CF} to V_{VF} terminal. Generalized control algorithm and simulated waveforms presented in Fig. 2. Switching period with the proposed control algorithm consists of twelve time intervals that are described in details further.

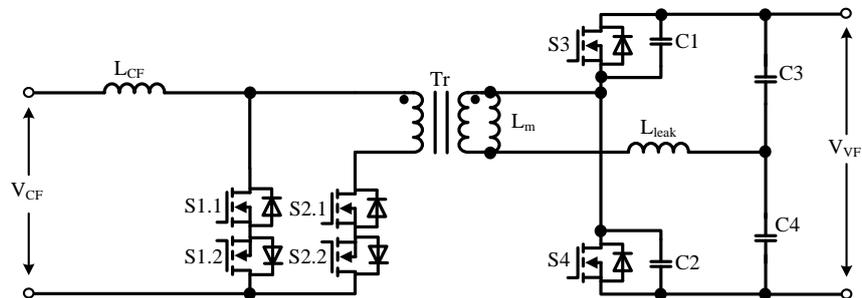


Fig. 1. Proposed converter topology.

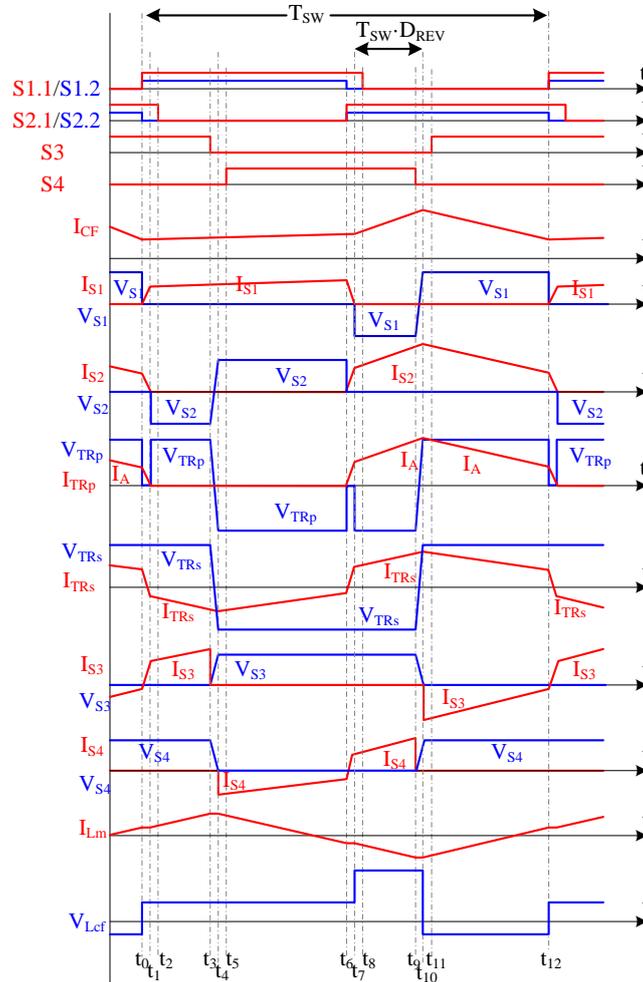


Fig. 2. Simulated operation waveforms.

Interval 1 ($t_0 < t < t_1$). Interval starts with turn off of switch S2.2. Current is been redirected to the body diode (BD) of S2.2. S1 with assistance of the transformer leakage inductance L_{leak} is turned on under soft-switching conditions. Leakage inductance acts like a snubber by slowing down current rise in S1 to separate voltage fall and current rise and thereby to minimize switching losses. The inductor L_{CF} is storing energy. Switch S3 is kept on forcing the inverter side transformer current to transfer from S2 to S1.

Interval 2 ($t_1 < t < t_2$). Interval starts after S2 current reaches zero and BD of S2.2 is turned off naturally. Inductor L_{CF} is storing energy from CF terminal. Transformer-magnetizing inductance starts accumulating energy from C3 through S3. The duration of this interval is calculated so that the current through S1 will have sufficient time to drop to zero at minimal input voltage at nominal power.

Interval 3 ($t_2 < t < t_3$). Interval starts with turning off switch S2.1 under ZCS conditions. Interval is needed to separate switching transitions in CF and VF sides and in most cases it can be omitted.

Interval 4 ($t_3 < t < t_4$). Switch S3 is turned off with soft-switching assisted by snubber capacitor C1. Capacitor C1 is charging from zero to VVF and C2 is discharged from VVF to zero. The transformer output The voltage polarity at the transformer output is changed.

