

# Research on Single-Input Multiple-Output Converter for Rotorcraft Unmanned Aerial Vehicle

Yifan Gan<sup>1,2</sup> and Chunxiao Xu<sup>1</sup>

1. Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, 100190, China

2. University of Chinese Academy of Sciences, Beijing, 100049, China

Email: ganyifan@mail.iee.ac.cn

**Abstract.** To satisfy the different voltage requirements of different power units in small rotorcraft unmanned aerial vehicle (UAV), we investigated two different single-input and multiple-output converters, three-output flyback converter and single inductor three-output Buck converter. The hardware components and operating principles of the two single-input and multiple-output converters were analyzed, and the control strategies of them were designed. Furthermore, operations of the two single-input multiple-output converters were simulated using Simulink in Matlab. We found that the three-output flyback converter can be used in the design of UAV when its components are settled and the voltage quality requirements are not strict. When the expansibility of component and high-stable voltage are required for the design of UAV, the single inductor three-output Buck converter should be used.

## 1. Introduction

Due to its low cost, high cost-effectiveness, strong survivability, mobility, ease of use, strong adaptive capacity to environment, and no risk of injury, small rotorcraft unmanned aerial vehicle (UAV) was widely used in transport, detection, investigation, fighting against terrorism, communication, etc. The application area of small rotorcraft UAV will be more and more widely with the increase in UAV performance [1-4], which will result in the increase of electrical units in UAV. However, the voltage of battery carried by the small rotorcraft UAV is constant, and the voltage required for each power unit may be different. Therefore, a single-input multi-output (SIMO) DC-DC converter that can convert a single voltage to multiple voltages is required[4].

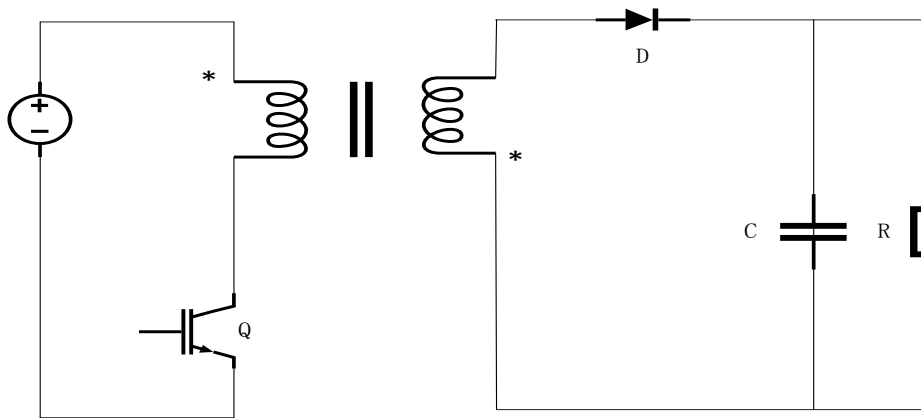
In research of single-input multi-output DC-DC converters, the shunt neutralization of single-input single-output (SISO) DC-DC converters was proposed. The combination of multiple SISO converters with different voltages could produce various voltage outputs. However, this led to the increase of system cost and control complexity[5]. SIMO converters can reduce system complexity and make control easier, and were widely used in renewable energy systems and electric vehicles[6, 7]. In research of topology and control of SIMO converter, a shared ZCS (Zero-Current-Switch) was used to lag the branch topology and soft-switching technology to reduce loss. However, the circuit of SIMO converter has three full-bridge converters, which increased component density and cost, reduced efficiency, and was not suitable for small rotorcraft UAV[8]. To reduce the number of switching tubes and the switching loss, a new SIMO Buck converter was proposed. However, it still has multiple inductors in the circuit topology, which led to complexity of the circuit structure and control strategy[9]. Cavalcanti et al. calculated the switching loss of a single-inductance three-output DC-DC converter model, and analyzed the relation between the power loss of IGBT and circuit and the operating parameters for the direction of specific application [10].



To identify suitable SIMO converter for small rotorcraft UAV, we improved the topology and control strategy of a single-inductor multi-output DC-DC converter, and compared it with a three-output flyback converter.

