Modeling and simulation of constant current converter in energy branch unit

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Abstract. As an important part of electric energy branch unit, constant current converter has the characteristics of simple structure and high efficiency. In this paper, a constant-current converter used in underwater power branching unit is modeled and simulated. The model of constant-current converter circuit is established by using state space method, and the steady-state operating point of DC is calculated. Based on the model, maximum impulse current and drain-source voltage of switching transistor in constant current converter are studied. The simulation test of constant-current converter is carried out by Saber simulation software. The results show that the circuit efficiency can be maintained above 90% while the reliability of the converter is guaranteed, which provides a theoretical basis for the analysis and research of efficient and reliable underwater power branch units.

1. Introduction

Cabled underwater information networks (abbreviation: CUINs) is the third observing platform capable of providing early warning detection, power and communication services for a long time [1-3]. The underwater remote power supply (abbreviation: remote supply) system is the energy foundation of CUINs. It is related to whether the whole system can work normally and is of great significance to the whole system. The current mainstream power supply methods are divided into constant voltage power supply (OOI [4], Canada NEPTUNE-Canada [5]) and constant current power supply (Japan DONET [6]). Constant current power supply has the advantages of self-healing, no need for high-medium pressure medium-low voltage conversion, and is more suitable for CUINs in China [7].

In the constant current remote power supply system of CUINs, in order to carry more active devices, it is necessary to use electric energy branch unit to branch the main line current through the master node. The power branch unit is composed of one or more constant current converters in series, so the core part of the unit is constant current converter. In reference [8] studies the constant current multi-branch technology to maintain constant current characteristics of the whole network. In reference [9], a wireless charger powered by an underwater constant current distribution cable is analyzed and designed, and effectiveness of the design is verified by experiments. In reference [10], for the power supply module of small and medium-sized power equipment in underwater information network, the method of power conversion using regulated diode is designed and studied. These references have analyzed and studied electric energy branch unit, but have not analyzed the performance of the main part of the constant current converter.

For isolated high-frequency switching constant current converter [11] (abbreviation: constant current converter) in the electric energy branch unit, the circuit is modeled and simulated. Analyzed the
working principle of the circuit, establish corresponding state space model and calculate the DC steady-state operating point; use the model to quantitatively analyze maximum impulse current and drain-source voltage of the switching tube in the circuit, which provides a basis for improving reliability of the circuit; The test analyzes influence of circuit parameters on maximum inrush current and drain-source voltage of the switching transistor. The simulation results show that the proper selection of circuit parameters can reduce the maximum impulse current and drain-source voltage, and improve reliability of the system. The circuit efficiency is guaranteed to be above 90%. It has a good theoretical reference value for designing an efficient and reliable electric energy branch unit in the future.

2. Constant current converter modeling based on state space average method

As the main component of the electric energy branch unit constant current converter has main function of making one constant current input into two constant current outputs, which plays an important role in the networking of the constant current power supply system. The schematic diagram of the constant current converter is shown in Figure 1. The constant current converter is a switching converter based on the principle of conventional push-pull conversion. Where: $I_{in}$ constant current is supplied by the remote power supply device; the capacitor $C_1$ supplies power to the output through charging and discharging in the circuit; $S_1$ and $S_2$ are two switching transistors that are turned on by the pulse control; $Tr$ is equal to the number of turns on both sides The high-frequency transformer; the output filter circuit is a π-type filter circuit composed of capacitor $C_2$, inductor $L$ and capacitor $C_3$; $I_{out}$ is the output current of the input loop of the constant current converter, and is set as the output current of the first output branch; $R_{load}$ is the total output load, and the current flowing through $I_{load}$ is set as the output current of the second output branch. In this paper, the switching transistor $S_1$ is turned on as an example. When $S_2$ is turned on, only the direction of the transformer current flowing through the input terminal is different.

![Figure 1: Constant current converter schematic](image)

Switching converter uses change of the operating state of switching element to adjust output voltage (current) of switching converter. In a switching cycle, switching converter is a time-varying circuit. In each switching state, switching converter is a linear circuit[12]. Switching circuit can’t be analyzed by linear circuit theory, and the state space average modeling it is an analytical method suitable for switching converters. For constant current converter, the state space method is used for modeling. The DC steady state equation of constant current converter can be calculated by the model, and the DC steady-state operating point of input-output current ratio and state variable is obtained. Study the characteristics of switch tube to lay the foundation.

