# A Current Transformer Feeding Power Supply for Distribution Automation Systems

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***Abstract*—To benefit the compact and insulation design of feeder switches, a current transformer feeding power supply is put forward. The non-linear behavior of the current transformer, the circuit topology and design considerations of the proposed power supply are detailed. Losses of the devices and the minimum primary current to ensure the performance of the power supply are analyzed, as well. Experiments are made on a current transformer feeding power supply, the results of which show that the suggested topology is feasible and the proposed approach is effective.**

***Index Terms*—DC-DC converters, switching converters, current transformers, PWM regulation, distribution automation**

## I. INTRODUCTION

In the distribution automation systems or distribution monitoring systems, power supply is one of the most important devices. The power supply not only provides the voltage needed for the iED to work, but also provide the operation energy for the switches [1].

Typically, the power supplies in the distribution automation systems are formed by buck, boost, buck-boost, flyback or forward switching converters [2]. The analysis and design of above switching converters have been well investigated [3][4] and have widely used in the practice. In order to maintain the iEDs working in the situation of the main fails, battery and super-capacitors are used as the back-up resources of the power supplies [5].

Most of the widely used power supplies for distribution automation systems are powered by voltage sources, the energy of which is fed by potential transformers (PT). The implantation of potential transformers (PT) in the body of a pole-mounted switch or a switch gear will not only greatly enlarge the size, weight and cost of the switch, but also face the difficulty of insulation [6].

Current transformers (CT) have the advantages of small size, light weight, easy to implant and insulate. Thus, power supplies fed by current transformers (CT) are of promising, especially in the cases of the switches with too small space to implant potential transformers (PT). Many achievements have been made on current transformers (CT). But they focus on the behavior of the current transformers (CT) in the linear region for current measurement purposes [7][8].

Recently, the non-linear performance of current transformers (CT) is also investigated [9]. In [10], the ideal of using current transformers (CT) as the resource of a power supply is discussed.

In this paper, a current transformer based switching power supply is proposed and analyzed. The design considerations are discussed. An example is given with the experiment results.

## II. BASIC PRINCIPLE

### A. Circuit Topology

The proposed current transformer based switching power supply is shown in Figure 1, which is based on a full bridge rectifier.

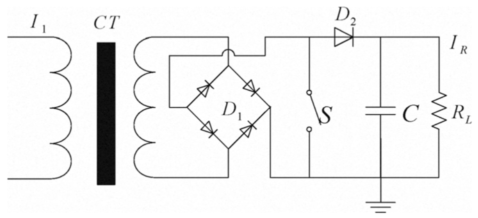


Figure 1. A current transformer based switching power supply

Diodes $D_{1,1}$~$D_{1,4}$ form a full bridge input rectifier. S is the main switch, typically, a MOSFET. C is the filter capacitor. S is working in a PWM mode.

In the half switching period of S being on, the secondary part of the Current Transformer (CT) is short-circuit, the supplying to the load ($R_L$) is maintained by the capacitor C. $D_2$ is used to cut off the releasing route of C through S.

In the half switching period of S being off, the Current Transformer (CT) provides the energy to the load and the charging of the capacitor C.

### B. Behaviour of CurrentTransformers

Traditionally, the Current Transformer (CT) is used in its linear part for current measurement. As for using in the power supplies, CT must be working in its non-linear part.

Typically behavior of the non-linear part of Current Transformer (CT) is shown in Figure 2.

It can be seen from Figure 2 that the secondary voltage $V_2$ of the Current Transformer (CT) varies with the primary current $I_1$ and the secondary equivalent resistance $R_2$ of the CT.

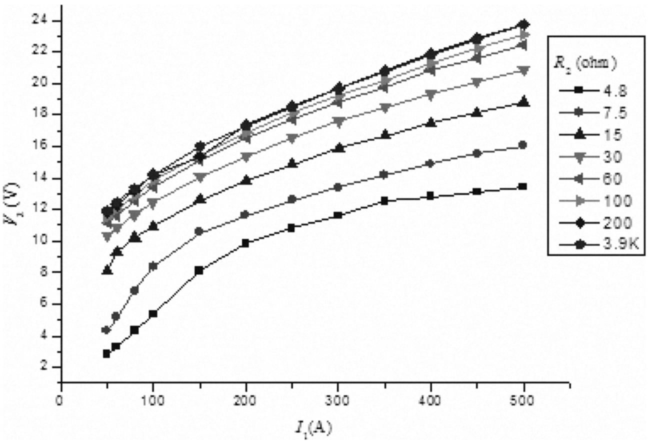


Figure 2. Typical behavior of a current transformer

The relationship of the secondary voltage $V_2$, the primary current $I_1$ and the secondary equivalent resistance $R_2$ can be formulated as

$$V_2 = f(I_1, R_2) \tag{1}$$

According to (1), the power transferring behavior of relationship of the secondary voltage, the primary current $I_1$ and the secondary equivalent resistance is obtained by

$$P_2 = \frac{V_2^2}{R_2} \tag{2}$$

Where, $P_2$ is the power transferred from CT.

