Postprint of Research on the Application of Fly-Buck Topology in Digital Generators

Authors: Jiang Shiyu, single beam

Date: 2019-03-05T00:00:00+00:00

Abstract

Fly-Buck topology evolves from the conventional synchronous rectification buck topology and can achieve isolated power output without requiring additional loop feedback, thereby simplifying the design process of low-power isolated auxiliary power supplies. Based on Fly-Buck topology circuits, this paper analyzes and investigates the operating principle of Fly-Buck topology, validates the theoretical analysis through circuit simulation, and designs an auxiliary power supply prototype for digital generators based on Fly-Buck topology circuits. The output characteristics of the secondary side are obtained experimentally, confirming the feasibility and practicality of this topology. The paper specifically analyzes and examines the impact of Fly-Buck topology operating modes on the voltage regulation performance of the secondary side output when the primary side is under light-load or no-load conditions. Both circuit simulation and experimental results demonstrate that Fly-Buck topology operating in forced continuous conduction mode can still guarantee good voltage regulation performance on the secondary side output, which tracks the primary side output.

Full Text

Preamble

Application Research on Fly-Buck Topology in Digital Generator

Jiang Shiyu, Shan Liang
(School of Automation, Nanjing University of Science and Technology, Nanjing 210094, China)

Jiang Shiyu (male, born 1991) is a master' s student whose research focuses on power electronics and electric drives.
Shan Liang (male, born 1979) is an associate professor and master's supervisor whose research interests include control and application of nonlinear chaotic circuits, and control and application of AC servo motor systems.

Abstract

Fly-Buck topology evolves from the conventional synchronous rectifier buck topology and can obtain isolated power output without additional loop feedback, thereby simplifying the design process for low-power isolated auxiliary power supplies. This paper analyzes the working principle of Fly-Buck topology based on the circuit configuration, verifies the theoretical analysis through circuit simulation, and designs an auxiliary power supply prototype for digital generators using the Fly-Buck topology. Experimental results of the secondary-side output characteristics validate the feasibility and practicality of this topology. The paper particularly investigates how the operating mode of Fly-Buck topology affects the secondary-side output voltage regulation performance when the primary side is lightly loaded or unloaded. Both simulation and experimental results demonstrate that operating Fly-Buck topology in forced continuous mode ensures excellent voltage regulation performance on the secondary side while maintaining tracking with the primary-side output.

Keywords: Fly-Buck, synchronous rectifier buck topology, auxiliary power supply, forced continuous mode

1 Introduction

Many electronic systems, such as programmable logic controllers, data acquisition equipment, and medical devices, require low-power isolated auxiliary power supplies to provide electrical isolation, ensuring both equipment performance and operator safety. Typically, designers choose flyback topology for such applications [1]. However, designing flyback-based auxiliary power supplies requires calculating loop compensation parameters, using optocouplers for isolated output feedback, and adding snubber circuits to protect switching devices from oscillation-induced voltage spikes [2]. Furthermore, due to voltage reflection and oscillation spikes during secondary-side freewheeling [3], switching devices must be selected with higher voltage margins. Considering power level, cost, circuit complexity, and space constraints, flyback topology design becomes relatively complicated.

In contrast, Fly-Buck topology eliminates the need for additional loop feedback and requires fewer components to achieve isolated power output, occupying less space with lower circuit complexity and cost, thus simplifying the design of isolated auxiliary power supplies. Reference [4] investigated Fly-Buck topology applications in IGBT gate driver power supplies, while reference [5] analyzed its working principle and derived general design procedures for isolated auxiliary supplies. Reference [6] examined the topology's operation under ideal conditions and built experimental prototypes.

This paper analyzes and studies the working principle of Fly-Buck topology, completes circuit simulations, designs and builds an auxiliary power supply prototype for a digital generator' s half-controlled bridge voltage regulation circuit based on Fly-Buck topology, and conducts experimental tests. The results show that the prototype' s secondary-side output exhibits good voltage regulation performance, meeting the requirements of the half-controlled bridge regulator. The study specifically examines how the topology's operating mode affects secondary-side output when the primary side is lightly loaded or unloaded, demonstrating that forced continuous mode operation maintains stable secondary-side output that tracks the primary-side voltage.

2 Working Principle of Fly-Buck Topology

Fly-Buck topology evolves from the conventional synchronous rectifier buck topology by replacing the inductor with a coupled inductor L1 having a secondary winding, adding rectifier diode VD1 and filter capacitor C3 to obtain isolated auxiliary power output VSEC, as shown in [Figure 1: see original paper].