## 2. Topology and Control Strategy of Three-output Flyback Converter

The flyback converter that has a simple circuit structure, a wide input voltage range, low circuit loss and stable output is suitable for low power multi-output requirement (Fig. 1). [11]. When IGBT is turned on, the DC power supplies power to the primary winding of the transformer; when IGBT is turned off, the power of the primary winding of the transformer is transferred to the secondary winding, and the load resistance is supplied through the freewheeling diode D and the filter capacitor C.



**Figure 1.** Basic structure of flyback converter

In steady state, the average voltage of the inductor in one cycle is 0 according to the volt-second principle.

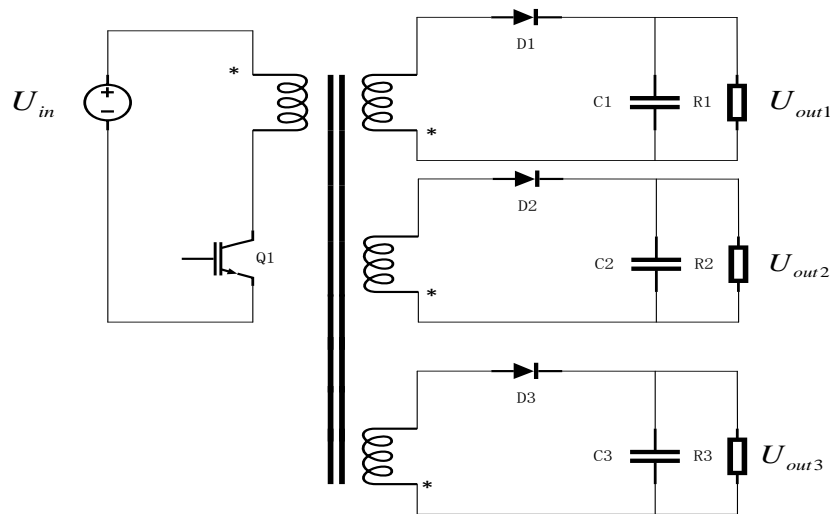
$$V_{in}t_{on} + \left(-\frac{N_1}{N_2}V_o\right)(T_s - t_{on}) = 0 \quad (1)$$

Here,  $V_{in}$  is the input voltage,  $V_o$  is the output voltage,  $t_{on}$  is the on-time of the switch,  $T_s$  is a cycle time,  $\frac{N_1}{N_2}$  is the turns ratio of the primary and secondary sides of the transformer.

Therefore, the transformer ratio of flyback converter can be obtained as follows:

$$M = \frac{V_o}{V_{in}} = \frac{N_2}{N_1} \frac{t_{on}}{T_s - t_{on}} \quad (2)$$

Another feature of the flyback converter is that it can add multiple coils to the secondary winding to generate multiple outputs according to the user's requirement. In our research, a three-output flyback converter was used for further analysis (Fig. 2)[12]. The operating principle of this three-output flyback converter is similar to that of a single output flyback converter.



**Figure 2.** Three-output flyback converter

Similarly, the transformer ratio of the three-output flyback converter can be obtained as follows:

$$\begin{aligned}
 M_1 &= \frac{U_{out1}}{U_{in}} = \frac{N_1}{N_0} \frac{t_{on}}{T_s - t_{on}} \\
 M_2 &= \frac{U_{out2}}{U_{in}} = \frac{N_2}{N_0} \frac{t_{on}}{T_s - t_{on}} \\
 M_3 &= \frac{U_{out3}}{U_{in}} = \frac{N_3}{N_0} \frac{t_{on}}{T_s - t_{on}}
 \end{aligned} \tag{3}$$

Here,  $M_1$ ,  $M_2$  and  $M_3$  are transformer ratios of different branches;  $N_0$  is the number of turns of the transformer primary winding;  $N_1$ ,  $N_2$  and  $N_3$  are numbers of turns of the different branches of the transformer secondary winding;  $U_{in}$  is the input voltage;  $U_{out1}$ ,  $U_{out2}$  and  $U_{out3}$  are output voltages;  $t_{on}$  is the switch on time;  $T_s$  is a cycle time.

In the three branches, the duty ratios of IGBT are the same. Therefore, only one feedback loop is needed, which greatly simplifies the control loop. According to the above analysis, we designed the control strategy of three-output flyback converter as follows: In the three outputs of the converter circuit, the branch that has the feedback loop was defined as the control branch, and other branches were defined as follower branches. The reference voltage was set in the control branch, and the on/off of IGBT was controlled through the appropriate output of duty ratio from the feedback loop. When the duty ratio of IGBT is constant, the given voltage of the branch output is determined by the turns ratio of the primary winding and the secondary winding of the transformer judged from formula (3). Once the hardware circuit of converter is determined, only the voltage of the control branch can be changed. Voltages of the following branches can only be changed proportionally with the change of control branch voltage.

