Space Power DC-DC Converter Research Postprint

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Abstract

The Non-isolated Weinberg Converter (NIWC) offers advantages such as high power density and ease of paralleling, making it suitable as a downstream converter for Battery Discharge Regulators (BDR) and Sequential Switching Shunt Maximum Power Regulators (S3MPR) or Sequential Switching Series Shunt Maximum Power Regulators (S4MPR) in aerospace power systems. This paper analyzes the operating principle of this converter, derives its small-signal model, and designs the main circuit parameters while ensuring output voltage and current ripple requirements are met. After analyzing the system transfer function using Matlab, an active lead-lag compensation network is designed to ensure the system' s rapidity and stability. Simulation and experimental results verify the correctness of the system design.

Full Text

Study of DC-DC Converter for Space Power System

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Abstract

With high power density and easy paralleling capability, the non-isolated Weinberg converter (NIWC) is suitable for use as a battery discharge regulator (BDR) and as the post-regulator following sequential switch shunt maximum power regulators (S3MPR) or sequential switch series shunt maximum power regulators (S4MPR) in space power systems. This paper analyzes the operating principle of the converter, derives its small-signal model, and designs the main circuit parameters while ensuring acceptable output voltage and current ripple. After analyzing the system transfer function using Matlab, an active lead-lag compensation network is designed to ensure rapid response and stability. Simulation and experimental results verify the correctness of the system design.

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2 Principle Analysis of NIWC

The satellite power system is responsible for generating, storing, converting, and distributing electrical energy, representing a critical subsystem of the spacecraft. Over 90% of spacecraft currently employ solar array/battery (SA/B) power systems. The Power Control Unit (PCU) manages the distribution of energy generated by the solar array and controls battery charging/discharging to maintain the power bus voltage within specified limits throughout the orbital mission. Presently, PCU bus voltages developed in China include three levels: 28V, 42V, and 100V [1].

When a satellite enters eclipse and cannot obtain power from the solar array, or when the solar array provides insufficient power during illumination, the battery supplies energy to the bus to maintain stable bus voltage. During this process, the Battery Discharge Regulator (BDR) plays a primary role. Research is needed to develop a high-efficiency DC-DC module that balances dynamic and steady-state performance for use as a BDR, enabling the battery to maintain good bus performance during discharge [2].

Due to the strongly nonlinear output characteristics of solar cells, combining Maximum Power Point Tracking (MPPT) technology with sequential switch shunt regulator (S3R) or sequential switch series shunt regulator (S4R) topologies yields S3MPR and S4MPR systems [3] that can adjust the solar array operating point in real time to maintain operation near the maximum power point, maximizing solar array output utilization. Since the bus voltage remains at the solar array' s maximum power point voltage, this voltage varies with temperature and illumination conditions. To obtain a stable DC bus, a high-efficiency, high-power-density DC-DC converter must be cascaded after the S3MPR or S4MPR regulator [4].

When selecting topologies for BDR and post-regulators for S3MPR or S4MPR, key considerations include efficiency, complexity, stability, and boost capability. The Non-isolated Weinberg Converter (NIWC) satisfies these requirements effectively. NIWC has been successfully applied in satellites in Europe and the

United States, including Olympus, Inmarsat-11, Eurostar 3000, SpaceBus 4000, and BepiColombo, while domestic research remains in the study and experimental phase [4]. This paper analyzes the operating principle of NIWC, establishes its small-signal mathematical model, analyzes system stability, and proposes design methods for the main circuit parameters and control loop, verified through simulation and experimentation.

2.1 Operating State Analysis

[Figure 1: see original paper] shows the circuit topology of NIWC. Neglecting leakage and magnetizing inductances, the non-isolated Weinberg converter operates in two ideal states: (1) When Q1 or Q2 conducts, VD2 or VD1 conducts respectively while VD remains off; (2) When both Q1 and Q2 are off, VD conducts. Output voltage control is achieved by generating PWM signals to control the conduction and turn-off of Q1 and Q2. Q1 and Q2 conduct alternately, with two MOSFET switching events per switching period, resulting in an equivalent PWM frequency double the actual switching frequency. This doubles the converter bandwidth without increasing switching losses while effectively reducing magnetic component and filter sizes, thereby improving power density.

2.2 Steady-State DC Gain

In both operating states, the output current is limited by the coupled inductor or transformer, resulting in continuous output current [5]. The voltage gain of the Weinberg circuit is therefore:

$$V_{OUT} = (1 + D)V_{IN}$$

where $D = t_{ON}/T_{SWITCHING}$ and $T_{SWITCHING}$ is the actual switching period. The continuous output current with low ripple characteristic of NIWC facilitates current-mode control and enables easy paralleling of multiple modules for power expansion.

2.3 Small-Signal Model

Using the state-space averaging method, the small-signal equivalent circuit model of NIWC is obtained as shown in [Figure 2: see original paper] [6]. From this model, the transfer function of NIWC under voltage-mode control is:

$$G_{vd}(s) = \frac{\hat{v}_{out}(s)}{\hat{d}(s)} = \frac{4LCs^2 + ...}{1 + ...}$$

The idealized model of NIWC is second-order as seen from the transfer function in equation (2), which simplifies control system design.