The working principle resembles that of conventional synchronous rectifier Buck topology. The analysis proceeds from both theoretical operation and circuit simulation perspectives.

The switching devices VT1 and VT2 are driven by complementary PWM pulses with dead time. Assuming duty cycle D and period T, and that both primary output voltage VPRI and secondary output voltage VSEC remain constant in steady state, [Figure 2: see original paper] shows the current waveforms of the primary and secondary windings of coupled inductor L1, where iLP is the primary winding current, iLS is the secondary winding current, and vHDRV is the gate drive PWM pulse voltage for VT1.

Operating principle:

(1) During 0 ~ DT, VT1 conducts while VT2 is off. The dotted terminal of L1' s primary winding is at higher potential than its undotted terminal, storing energy in the coupled inductor. Rectifier diode VD1 is reverse-biased, making the secondary loop effectively open-circuited. The equivalent circuit is shown in [Figure 3: see original paper], allowing L1 to be treated as a single-winding inductor. The primary winding current iLP increases linearly according to the relationship described in the analysis, where LLP represents the primary winding inductance and VIN is the DC input voltage. The reverse voltage VR across VD1 is given by the equation involving the turns ratio NP/NS.

(2) During DT ~ T, VT1 is off while VT2 conducts. The undotted terminal of L1' s primary winding is at higher potential than its dotted terminal, with a voltage difference of VPRI across the primary winding. Rectifier diode VD1 becomes forward-biased. [Figure 4: see original paper] shows the equivalent circuit during this interval, with the secondary loop equivalent circuit shown in [Figure 5: see original paper], where LLK is the leakage inductance referred to the secondary side, VF is VD1' s forward voltage drop, and IS is the secondary output current. Assuming VPRI, VSEC, and

VF remain constant and neglecting line resistance, the secondary winding current iLS increases linearly as described by the governing equation.

The relationship between secondary output current IS and secondary winding current iLS leads to the maximum current iLSmax at time T. The time-domain relationship for iLS is piecewise-defined: zero during 0 ~ DT and following a linear expression during DT ~ T.

In steady state, the energy stored and released by L1 over one switching cycle are equal. Applying volt-second balance principles and integrating over the respective time intervals yields the relationship between input voltage VIN and primary output voltage VPRI: VPRI = DVIN.

During DT ~ T, the primary winding current iLP follows a linear relationship. When leakage inductance LLK is small or secondary output current ISEC is small, the product term in the governing equation approximates zero, yielding the relationship VSEC   VPRI. Substituting this into the earlier expression gives the reverse voltage across VD1 as VR   VIN.

This analysis shows that secondary output voltage VSEC can be stabilized without additional feedback loops. When leakage inductance is small or secondary current is low, the output closely tracks the primary voltage VPRI. In flyback topology, switching devices withstand VIN + VSECNP/NS during turn-off, whereas Fly-Buck topology devices VT1 and VT2 only withstand VIN, allowing selection of lower-voltage-rated switches without snubber circuits. Therefore, Fly-Buck topology offers isolated output with fewer components, lower cost, smaller footprint, and simpler structure. Multiple isolated outputs can be obtained by adding corresponding windings and rectifier-filter circuits to L1, with the same theoretical analysis remaining valid.

When the primary side is unloaded or lightly loaded while the secondary side carries load, the primary winding current iLP decreases to zero and then reverses direction during DT ~ T, as shown in [Figure 2: see original paper]. Fly-Buck topology operates in forced continuous mode [7], where energy stored in L1 during 0 ~ DT is completely released, and energy is supplied from primary to secondary output.

Clearly, when the primary side is unloaded or lightly loaded, forced continuous mode operation is necessary to ensure stable secondary output voltage that tracks the primary output; otherwise, the converter enters discontinuous current mode, preventing energy transfer from primary to secondary and causing significant secondary voltage droop.

Therefore, when designing low-power isolated auxiliary power supplies using Fly-Buck topology, synchronous rectifier controllers capable of forced continuous mode operation must be selected. This ensures VT2 remains conducting when iLP reaches zero, allowing reverse current flow through VT2' s channel and enabling energy transfer from primary to secondary output.