### 3. Topology and Control Strategy of Single Inductor Three Output Buck Converter

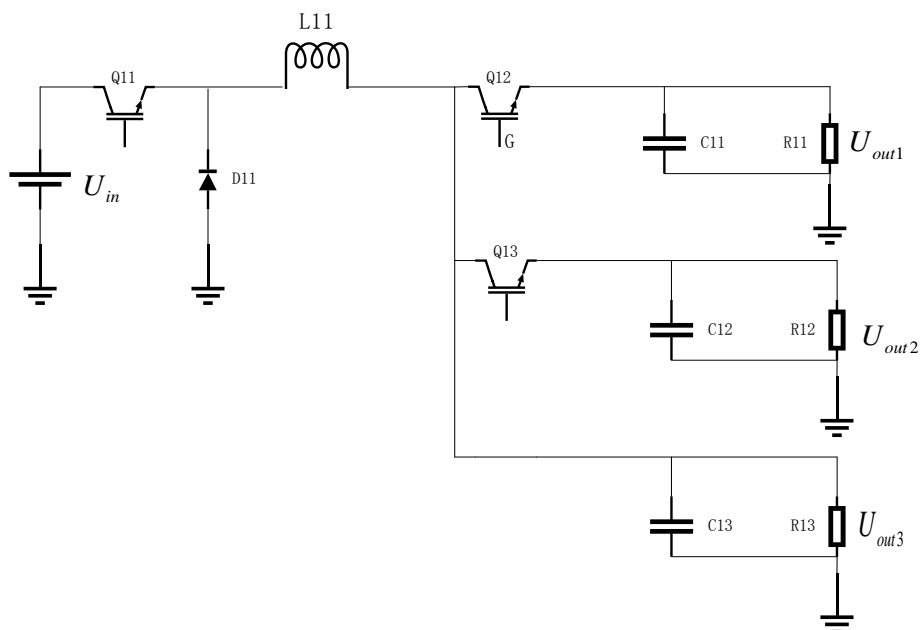
The basic structure of a single-inductor three-output Buck converter is shown in Fig. 3. [13]. When the IGBT  $Q_{I1}$  is turned on and the freewheeling diode  $D_{I1}$  is turned off, the input battery then charges the storage inductor  $L_{I1}$ , the filter capacitor  $C_{I3}$  and the load 3. Meanwhile, the filter capacitor  $C_{I1}$ , the filter capacitor  $C_{I2}$ , the load 1 and the load 2 are charged when the IGBT  $Q_{I2}$  and the IGBT  $Q_{I3}$  are turned on. When the IGBT  $Q_{I1}$  is turned off and the freewheeling diode  $D_{I1}$  is turned on, the energy storage inductor  $L_{I1}$  charges the filter capacitor  $C_{I3}$  and the load 3. At the same time, the filter capacitor  $C_{I1}$ , the filter capacitor  $C_{I2}$ , the load 1 and the load 2 are charged when the IGBT  $Q_{I2}$  and the

IGBT  $Q_{13}$  are turned on. According to the secondary volt balance, the transformer ratio is:

$$M = \frac{U_{out}}{U_{in}} = \frac{t_{on}}{T_s} \quad (4)$$

Here,  $U_{in}$  is the input voltage,  $U_{out}$  is the output voltage,  $t_{on}$  is the switch on time,  $T_s$  is a cycle time.

According to the above analysis, the following control strategy was set as follows: the branch of the load 3 was set as the main control branch, and the reference value of output voltage was set as  $U_{ref3}$  to ensure that  $U_{ref3}$  was the maximum output voltage.  $U_{ref3}$  and the actual output voltage  $U_{out3}$  were input into the corresponding PID controller, and then the PID controller output to the PWM generating device to control the on/off of the IGBT  $Q_{11}$  of the main control branch, and output the required waveform. The load 1 and load 2 branches were follower branches, and the reference values of output voltages of  $U_{ref1}$  and  $U_{ref2}$  were set by the comparison control method. The actual values of output voltages of  $U_{out1}$  and  $U_{out2}$  were compared with  $U_{ref1}$  and  $U_{ref2}$ , respectively. When  $U_{out1}$  and  $U_{out2}$  were less than  $U_{ref1}$  and  $U_{ref2}$ , the IGBT of the corresponding branch was turned on. When  $U_{out1}$  and  $U_{out2}$  were greater than  $U_{ref1}$  and  $U_{ref2}$ , the IGBT of the corresponding branch was turned off. These could ensure the simplicity and feasibility of the control method. Moreover, the control loop was reduced greatly.