2.1 Constant current converter working principle
In order to analyze the steady-state characteristics of constant-current converter, the following assumptions are made: all components in the circuit are ideal components, in which voltage drop of switching transistor is zero at turn-on and the leakage current is zero at cut-off; the distributed capacitance and core loss of the transformer are neglected; and the passive components in the circuit are invariable for linear time.

After constant current converter is stabilized, according to the turn-on conduction of switching transistors $S_1$ and $S_2$, working process of the circuit is divided into four stages, and $T_s$ represents a switching cycle; $t_1$ is the beginning of cycle, $S_1$ starts to turn-on, $S_2$ cut-off; The time of $t_2$ is $S_1$ from turn-on to cut-off, and $S_2$ is cut-off; The time of $t_3$ is $S_2$ from cut-off to turn-on, and $S_1$ is cut-off; The time of $t_4$ is $S_2$ from turn-on to cut-off and $S_1$ is cut-off; $t_5$ is the end of the cycle, $S_1$ and $S_2$ are cut-off States. According to this, the ideal waveform of the current and current of the main components in the circuit can be obtained as shown in Figure 2.

![Figure 2: Electric energy branch unit working waveform diagram.](image)

These four stages can be divided into two states: close state and open state. The close state is $S_1$ or $S_2$, corresponding to $t_1 - t_2$ ($S_1$ turn-on, $S_2$ cut-off) and $t_3 - t_4$ ($S_2$ turn-on, $S_1$ cut-off) in the waveform, and the circuit equivalent diagram is shown in Figure 3 (a) and (b); Open state is that $S_1$ and $S_2$ are both cut-off, corresponding to the $t_1 - t_3$ time period and the $t_4 - t_5$ time period in the working waveform diagram, and the circuit equivalent diagram is shown in Figure 3 (c). The working process and principle in the two states are as follows:

**Close state:** In $t_1 - t_2$ period, $S_1$ is turn-on, $S_2$ is cut-off, capacitor $C_1$ is discharged; drain-source voltage $V_{DS1}$ of $S_1$ is zero, polarity of transformer $N_1$ is positive and negative, because the number of turns of the transformer is the same, if the primary voltage of transformer is $V_N$, the relationship of transformer three-terminal voltage is as in equation (1):

$$V_w = V_{ch} = V_{c1} - I_c R$$

Where: $I_w = I_m + I_{c1}$, the drain-source voltage of $S_2$ is $V_{DS2} = V_w + V_{c1}$, and the voltage of the secondary winding $N_3$ of the transformer is $V_{N3} = V_N = V_{c1} - I_{ch} R$. According to the judgment of dotted terminal, the polarity of $N_3$ is positive and negative polarity; the output filter circuit stores energy. The load is simultaneously supplied by the input constant current source and capacitor $C_1$.

**Open state:** Both $S_1$ and $S_2$ are cut off, capacitor $C_1$ is in the state of charge, and the voltage rises linearly; the primary and secondary voltages of the transformer are both zero. At this time, drain-
source voltage of $S_1$ and $S_2$ is $V_{DS1} = V_{DS2} = V_C$; the output filter circuit releases energy as a load.

![Diagram](image)

Figure 3: Constant current converter equivalent state equivalent circuit diagram. (a) Circuit equivalent diagram of $t_1 - t_2$ time period, (b) Circuit equivalent diagram of $t_2 - t_3$ time period and (c) Circuit equivalent diagram of $t_3 - t_4$ time period

2.2 State space average model of constant current converter

By analyzing the working principle of constant current converter, $V_{C1}$, $V_{C2}$, $V_{C3}$ and $I_L$ are selected as state variables, constant current input $I_w$ of constant current source is the input variable, the current $I_{load}$ flowing through the load $R_{load}$ and the input circuit from the converter. The output current $I_{out}$ is the output variable. Let state vector $x = [V_{C1}, V_{C2}, V_{C3}, I_L]^T$, input vector $u = [I_w]$; output vector $y = [I_{out}, I_{load}]^T$, switch tube duty ratio: $d$ and $d'=1-d$. According to the analysis of the circuit working process in Section 2.1, the corresponding state equations are established for the two states as follows:

In the closed state, the equation of state is shown in equation (2):

$$\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx + Du
\end{align*}$$

Where as in equation (3):
In the open state, the equation of state is shown in equation (4):

\[
\begin{align*}
\dot{x} &= A x + B u \\
y &= C x + D u
\end{align*}
\]

Where as in equation (5):

\[
\begin{align*}
A &= \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1/C_s \\
0 & 1/L & -1/L & 0
\end{bmatrix} \\
B &= \begin{bmatrix}
1/C_s \\
0 \\
0
\end{bmatrix} \\
C &= \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 1/R_{load}
\end{bmatrix} \\
D &= \begin{bmatrix}
1 \\
0
\end{bmatrix}
\]

A weighted average of two sets of state equations yields an average output equation of as in equation (6):

\[
\begin{align*}
\bar{x} &= \bar{A} \bar{x} + \bar{B} \bar{u} \\
\bar{y} &= \bar{C} \bar{x} + \bar{D} \bar{u}
\end{align*}
\]

Where as in equation (7):

\[
\begin{align*}
\bar{A} &= \begin{bmatrix}
d/C_s & -d/C_s & 0 & 0 \\
d/C_s & -d/C_s & 0 & 0 \\
0 & -1/L & (2d - 1)/C_s & (2d - 1)/C_s \\
0 & (2d - 1)/C_s & 0 & 0
\end{bmatrix} \\
\bar{B} &= \begin{bmatrix}
(1 - 2d)/C_s \\
(1 - 2d)/C_s \\
0 \\
0
\end{bmatrix} \\
\bar{C} &= \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 1/R_{load}
\end{bmatrix} \\
\bar{D} &= \begin{bmatrix}
d \\
0
\end{bmatrix}
\]

In the DC steady state, \( \bar{x} = 0 \). By solving the DC steady state equation, the DC steady state operating point of the main circuit of the underwater power branching unit can be obtained as in equation (8):

\[
\begin{align*}
\bar{x} &= -\bar{A}^{-1} \bar{B} \bar{u} \\
\bar{y} &= \bar{C} \bar{A}^{-1} \bar{B} \bar{u}
\end{align*}
\]

Substituting equation (7) into equation (8), the relationship between input and output current can be obtained as in equation (9):

\[
\begin{align*}
\bar{I}_{out} &= d \bar{I}_{in} \\
\bar{I}_{load} &= \bar{I}_{in}
\end{align*}
\]

Where, \( \bar{I}_{out} \) and \( \bar{I}_{load} \) are the DC steady-state operating points of two output currents. It can be concluded that output current \( \bar{I}_{out} \) of first branch is proportional to input current \( \bar{I}_{in} \), the proportional coefficient is \( d \), which is the down-regulation output related to duty cycle; output \( \bar{I}_{load} \) of second branch is not subject to the duty cycle. The effect is consistent with the input current.

3. Research on switching transistors in constant current converters
According to the component stress analysis method, the failure rate of components is positively correlated with the current and voltage \[I_{\text{max}}\] [13]. In constant current converter, the possibility of failure of switching tube is the greatest, so study switching transistor of maximum impulse current \(I_{\text{max}}\) and drain-source voltage \(V_{\text{DS,open}}\) can provide a theoretical basis for optimizing constant current converter and improving its reliability.

### 3.1 Study on maximum impulse current

In close state, discharge voltage of capacitor \(C_1\) decreases while charge voltage of capacitor \(C_2\) increases, so current flowing through switching transistor is the largest when switch transistor is closed. For convenience of calculation, if closing instant is 0, when \(t = dT\), close state is changed to open state, and when \(t = T\), the period ends, the maximum current flowing through switching transistor can be obtained at \(t = 0\). Using the state space equation of close state obtained in section 2.2, the expression of the maximum impact current can be obtained as in equation (10):

\[
I_{\text{max}} = \frac{V_{C_{1,\text{close}}}(0) - V_{C_{2,\text{close}}}(0)}{R_s}
\]

Where: \(V_{C_{1,\text{close}}}(0)\) and \(V_{C_{2,\text{close}}}(0)\) represent the voltages of capacitor \(C_1\) and capacitor \(C_2\), at the moment of closure.