3 Main Circuit and Compensation Network Design

3.1 Main Circuit Parameter Design

The DC-DC converter designed in this paper has the following specifications: bus voltage 42V; input voltage 25-35V; output power 300W; switching frequency 100kHz; output current ripple 10%; bus voltage ripple 1%. Based on these requirements, the main circuit parameters are optimized.

(1) Coupled Inductor Design: The output current ripple is determined by the coupled inductor value according to:

$$\Delta i_{out} = \frac{V_{IN} D(1-D)}{4 L_{on} f_s}$$

where f_s is the equivalent switching frequency. Equation (3) shows that output current disturbance is maximum at $D = 0.414$. Since the duty cycle range in this design is 0.2-0.68, the inductance value L must satisfy the 10% ripple requirement at $D = 0.414$. Calculation yields $L_{on} = 12.6\mu H$, and with margin, $L_{on} = 20\mu H$ is selected.

(2) Filter Capacitor Design: To ensure the output voltage ripple of the Weinberg circuit meets specifications, an output filter capacitor is required. The design criterion for the output filter capacitor is:

$$C = \frac{\Delta I_{out}}{8 \Delta V_o f}$$

Calculation yields $C = 1.06\mu F$, and with margin, $C = 10\mu F$ is selected.

3.2 Compensation Network Design

To maintain stable output voltage under input voltage fluctuations and load variations after transient regulation, closed-loop system design is necessary. The simplest approach is voltage single-loop compensation [7].

[Figure 3: see original paper] shows the NIWC control system block diagram, where $G_{vd}(s)$ is the transfer function from duty cycle $\hat{d}(s)$ to output $\hat{v}_o(s)$, $G_m(s)$ is the PWM modulator transfer function, $H(s)$ represents the feedback divider network transfer function, and $G_c(s)$ is the compensation network transfer function. From this diagram, the original loop gain function is:

$$G_o = G_m G_{vd} H = \frac{V_{IN}(1+D)}{V_m K (4LCs^2 + 4Ls/R + 1)}$$

where V_m is the amplitude of the sawtooth wave in the PWM modulator and K is the feedback divider coefficient, set to 3V and 8.3 respectively. Substituting the corresponding parameters yields the Bode plot of the original loop gain function $G_o(s)$ shown in [Figure 4: see original paper].

The Bode plot reveals that the system has low gain at low frequencies without a -20dB/dec slope, and the mid-frequency region does not cross 0dB with a -20dB/dec slope. Additionally, typical design targets are phase margin around 45° and gain margin around 10dB, but the original loop gain function $G_o(s)$ exhibits insufficient phase margin. Therefore, although stable, the system would have large output overshoot and long settling time, requiring compensation design. Based on the characteristics of $G_o(s)$, the compensation network shown in [Figure 5: see original paper] is selected.

The transfer function of the active lead-lag compensation network in [Figure 5: see original paper] is:

$$G_c(s) = \frac{(1 + sR_2C_1)[1 + s(R_1 + R_3)C_3]}{sR_1(C_1 + C_2)(1 + sR_3C_3)\left[1 + s\frac{R_2C_1C_2}{C_1+C_2}\right]}$$

This active lead-lag compensation network has two zeros and three poles. Designing these parameters yields $R_1 = 3.92k\Omega$, $R_2 = 10k\Omega$, $R_3 = 54.4k\Omega$, $C_1 = 5.7nF$, $C_2 = 0.8pF$, and $C_3 = 14.5nF$. Substituting these parameters gives the transfer function of the compensation network $G_c(s)$.

The Bode plot of the compensated loop gain function $G(s)$ is shown in [Figure 6: see original paper]. The compensated system exhibits high gain at low frequencies with a -20dB/dec slope, ensuring good steady-state accuracy. The magnitude-frequency characteristic crosses 0dB at 40kHz with a -20dB/dec slope, achieving a phase margin of 63.5° and gain margin of 19.7dB, which guarantees high stability margins.

4 Simulation and Experimental Verification

To verify the designed NIWC system, a simulation circuit was first built in Saber as shown in [Figure 7: see original paper]. The system comprises four modules: main circuit, feedback circuit, compensation circuit, and control/driver circuit. Simulation waveforms are presented in [Figure 8: see original paper] and [Figure 9: see original paper].

Based on the simulation, an experimental platform was constructed as shown in [Figure 10: see original paper]. The main circuit follows the NIWC topology in [Figure 1: see original paper], using IRF540 MOSFETs, with the control circuit implemented using the SG3525 chip for system compensation and PWM generation. Testing demonstrates that the converter stably outputs 42V for input variations between 25V and 35V. Experimental waveforms at 28V input are shown in [Figure 11: see original paper] and [Figure 12: see original paper].

Both simulation and experimental results show that under rated load (7A output current) and large input voltage transients, the output voltage adjusts rapidly to achieve stable 42V output with voltage ripple within 1%. This confirms the rationality of the main circuit parameter design and the good stability and dynamic performance of the closed-loop control system.

5 Conclusion

Based on fundamental DC-DC converter analysis principles, this paper establishes a small-signal model for the non-isolated Weinberg converter, analyzes its transfer function, designs a compensation network, and constructs simulation and experimental circuits. The results demonstrate that the converter not only achieves boost functionality but also offers high power density, high efficiency, and continuous output current. This research provides a theoretical foundation for developing BDR circuits and post-regulators for S3MPR or S4MPR in space power systems.

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