**Figure 3.** Basic structure of single inductor three output Buck converter

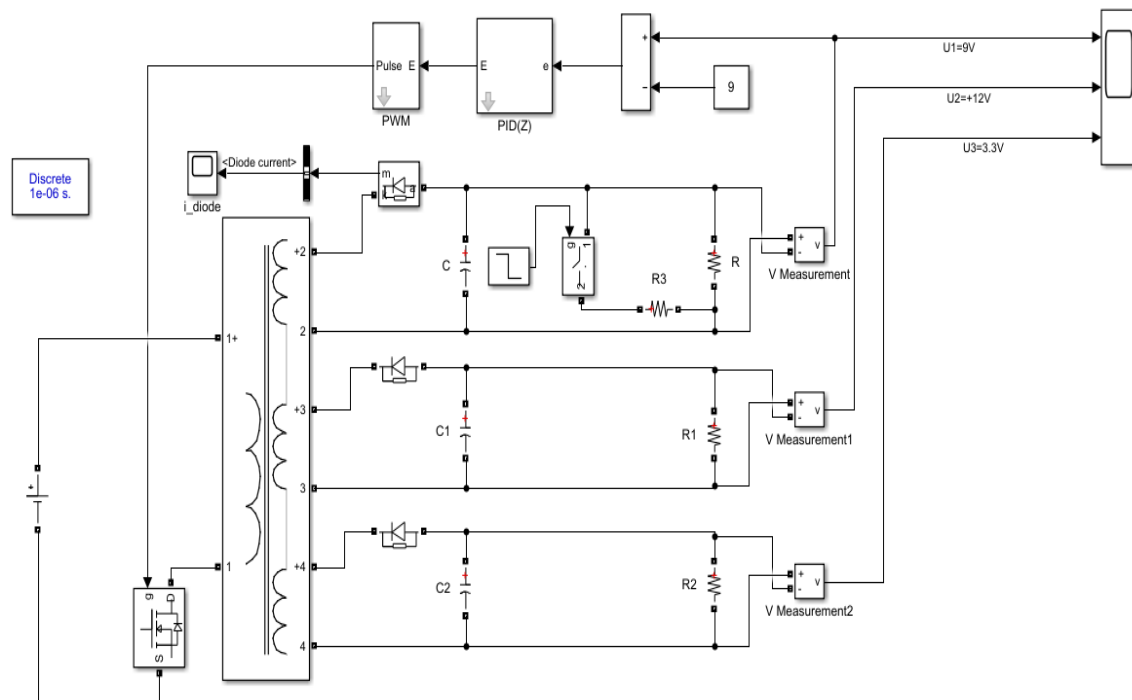
#### 4. Simulation of Single-Input Multi-Output Converters

The three-output flyback converter and the single-inductor three-output Buck converter were simulated according to the actual situation of the small rotorcraft UAV system. The simulation tool was Simulink in Matlab. The simulation requirements were as follows: the input voltage was 24V; three output voltages were 3.3V, 9V and 12V, respectively; the required voltage fluctuation did not exceed 5%; the voltage fluctuation was required to be less than 5% when any load changed.