The power transferring behavior of the CT in Figure 2 is shown in Figure 3.

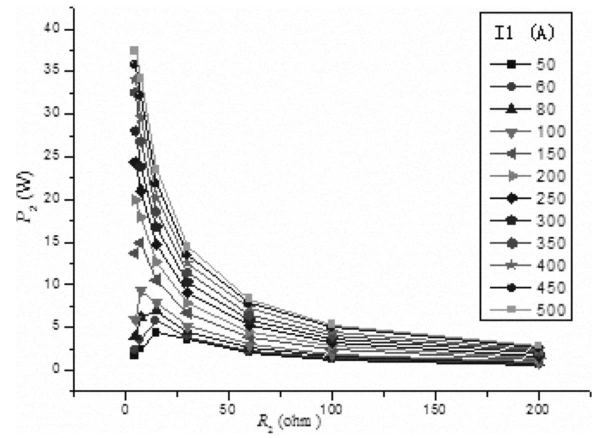


Figure 3. Typical power transferring behaviour of a current transformer

## III. Analysis And Design Considerations

### A. Design of Capacitor

In the situation of the largest output current, *i.e.*, the minimum load resistance of $R_{L,\min}$, supposing that the load current is maintained completely by the capacitor C in a quarter of the period of the main AC source, which is worse that the real condition, we have

$$C > \lambda T_{50}/(8R_{L,\min}\alpha\%) \tag{3}$$

Where, $T_{50}$ is the period of the main AC source, typically 20ms as for 50Hz. $\alpha\%$ is the allowed output voltage deviation, $\lambda$ is the parameter to correct the high-frequency cut-down and ESR of the capacitor.

### B. Loss of $D_2$

In one period of $T_{50}$, the energy consumed in the load in the half switching period of S being off and $D_2$ being on is

$$W_{R,d} = \frac{V_E^{\ 2}}{R_L}(1-d)T_{50} \tag{4}$$

Where, $V_E$ is the desired output voltage, $d$ is the conducting ratio of S.

Meanwhile, the capacitor has to store some energy ($W_C$) so as to keep supplying to the load in the half switching period of S being on and $D_2$ being off, *i.e.*,

$$W_C = \frac{V_E}{R_L} dT_{50} \tag{5}$$

The averaged capacitor charging current in the half switching period of S being off is

$$I_C = \frac{W_C}{(1-d)T_{50}V_E} = \frac{V_E d}{(1-d)R_L} \tag{6}$$

The current through $D_2$ in the half switching period of S being off is

$$I_{D2} = I_R + I_C = \frac{V_E}{(1-d)R_L} \tag{7}$$

The loss energy of $D_2$ in the half switching period of S being off is

$$W_{D2} = I_{D2}V_{D2}T_{50}(1-d) = \frac{V_E V_{D2} T_{50}}{R_L} \tag{8}$$

Where, $V_{D2}$ is the conducting voltage on $D_2$.

The averaged loss power of $D_2$ in one period of $T_{50}$ is

$$P_{D2} = W_{D2}/T_{50} \approx \frac{V_{D2}V_E}{R_L} \tag{9}$$

The averaged current through $D_2$ in one period of $T_{50}$ is

$$I_{D2} = V_E/R_L \tag{10}$$

*C. Losses of $D_{1,1}$ to $D_{1,4}$ and S*

In the situation of S being on in one period of $T_{50}$, because the secondary of the CT is short-circuit, the secondary current of CT is in proportion to its primary current. Thus, the loss energy of $D_{1,i}$ is

$$W_{D1,i}' = V_{D1}\beta I_1 d T_{50} \tag{11}$$

Where, $V_{D1}$ is the conducting voltage on $D_{1,1}$ to $D_{1,4}$, β is the ratio of secondary current to primary current of the CT.