Interval 5 ($t_4 < t < t_5$). Interval begins when the transformer current starts flowing through BD of S4. This interval is a part of power delivery mode from CF to VF terminal. Energy accumulated in the transformer magnetizing inductance L_M is delivered to the output terminal through the BD of S4. Interval duration is Duration of this interval is calculated so that it is equal to the snubber capacitor recharge time in point of the minimal operational power. In this case soft-switching will be achieved in the whole operation range while the conduction losses across BD will be minimized.

Interval 6 ($t_5 < t < t_6$). During this interval S4 turned on at ZVS conditions. Energy accumulated in L_M is delivered to the VF terminal through switch S4.

Interval 7 ($t_6 < t < t_7$). Switch transients on this interval are analogical to those on **interval 1**. 4Q switch S2 is turned on with soft-switching assisted by L_{leak} .

Interval 8 ($t_7 < t < t_8$). Interval is analogical to **interval 2**. At the beginning of interval current through S2 reaches zero by those forcing BD of S2.1 to turn off naturally. Reverse energy transfer interval is started. LCF accumulating energy from VF (C4 through S3 and Tr) and CF terminals.

Interval 9 ($t_8 < t < t_9$). During this interval S2.1 turned off under ZCS conditions. Processes in converter are analogical to **interval 8**. Duration of intervals 8 and 9 defines the converter gain factor.

Simplified converter voltage gain factor can be derived analogically to [25] and is expressed as follows:

$$F_{FRW} = \frac{V_{VF}}{2nV_{CF}} = \frac{2}{1-4 \cdot D_{REV}}, \quad (1)$$

where n is the transformer turns ratio.

Interval 10 ($t_9 < t < t_{10}$) and **Interval 11** ($t_{10} < t < t_{11}$). Are analogical to intervals 4 and 5 accordingly. Starting from instant t_{10} energy is delivered to transferred from the input to the output terminal through the transformer and body diode of S4 like in classical forward DC-DC converter.

Interval 12 ($t_{11} < t < t_{12}$). At the instant t_{11} switch S4 is turned on under ZVS conditions. Current is transferred from BD to switch thereby decreasing conduction losses.

5 Experimental Results

For the experimental study converter was designed to operate with a 4-cell LiFePO₄ battery was selected. Experimental prototype design parameters are shown in Table 1. Semiconductor devices parameters used are shown in Table 2.

Experimental data is shown in Table 3. The difference in theoretical and experimental voltage gains can be explained by the assumptions and simplifications used in theoretical equation.

Table 1. Converter Parameters

Parameter	Designator	Value
Nominal power, W	P	100
CF voltage, V	V_{CF}	10-15
VF voltage, V	V_{VF}	400
Operation frequency, kHz	f_{sw}	100
Transformer turns ratio (N_p/N_s)	N	1:6
Magnetizing inductance, mH	L_{TX_m}	3.4
Transformer secondary leakage ind., uH	L_{TX_leak}	8
Inductance of input inductors, uH	$L_{A, LB}$	44
Capacitance of output filter, uF	C_3, C_4	2.2
Capacitance of snubber, pF	C_1, C_2	265

Table 2. P Semiconductor Devices Parameters

Component	Device	Parameters
CF MOSFETs	Infineon BSC035N10NS5	$V_{DS}=100V$; $R_{DS(on)}=3.5m\Omega$ $I_D=100A$, $t_{rr}=62$ ns, $C_{OSS}=770$ pF
VF MOSFETs	Infineon IPB60R190C6	$V_{DS}=650V$; $R_{DS(on)}=190m\Omega$ $I_D=59$ A, $t_{rr}=430$ ns, $C_{OSS}=85$ pF

Table 3. Experimental Results Forward Operation

V_{CF} , V	D_{REV}	Theoretical gain	Experim. gain	Losses, W	η , %
10	0.104	3.42	3.33	7.89	92.11
11	0.086	3.05	3.03	6.29	93.71
12	0.069	2.77	2.78	5.39	94.61
13	0.051	2.51	2.56	4.53	95.47
14	0.033	2.31	2.38	3.81	96.19
15	0.017	2.15	2.22	3.66	96.34

6 Conclusions

A novel current-fed flyback converter was proposed and analyzed. One of the main features of proposed converter is that all semiconductors are operating under soft-switching conditions at all switching transients. Also proposed converter due to utilization of the circulating energy features higher DC voltage gain than in traditional current-fed converters. Moreover, due to the special control algorithm it features natural clamping of input inductor converter does not require any additional clamping circuits. Peak power stage efficiency during experimental verification reached 96.34%. Converter switching frequency can be increased without significant efficiency drop thanks to the soft-switching operation. This allowing to decrease size and price of magnetic components and so the price of BESS in general.

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