##### 4.1. Simulation of the Flyback Converter with Three Outputs

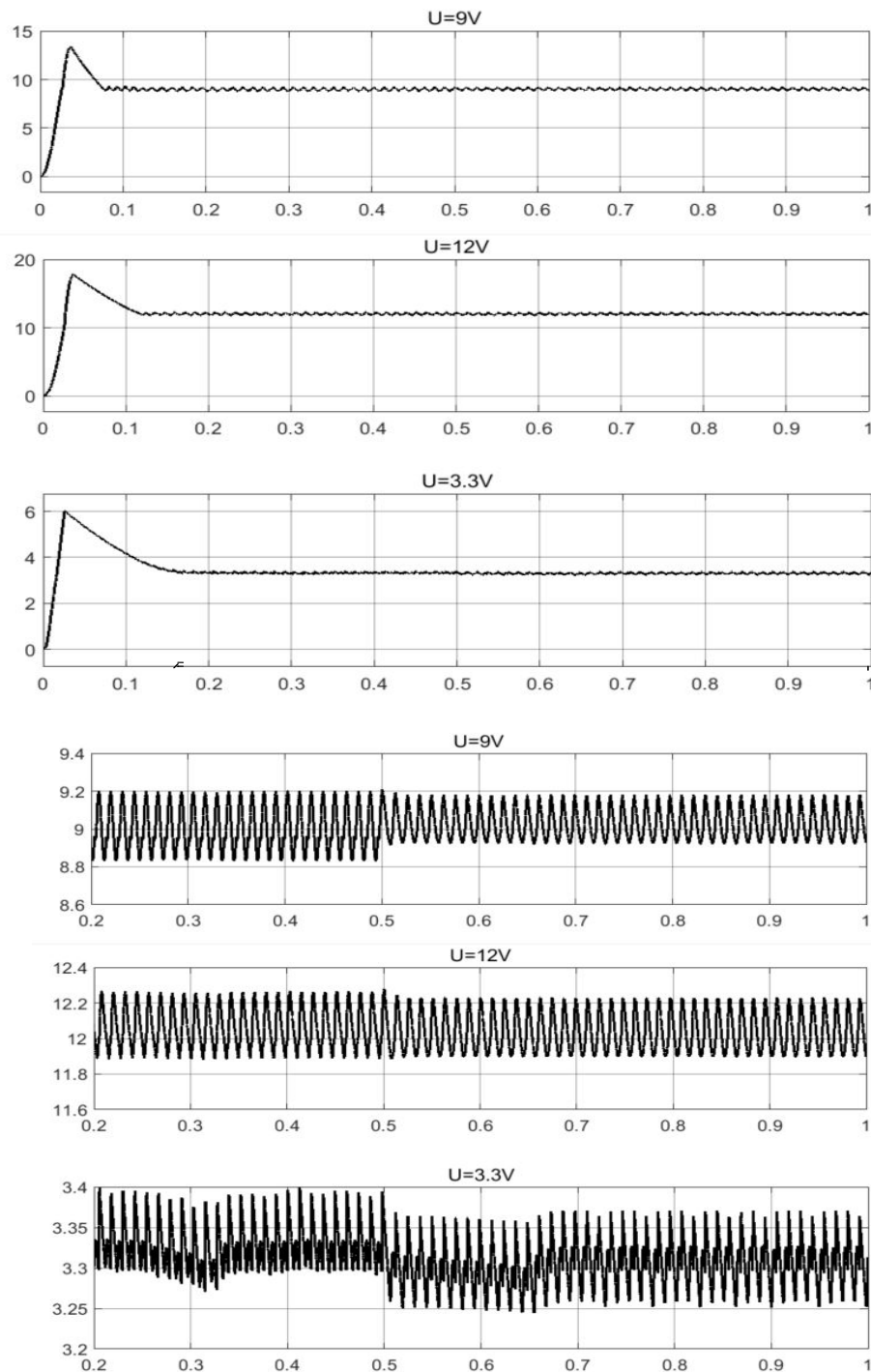
The main branch of the three-output flyback converter was controlled by voltage plus PID whose parameters were 30, 0.1 and 0, respectively. The follower branches were open loop controlled. The load was set as the resistive load with  $10\Omega$  to verify the stability of the circuit when the load changed, after 10s, the  $10\Omega$  resistive load was connected in parallel to the main control branch to reduce the

load. The simulation circuit was shown in Fig. 4.