Since the function of the output filter circuit is to make the output current more stable and solve problem of excessive current ripple, the filter circuit can be ignored here, and the influence on calculation result can be neglected. In close state, through analysis of the previous working process of the circuit, the capacitor \(C_1\) and the constant current source jointly supply energy to the load, and a simplified equivalent circuit diagram as shown in Figure 4 can be obtained:

![Simplified equivalent circuit diagram](image)

According to the relationship between capacitance current and voltage \(I_C = C \frac{dV_C}{dt}\), it can be concluded that in close state, there is following equation (11):

\[
I_n = C_1 \frac{dV_{C_{1,\text{close}}}}{dt}(t) = \frac{V_{C_{1,\text{close}}}(t)}{R_{\text{load}} + R_s}
\]

Where: \(V_{C_{1,\text{close}}}(t)\) is voltage of the capacitor \(C_1\) in close state.

According to the volt-second balance principle, voltage reduction of capacitor \(C_1\) in close state is equal to the voltage increase in open state, as in equation (12):

\[
\Delta V_{C_{1,\text{close}}} = V_{C_{1,\text{close}}}(0) - V_{C_{1,\text{close}}}(dT) = \frac{I}{C_1} dT
\]

The simultaneous (11) and (12) equations and \(t = 0\), find voltage of the closed-circuit capacitor \(C_1\) as in equation (13):
According to Ohm's law, the resistance of inductor is very small, current flowing over load in open state is equal to input current of constant current source. So when capacitor $C_2$ voltage is disconnected, linear decrease $\Delta V_{c2, \text{open}}$ of capacitor $C_2$ voltage is as in equation (15):

$$\Delta V_{c2, \text{open}} = \int_0^t \frac{T_{\text{load}}}{C_2} dt = \frac{I_2}{C_2} dT$$

(15)

The voltage of the capacitor $C_2$ drops to the lowest point at the moment switching transistor is closed, so voltage value of the capacitor $C_2$ at the closing instant can be calculated as in equation (16):

$$V_{c2, \text{close}}(0) = I_s R_{\text{load}} - \frac{I_2}{C_2} dT$$

(16)

Bringing equations (13) and (16) into equation (10), the expression for maximum impulse current as in equation (17):

$$I_{\text{max}} = I_s + \frac{I_2}{R_s} \left( \frac{1}{C_2(1-e^{-\frac{2z_{\text{load}}+R_s}})} + \frac{1}{C_2} \right)$$

(17)

### 3.2 Study on drain-source voltage

Let $V_{DS, \text{open}}$ denote drain-source voltage of the open switching transistor in close state. At this time, the voltage $V_{c1}$ of capacitor $C_1$ satisfies the following equation (19):

$$V_{c1} = V_{c2} + V_{DS} \geq V_{\text{operation}} + V_{R_s}$$

(18)

From the analysis of working principle of constant current converter in Section 2.1, when the $S1$ is closed, drain-source voltage of the $S2$ is $V_{DS, \text{open}} \approx 2V_{\text{load}} + V_{R_s}$, and the $V_{DS, \text{open}}$ increases with increase of the load. The following is the analysis of drain-source voltage $V_{DS, \text{open}}$. According to Ohm's law $V = IR$, $V_{DS, \text{open}}$ is obtained as in equation (19):

$$V_{DS, \text{open}} = 2I_{\text{load}} R_s + I_{\text{max}} R_s$$

(19)

The expressions of $I_{\text{load}}$ and $I_{\text{max}}$ can be obtained by using expressions (9) and (17) through the modeling and analysis of constant current converter. Because when $0 < x < 1$, there is $e^x - 1 \approx x$. In order to simplify the calculation, the simplified expression of $I_{\text{max}}$ can be obtained by introducing this equation into equation (19). Finally, the expression of drain-source voltage can be obtained as in equation (20):

$$V_{DS, \text{open}} = I_{\text{load}} \left[ \frac{d}{d} + \frac{R_s}{R_{\text{load}}} + \frac{d}{d} \left( \frac{1}{C_2} \right) \right]$$

(20)

Since maximum impulse current and drain-source voltage of switching transistor affect reliability of constant current converter, quantitative analysis and research can provide a theoretical reference for designing a high reliability constant current converter, which has important practical significance.