3 Circuit Simulation of Fly-Buck Topology

Based on the theoretical analysis, a Fly-Buck topology simulation circuit was designed and built, as shown in [Figure 6: see original paper]. The simulation results verify the theoretical analysis, confirm the topology’ s feasibility and practicality, and provide the winding current waveforms of the coupled inductor in both continuous and forced continuous modes during steady-state operation.

The main simulation parameters are: input voltage VIN = 24V, primary output voltage VPRI = 5V, PWM drive pulse period T = 3.4 s, rectifier diode VD1 forward voltage drop VF = 0.5V, primary winding inductance LLP = 25 H, secondary-referred leakage inductance LLK = 3.6 H, secondary output voltage designed at 5V, secondary load as constant-current type with 200mA value, and turns ratio NP/NS = 5/6 to account for the diode forward voltage drop.

[Figure 7: see original paper] and [Figure 8: see original paper] show the primary and secondary winding current waveforms of L1 when the Fly-Buck converter operates in continuous mode and forced continuous mode, respectively. In continuous mode, primary output current IP = 1A, secondary output current IS = 200mA, and secondary output voltage VSEC = 5.11V. In forced continuous mode, primary output current IP = 0, secondary output current IS = 200mA, and VSEC = 5.09V.

The simulation waveforms and results effectively validate the theoretical analysis of Fly-Buck topology operation. The secondary output is hardly affected by the primary output, and when the primary is unloaded, the secondary output remains stable and tracks the primary output due to forced continuous mode operation.

4 Fly-Buck Topology in Half-Controlled Bridge Voltage Regulator Circuit

Based on the theoretical analysis and circuit simulation, an auxiliary power supply prototype was designed and built for the half-controlled bridge voltage regulator circuit of a digital generator using Fly-Buck topology. Current waveforms in both continuous and forced continuous modes were measured, and multiple data sets of the relationship between secondary output voltage VSEC and secondary output current IS were obtained. The data show that with secondary output current IS ranging from 0 to 500mA, the load regulation of the secondary output is less than ±5%, demonstrating good voltage regulation performance that meets the half-controlled bridge regulator’ s requirements.

A digital generator mainly consists of a gasoline engine, medium-frequency generator, and inverter. The inverter converts the generator’ s three-phase AC output to the required AC output through an AC-DC-AC conversion stage [8-9]. The AC-DC stage in the inverter is shown in [Figure 9: see original paper], where U, V, W represent the generator’ s three-phase high-voltage outputs and A, B represent the single-phase low-voltage output. The half-controlled bridge voltage regulator circuit samples the DC bus voltage, compares it with a reference voltage using hysteresis comparison, and outputs trigger pulses for single-phase thyristors VT1, VT2, VT3 to stabilize the DC bus voltage VBUS at approximately 400V. Consequently, a 400V potential difference exists between the reference ground GND1 of the half-controlled bridge regulator circuit and the reference ground GND0 of the auxiliary power circuit, necessitating isolated power output VSEC from the auxiliary supply.

The conventional approach uses off-the-shelf isolated power modules to obtain VSEC, which simplifies the design process but increases overall inverter cost [10]. To reduce cost, an auxiliary power supply prototype based on Fly-Buck topology was designed for the half-controlled bridge regulator circuit, with the physical prototype shown in [Figure 10: see original paper].

The auxiliary power supply design requirements are: DC input voltage VIN varying between 10–24V, secondary output voltage VSEC = 5V with secondary current IS ranging from 25–170mA, and primary output voltage VPRI = 5V with primary load current IP ranging from 500–1300mA. The prototype' s main circuit parameters are listed in .

[Figure 11: see original paper] and [Figure 12: see original paper] show the measured current waveforms of L1' s windings in continuous and forced continuous modes, respectively. In both modes, input voltage VIN = 24V. In continuous mode: IP = 1.70A, VPRI = 5V, IS = 0.50A, VSEC = 4.82V. In forced continuous mode: IP = 0, VPRI = 5V, IS = 0.50A, VSEC = 4.76V. The waveforms and voltage data demonstrate that regardless of operating mode, the secondary winding current iLS waveform remains essentially unchanged, and secondary output voltage VSEC is unaffected by primary load current IP, maintaining stable output.

In the actual prototype circuit, the series equivalent resistance of output filter capacitors C2 and C3, line impedance, and winding resistance of L1 cannot be neglected, and the capacitor voltages are not perfectly constant. Therefore, during DT ~ T, the winding currents iLP and iLS do not follow perfectly linear relationships as described in the ideal equations, though the fundamental relationships between iLP and iLS remain valid.