In the situation of S being off in one period of $T_{50}$, the current through $D_{1,i}$ is approximately as

$$I_{D1,i}' = I_{D2} = \frac{V_E}{(1-d)R_L} \tag{12}$$

The loss energy of $D_{1,i}$ in the situation of S being off in one period of $T_{50}$ is approximately as

$$W_{D1,i}'' = V_{D1} I_{D1,i}(1-d)T_{50} = \frac{V_{D1}V_E T_{50}}{R_L} \tag{13}$$

Thus, the averaged loss power of $D_{1,i}$ in one period of $T_{50}$ is

$$P_{D1,i} = \frac{W_{D1,i}' + W_{D1,i}''}{T_{50}} = V_{D1}\beta I_1 d + \frac{V_{D1}V_E}{R_L} \tag{14}$$

The averaged current through $D_{1,i}$ in one period of $T_{50}$ is

$$I_{D1,i} = \frac{V_E}{R_L} + \beta I_1 d \tag{15}$$

The total averaged loss energy of $D_{1,1}$ to $D_{1,4}$ in one period of $T_{50}$ is

$$P_{D1} = 2P_{D1,i} = 2V_{D1}\beta I_1 d + \frac{2V_{D1}V_E}{R_L} \tag{16}$$

In the situation of S being on in one period of $T_{50}$, the current through S is in proportion to the CT's primary current. Therefore, the averaged loss power of S energy in one period of $T_{50}$ is

$$P_s = \beta^2 I_1^2 R_{on} d \tag{17}$$

Where, $R_{on}$ is the conducting resistance of S.

*D. Efficiency*

In one period of $T_{50}$, the total energy supplied from the current transformer (CT) is

$$W_{TA} = W_{D1} + W_{D2} + W_S + W_{R,T} \tag{18}$$

Where, $W_{R,T}$ is the energy the load consumed in one period of $T_{50}$, and

$$W_{R,T} = \frac{V_E^2 T_{50}}{R_L} \tag{19}$$

From (4) and (18), we have the efficiency of the proposed power supply as

$$\eta = \frac{W_{R,T}}{W_{TA}} = \frac{W_{R,T}}{W_{R,T} + W_S + W_{D1} + W_{D2}} \tag{20}$$

Substitute (9), (16), (17) and (19) into (20), we have

$$\eta = \frac{V_E^2}{V_E^2 + V_E V_{D2} + 2V_{D1}R_L\beta I_1 d + 2V_{D1}V_E + R_{on}R_L\beta^2 I_1^2 d} \tag{21}$$

*E. Limitations Analysis*

In order to evaluate the maximum output power of the supply, we consider the situation of S keeping off. The secondary equivalent resistance $R_{2,E}$ of the current transformer in such case is

$$R_{2,E} = \frac{W_{TA}}{I_{D1,i}^2 T_{50}} \tag{22}$$

In the case of the largest output current, i.e., the minimum load resistance, we have

$$R_{2,E} = \frac{V_E + 2V_{D1} + V_{D2}}{V_E} R_{L,\min} \tag{23}$$

Substitute (22) into (1) and (2), we obtain the behavior of the secondary voltage and the power transferring function of $V_2(I_1) = f(I_1, R_{2,E,\min})$ and $P_2(I_1) = g(I_1, R_{2,E,\min})$.

To make the power supply work, the input voltage can not be too low. Thus, we have

$$V_2(I_1) > V_E + V_{D2} + 2V_{D1} \tag{24}$$

To meet the require ment of the output power, we must have

$$P_2(I_1) > P_{2,E} \tag{25}$$

Where

$$P_{2,E} = \frac{W_{TA,\max}}{T_{50}} \quad (26)$$

Both (23) and (24) must be reached; otherwise, the power supply may not meet the desired performance. Thus, the minimum allowed primary current of the current transformer, i.e., $I_{1,\min}$, can be determined by (23) and (24).

## IV. EXPERIMENT RESULTS

A current transformer feeding power supply based on the proposed approach is implanted. $D_{1,1}$ to $D_{1,4}$ are made of 10A10MIC. $D_2$ is made of MBR3060. S is made of MOSFET IRF540. The capacitor is of 12000μF. The current transformer has the current ratio of 500/5, whose non-linear behavior is shown in Figure 1 and Figure 2. The desired output voltage is DC 5V. The output current ranges from 10mA to 500mA.

The controller is a combination of PWM and voltage level control. Whenever the output voltage is higher than $(1+\alpha\%)V_E$, S is forced to be on. Whenever the output voltage is lower than $V_E$, S is forced to be off. In the other situations, PWM regulation is working to slightly adjust the output voltage to the desired value.