**Figure 4.** Three-output flyback converter simulation circuit

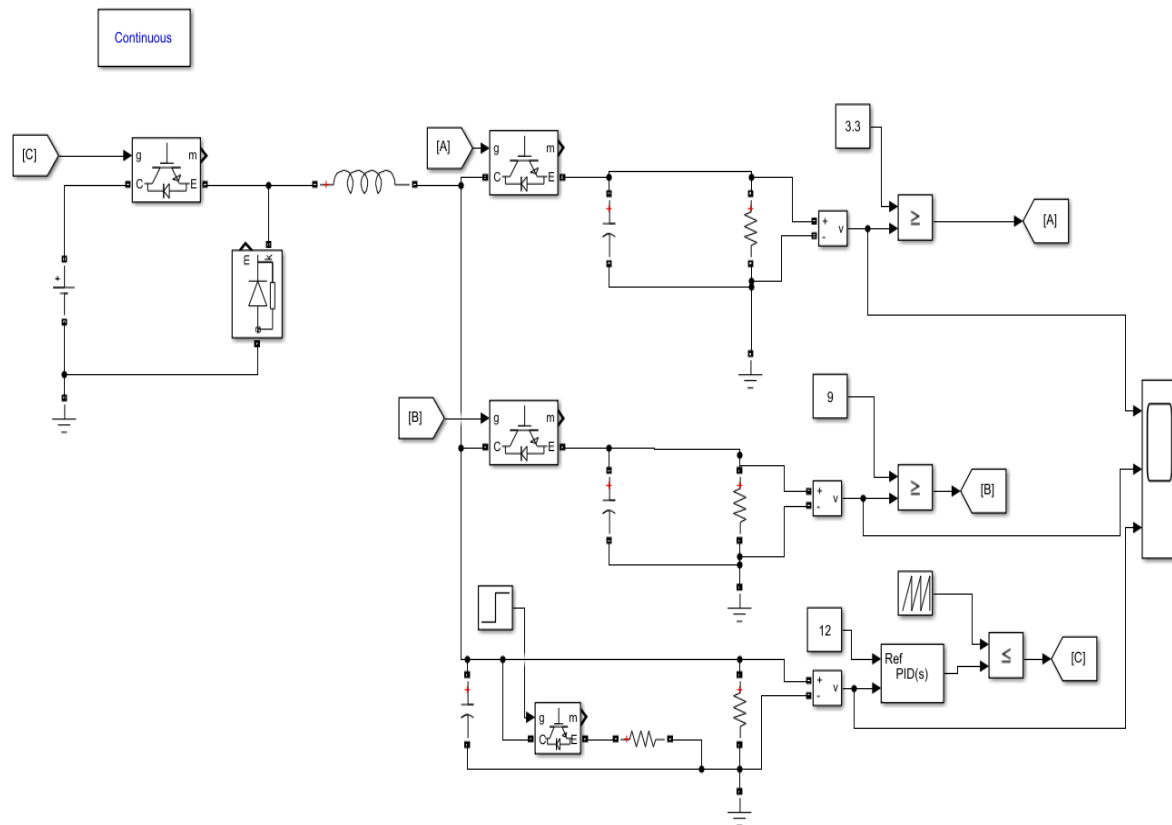
The simulation results were shown in Fig. 5. The three outputs of the three-way output flyback converter were overshooted, which were larger than 50% of the required output voltages before 0.15s. When the load changed abruptly at 0.5s, the output voltages did not change significantly. After 0.15s, the outputs were stable, and the voltage fluctuation of the three-output flyback converter did not exceed 5%. Before 0.5s, the output voltage of the main control branch was among the range of 8.8V~9.2V. The fluctuation was approximately 2.2%. In the follower loops, the output voltage of the branch with 12V reference voltage was between 11.8 and 12.2V with a fluctuation of approximately 1.7%. The output voltage of the other branch with 3.3V reference voltage was between 3.3V and 3.4V with a fluctuation of approximately 3%. After 0.5 s, the voltage fluctuations became smaller after the load was reduced, which satisfied the requirements.