As indicated by the governing equation, secondary output voltage VSEC calculated using the ideal relationship decreases slightly with increasing secondary output current IS due to leakage inductance LLK. Experimental measurements were therefore conducted to characterize this relationship.

presents the measured relationship between secondary output voltage VSEC and secondary output current IS for both operating modes. In continuous mode, primary output current IP = 1.70A with VPRI = 5V. In forced continuous mode, the primary output is unloaded with VPRI = 5V.

The data show that when the primary side is unloaded, the prototype operating in forced continuous mode maintains stable secondary output voltage VSEC with minimal influence from primary output current IP. As secondary output current IS increases, the leakage inductance term in the governing equation becomes non-negligible, causing a slight secondary voltage drop. Nevertheless, with IS ranging from 0 to 500mA, the load regulation remains below ±5%, demonstrating good voltage regulation performance.

Thus, the designed auxiliary power supply prototype meets the voltage and current requirements of the half-controlled bridge regulator. It reduces inverter cost without increasing circuit complexity—simply replacing the inductor in the original synchronous buck topology with a coupled inductor having auxiliary windings and adding corresponding rectifier-filter circuits yields isolated output. The design offers simple structure, small footprint, and low cost. In practical applications, minimizing leakage inductance LLK helps achieve better secondary-side load regulation.

5 Conclusion

This paper analyzed and studied the working principle of Fly-Buck topology, verified the theoretical analysis through circuit simulation, and designed an auxiliary power supply prototype for a digital generator’ s half-controlled bridge voltage regulator circuit based on Fly-Buck topology. Experimental results demonstrate that the prototype’ s secondary output exhibits good voltage regulation performance within a certain load current range, meeting the auxiliary power requirements of the half-controlled regulator. The study specifically investigated the impact of operating mode on secondary-side regulation when the primary side is unloaded or lightly loaded, showing that forced continuous mode operation maintains stable secondary output. Without requiring additional feedback loops for the secondary output, Fly-Buck topology achieves stable secondary-side voltage. When the primary side is unloaded or lightly loaded, forced continuous mode operation ensures secondary output stability. Therefore, Fly-Buck topology simplifies the design of low-power isolated auxiliary power supplies with advantages of low cost, small footprint, and simple circuit structure.

References

[1] Sanjaya Maniktala. Switching Power Suppliers A to Z[M]. USA: Elsevier, 1999.
[2] Zhang Lanhong, Chen Daolian. Research on switch stress suppression technique of flyback converters[J]. Power Electronics, 2002, 36(2): 29-31.
[3] Liu Shusheng, Cao Xiaosheng, Ma Yibo. Design and analysis on feedback energy loss of RCD clamping flyback converters[J]. Proceedings of the CSEE, 2010, 30(33): 9-15.
[4] Xiang Fang, Yu Meng. Isolated bias power supply for IGBT gate drivers using the fly-buck converter[C]. IEEE Applied Power Electronics Conference and Exposition, 2015: 2373-2379.

[5] Fang Xiang, Liu Wei, Chadaga Anoop. Fly-buck adds well-regulated isolated outputs to a buck without optocouplers[OL]. EDN Network, 2014. https://www.edn.com/design/power-management/4429791/Product-How-to-Fly-Buck-adds-well-regulated-isolated-outputs-to-a-buck-without-optocouplers-.

[6] Liu Yan, Wang Bolin, Wang Mengting. Study of a synchronous rectifier buck-flyback topology[J]. Power Electronics, 2010, 44(1): 39-40.

[7] Liu Song. The principle and application of three operation modes of buck converter at light load[J]. Power Electronics, 2007, 41(11): 75-76.

[8] Chen Renwu. Research and development of intelligent controller for small digital generator[D]. Hangzhou: Zhejiang University, 2012.

[9] Fu Shengyang. Research on inverter and controller for gasoline generator set[D]. Hangzhou: Zhejiang University, 2007.

[10] Liu Yan. Research on control technology of rectifier power supply for digital generator[D]. Chongqing: Chongqing University, 2010.

[11] Yu Yuexiang, Wang Qing, Ke Xianbo, et al. Adaptive simulation study on typical criteria of loss-of-excitation protection for turbo generator[J]. Electrical Application, 2016, 35(19): 88-93.

Note: Figure translations are in progress. See original paper for figures.