### 4. Simulation analysis of constant current converter
Based on the theoretical derivation of maximum impulse current and drain-source voltage of switching transistors, the relationship between maximum impulse current and drain-source voltage with resistance $R_s$ is calculated by using MATLAB when the loads are 20Ω, 50Ω, 100Ω and 150Ω. The remaining parameters in the circuit are $I_a = 1.5A$, $T_o = 4\mu s$, $d = 80\%$, $L = 6mH$, $C_1 = 3.35\mu F$, $C_2 = 1.05\mu F$ and $C_3 = 2.25\mu F$. The results are shown in Figure. 5 (a) and (b):

![Figure 5](image)

(a) Diagram of maximum impulse current with $R_s$, (b) Diagram of drain-source voltage with $R_s$.

From Figure. 5 (a), it can be seen that maximum impulse current decreases slowly when the resistance $R_s \geq 2\Omega$. Because the circuit loss increases when resistance $R_s$ is too large, the efficiency and reliability of the circuit can be taken into account when the resistance $R_s = 2\Omega$. At the same time, maximum impulse current increases with increase of the load. From Figure. 5 (b), it can be seen that drain-source voltage increases with increase of the resistance $R_s$ and the load. Because there is a limit voltage between the drain poles of the switching transistor, the higher the limit drain-source voltage of switching transistor is, the higher the load that can be carried. For example, the maximum output load $R_{max} = 144.26\Omega$ can be calculated for the MOS transistor of IRF450, whose drain-source limit voltage is 500V. If the resistance is natural and other parameters remain unchanged, the maximum output load will damage switching transistor when the load exceeds that value, and the circuit will not work properly.

The circuit model of the constant current converter is built by Saber simulation software, and $R_s = 2\Omega$. Five sets of simulation tests are carried out with different resistance values of load $R_{load}$ of 20Ω, 40Ω, 60Ω, 80Ω and 100Ω respectively. Efficiency of the circuit can be calculated with the remaining parameters unchanged. The load-efficiency relationship diagram shown in Figure 6 is obtained:

![Figure 6](image)

Figure 6. Load and circuit efficiency diagram.
Therefore, when the resistance $R_s = 2 \Omega$, the load resistance is greater than 40$\Omega$ and does not exceed the maximum output load, the circuit efficiency is higher than 90% while ensuring high reliability. It can satisfy the application requirement of electric energy branch unit. Through the circuit simulation analysis of constant current converter, it can be concluded that when $R_s = 2 \Omega$, the maximum impulse current can be significantly reduced relative to the $R_s$ resistance value of 0. Load is the main factor affecting drain source voltage. For switching transistor with large drain source voltage, the circuit can carry a larger load. Maximum impulse current and drain source voltage of switching transistor are studied by simulation test, which has reference value for the design of high reliability constant current converter.

5. Conclusion

Constant current converter is an important part of electric energy branch unit, so it is of great significance to study it. This paper studies an existing constant current converter, establishes state-space model of the circuit, calculates the gain of input and output current and the steady-state operating point of DC, quantitatively analyses maximum impulse current and drain-source voltage of switching transistor in constant-current converter by using the model, simulates the circuit of the constant-current converter with the simulation software, and obtains that the circuit is properly set up. Medium resistance $R_s$ value and load resistance value can ensure the reliability of converter and make the efficiency more than 90%. The next step is to calculate the transfer function according to the model and design the corresponding feedback compensator to further improve the reliability of the circuit. The feasibility of the model is verified by experiments, which will lay the foundation for the future design of high efficiency and high reliability electric energy branch unit.

6. References

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