**Figure 5.** Three-output flyback converter output with partial enlargement

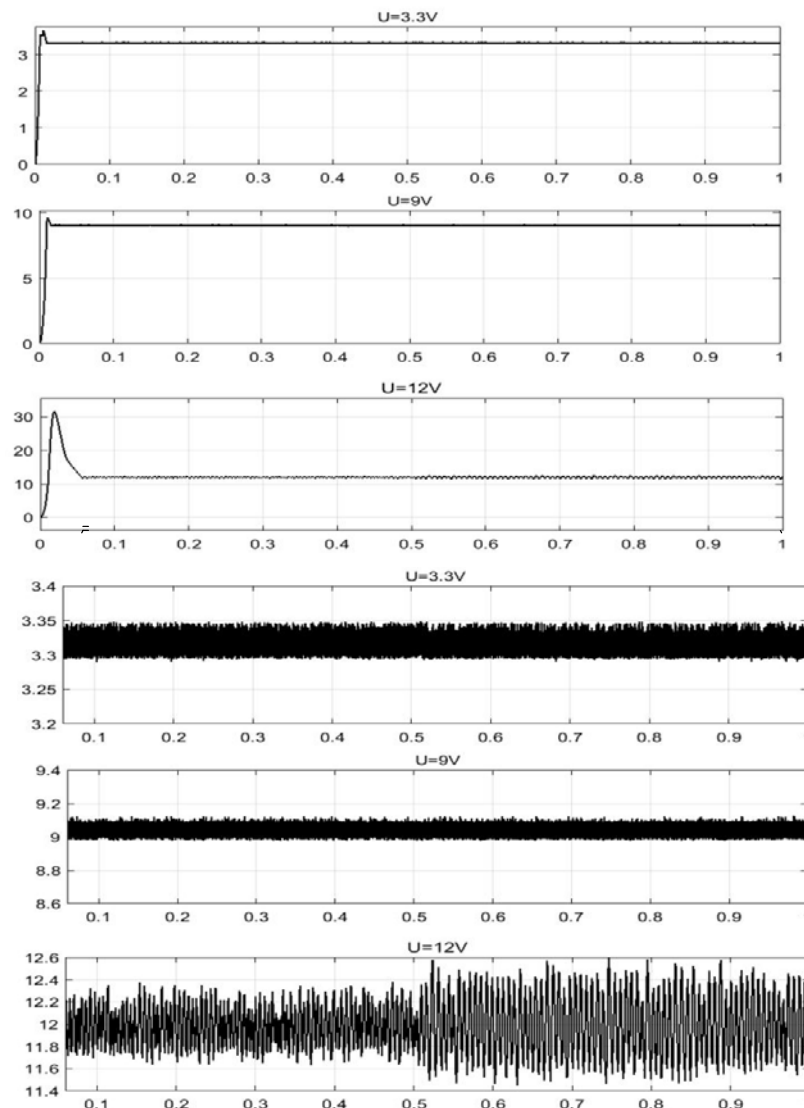
#### 4.2. Simulation of Single Inductor Three Output Buck Converter

In the single-inductance three-output Buck converter, the branch with 12V reference voltage output was set as the main control branch, which was controlled by voltage feedback plus PID. The PID parameters were 150, 0.1 and 1. The branches with 9V and 3.3V reference voltage outputs was set as follower branches, which were controlled by comparison control. The load was set as a resistive load of  $10\ \Omega$ . A  $10\ \Omega$  resistive load was in parallel with the main control branch after 0.5 s. The simulation circuit was shown in Fig. 6.



**Figure 6.** Single inductor three-output buck converter simulation circuit

The simulation results were shown in Fig. 7. The overshoots of the two follower branches were extremely small, while the overshoot of the main control branch was larger than twice of the reference voltage. After 0.05s, the voltages of all branches were stable and the adjustment time was short. When the 0.5s load was reduced, almost no change was found in the output voltage. When the voltage outputs after 0.05s were amplified, we found that fluctuations of the voltage outputs of the three branches did not exceed 5% of the reference voltages. The output voltage of the branch with 3.3V reference voltage was 3.3 V~3.35V, and the fluctuation was about 1.5%. The voltage output of the branch with 9V reference voltage was between 9V~9.1V, The fluctuation was about 1.1%. The actual output value of the main control branch was between 11.7V~12.3V. The voltage fluctuation was about 2.5%. After 0.5s, the voltage fluctuation of the main control loop increased to about 4.2%.



**Figure 7.** Single inductor three output Buck converter output with partial enlargement

#### 4.3. Comparison of Simulation Results

The follower branch of the single-inductance three-output Buck converter had a very small overshoot which only oscillated at a high frequency above the reference voltage compared with that of the three output flyback converter (Fig.5, Fig.7). However, the overshoot of the three output flyback converter oscillated around the reference voltage with a low frequency. The main control branch of the single-inductance three-output Buck converter had a larger overshoot and a larger voltage oscillation compared with those of the three output flyback converter. The overshoot oscillated around the reference voltage with a high frequency. However, the adjustment time is shorter than 0.05s. The quality of voltage output of the main control branch in the three output flyback converter was higher than that of the single-inductance three-output Buck converter.