The equivalent primary current $I_1$ of the current transformer is enlarged to ten times by circling the primary wire ten times through the current transformer. Thus, equivalent primary current of up to 500A can be realized by an AC current source with its maximum output current of 50A in the laboratory.

According to the proposed analysis approach, to ensure the power supply to reach the desired performance in case of the largest output current, the allowed primary current of the current transformer should be no less than 60A.

Experiments have been made on the current transformer feeding power supply, the results of which are shown in Figure 4 to Figure 7, Table I and Table II.

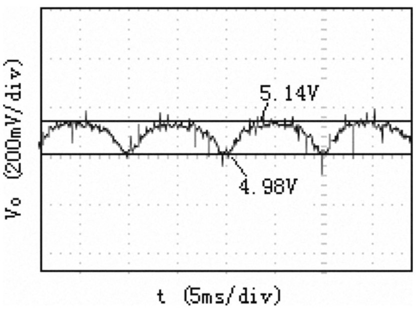


Figure 4. Output voltage in case of $I_o$=500mA, $I_1$=500A

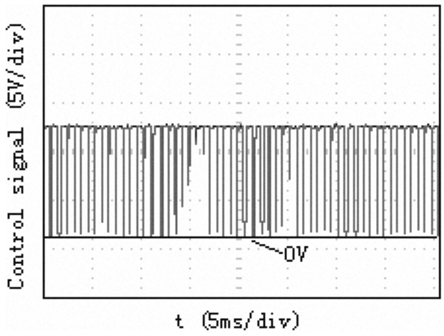


Figure 5. Control signal on S in case of $I_o$=500mA, $I_1$=500A

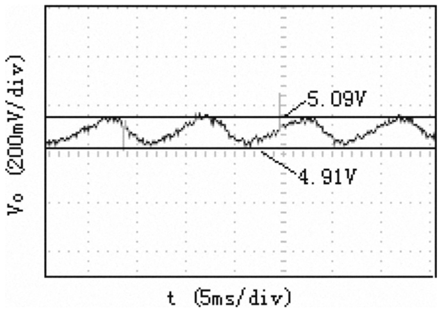


Figure 6. Output voltage in case of $I_o$=500mA, $I_1$=80A

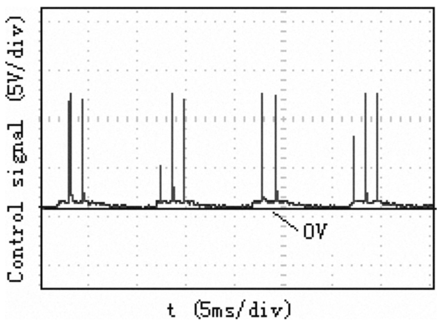


Figure 7. Control signal on S in case of $I_o$=500mA, $I_1$=80A

It can be seen from Figure 4 to Figure 7 that the output voltage reach the requirements and the control strategy is effective.

TABLE I. EXPERIMENT RESULTS OF THE OUTPUT VOLTAGE

| **$I_o$(mA)** | **Averaged Output Voltage (V)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | *$I_1$=50A* | *80A* | ***100A*** | ***150A*** | ***200A*** | ***400A*** | ***500A*** |
| 500 | 3.48 | 5.03 | 5.04 | 5.05 | 5.05 | 5.06 | 5.06 |
| 50 | 5.05 | 5.05 | 5.06 | 5.06 | 5.06 | 5.54 | 5.55 |
| 10 | 5.05 | 5.06 | 5.06 | 5.06 | 5.06 | 5.55 | 5.56 |

TABLE II. EXPERIMENT RESULTS OF THE OUTPUT RIPPLE VOLTAGE

| $I_o$(mA) | Output Ripple Voltage (Peak-to Peak : mV) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $I_1$=50A | 80A | 100A | 150A | 200A | 400A | 500A |
| 500 | 150 | 200 | 200 | 200 | 160 | 150 | 150 |
| 50 | 100 | 100 | 100 | 100 | 100 | 90 | 80 |
| 10 | 100 | 80 | 80 | 80 | 80 | 80 | 80 |

It can be seen from Table I and Table II, that the proposed power supply is able to reach the desired output voltage within the whole output current ranges if the primary current no less than 80A, which is a little larger than the analysis value. It is because the approximation in the analysis.

## V. CONCLUSIONS

Applying the non-linear behavior of current transformers, we may form a kind of voltage stable power supply fed by current transformer.

The proposed analysis approach is effective although with a little approximation, it is helpful to guide the design of current transformer fed power supplies.

The proposed topology of current transformer fed power supply is feasible. The hybrid control strategy of PWM and voltage level is also feasible.


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