The improvement of the voltage output quality of the single-inductor three-output buck converter can be achieved by increasing the follower branch with better voltage output. The main control branch can be connected to a smaller load to improve the quality of voltage output, though this will sacrifice a small amount of power and heat dissipation.

#### 5. Conclusion

The three output flyback converter, which has fewer components, simple circuit structure and wide

voltage output, can meet the power supply that the output voltage is higher than the input voltage. However, the voltage output quality of the three output flyback converter is poor compared to the single-inductor three-output Buck converter. In addition, once the circuit is completed, only the reference voltage of the main control branch in the three output flyback converter can be adjusted. The reference voltages of the follower branches can only be changed proportionally. Furthermore, the power interface cannot be reserved. Therefore, the three output flyback converter is only suitable for the design of small rotorcraft UAV with shaped component and low voltage quality requirement. If extensibility is required for the design of a small rotorcraft UAV, the three output flyback converter is difficult to power the functional components.

The voltage output quality of the single-inductor three-output Buck converter is high. Moreover, the single-inductor three-output Buck converter is easy to expand, and the reference voltage of branch in the single-inductor three-output Buck converter is easy to adjust. Therefore, when the single-inductor three-output Buck converter is used for the design of a small rotorcraft UAV, it can meet the power demand of various functional components in the UAV at the same time.

## 6. References

- [1] G. Ludeno, I. Catapano, A. Renga, A. R. Vetrella, G. Fasano, F. Soldovieri. Assessment of a micro-UAV system for microwave tomography radar imaging[J], *Remote Sensing of Environment*, 2018, 212:90-102.
- [2] E. J. Lee, S. Y. Shin, B. C. Ko, C. Chang. Early sinkhole detection using a drone-based thermal camera and image processing[J], *Infrared Physics & Technology*, 2016, 78:223-232.
- [3] Selvaganapathy S, Ilangumaran A. Design of Quadcopter for Aerial View and Organ Transportation Using Drone Technology [J]. *Asian Journal of Applied Science and Technology (AJAST)*, 2017, 1(3): 311-5.
- [4] Hassanalian M, Abdelkefi A. Classifications, applications, and design challenges of drones: a review [J]. *Progress in Aerospace Sciences*, 2017, 91:99-131.
- [5] Deshpande N, Chavhan RD, Deshpande N. Coupled inductor based single-input multiple-outputs boost converter; proceedings of the 2017 Third International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB), F, 2017 [C]. IEEE.
- [6] Ghodke DV, Chatterjee K, Fernandes BG. Modified soft-switched three-phase three-level DC–DC converter for high-power applications having extended duty cycle range [J]. *IEEE Transactions on Industrial Electronics*, 2011, 59(9): 3362-72.
- [7] Ouyang Z, Zhang Z, Thomsen OC, et al. Planar-integrated magnetics (PIM) module in hybrid bidirectional DC–DC converter for fuel cell application [J]. *IEEE Transactions on Power Electronics*, 2011, 26(11): 3254-64.
- [8] Chen Y, Kang Y, Nie S, et al. The multiple-output DC–DC converter with shared ZCS lagging leg [J]. *IEEE Transactions on Power Electronics*, 2010, 26(8): 2278-94.
- [9] Sabbarapu BK, Nezamuddin O, McGinnis A, et al. Single-input multiple-output synchronous DC-DC buck converter; proceedings of the 2016 IEEE Energy Conversion Congress and Exposition (ECCE), F, 2016 [C]. IEEE.
- [10] CAVALCANTI M C, DA SILVA E, BOROYEVICH D, et al. A feasible loss model for IGBT in soft-switching inverters; proceedings of the IEEE 34th Annual Conference on Power Electronics Specialist, 2003 PESC'03, F, 2003 [C]. IEEE.
- [11] Wang CM. A novel ZCS-PWM flyback converter with a simple ZCS-PWM commutation cell [J]. *IEEE Transactions on Industrial Electronics*, 2008, 55(2): 749-57.
- [12] El Kattel MB, Mayer R, Oliveira SVG, et al. Three-phase flyback/current-fed push-pull dc-dc converter with y- $\Delta$  connected transformer; proceedings of the 2015 IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC), F, 2015 [C]. IEEE.
- [13] Patra P, Patra A, Misra N. A single-inductor multiple-output switcher with simultaneous buck, boost, and inverted outputs [J]. *IEEE Transactions on Power Electronics*, 2011, 27(4): 1936-51.