A Stable Energy Acquisition System Based on Magnetic Circuit Coupled Current Transformer for Transmission Line

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Abstract. With the development of smart grids, high-voltage transmission line monitoring devices has become a new research hotspot, but the supply of stable energy for monitoring devices is a difficult point. By utilizing of current transformer (CT) to obtain stable energy from high-voltage transmission lines is one of promising approaches, but the current variation range of the high-voltage transmission line is often too large to be transformed linearly by the traditional electromagnetic CT. According to impedance matching principle, a method to regulate the load impedance of a CT is proposed in order to acquire energy effectively from a transmission line and provide stable output power. The method to regulate the load impedance of a CT can be implemented by controlling a single-phase PWM rectifier. It is proved by experiment that the PWM rectifier can be adjusted to supply a stable 20V output voltage and 9W output power for the DC load.

1. Introduction

With the continuous development of smart grids and the continuous popularization of on-line monitoring technology for high-voltage transmission lines, in order to ensure the stable operation of transmission line monitoring devices, providing a stable energy has become an important issue that needs to be solved.

Existing approaches of providing power for high-voltage transmission line monitoring devices consist of laser [1-3], solar panel, battery, and CT energy supply [4-5]. Power supplied by laser is limited by the low conversion efficiency and environmental impact. Power supplied by solar panel is sensitive to temperature and weather conditions. Power supplied by battery is limited by the cycle life of battery. So, they are not convenient to supply power for transmission line monitoring devices. Providing energy for transmission line monitoring devices by a CT has attracted much attention due to its adaptability, long service life and easy maintenance [6-8]. A series compensation capacitor is applied to resonate with the self-induce of the CT coil in order to provide sufficient energy [9], but the phenomenon of over voltage often takes place. This paper proposed an impedance regulator being applied to the AC power transmission line, which is connected in parallel with the secondary coil of the CT. When the primary side current varies widely, the excitation characteristics of the CT can be changed by the impedance regulator, thus the secondary side of CT can output stable power. More importantly, the use of single-phase AC/DC rectifier circuit to achieve the function of the impedance regulator eliminates the need of the rear-stage DC/DC circuit [10]. It can reduce circuit losses, decrease devices size and cost.
2. **Principle of CT**

In figure 1, the CT is composed of two semicircle iron core and air gap at the joint. In order to reduce the core loss, a kind of iron based nanocrystalline alloy (Fe_{73.5}CuNb_{3}Si_{13.5}B_{3}) is selected as the core material. \(N_1\) is the number of turns of primary winding, \(N_2\) is the number of turns of secondary winding, and \(Z_L\) is the impedance regulator.

![Figure 1. Schematic diagram of CT.](image)

According to the law of electromagnetic induction, when the iron core is in the linear region, the CT secondary side electromotive force can be expressed as:

\[
E_2 = -j4.44f N_2 \phi_m \tag{1}
\]

where, \(f\) is the operating frequency of the transmission line, and \(\phi_m\) is the magnetic flux passing through the coil.

When the CT works, because \(N_1=1\), the impedance of the primary side circuit is negligible. Thus, the simplified circuit of the CT in Figure 2 is obtained, and Figure 3 shown the load phase diagram of the CT.

![Figure 2. Simplified circuit diagram of CT.](image)

![Figure 3. Load vector diagram of CT.](image)

The permeability of the iron core with air gap is calculated as:

\[
\Lambda = \int_0^h \frac{\mu_{eq} h}{2 \pi x} dx \tag{2}
\]

where, \(h\) is the height of the iron core, \(R\) is the outer diameter of the iron core, \(r\) is the inner diameter of the iron core, and \(\mu_{eq}\) is the equivalent permeability of iron core with the air gap \(\mu_{eq} \approx l/\delta\).

The magnetic resistance \(R_\delta\) of iron core with air gap can be expressed as:

\[
R_\delta = 2\pi/\mu_{eq} h \ln(R/r) \tag{3}
\]

It can be seen from (3) that the magnetic reluctance of the iron core is increased by increasing the air gap. Thus, the linear working area of the iron core becomes larger to avoid magnetic saturation of the iron core, and the impedance regulator can be adjusted, which is paralleled on the secondary side of CT. When the primary side current is small. In order to increase the output power, the impedance regulator becomes capacitive to compensate for the excitation reactance.

The CT excitation impedance \(Z_m\) can be expressed as:

\[
Z_m = \omega L_m = \omega N_2^2 / R_\delta \tag{4}
\]

where, \(\omega\) is the angular frequency of the transmission line, and \(L_m\) is the excitation inductance.
3. Analysis of impedance regulator principle

Based on (1) and Ohm's law of magnetic circuit, the magnetomotive force balance equation can be expressed as:

\[ N_1 I_1 - j \omega \phi_m N_2^2 = R_m \phi_m \]  

(5)

where, \( I_1 \) is the primary side current, \( Z_0 \) is the secondary side equivalent load impedance and \( Z_0 = \frac{Z_L R_L}{Z_L + R_L} + j X_0 \). According to the load vector diagram of CT, \( \lambda \) can be calculated as \( \lambda = \arctan \left( \frac{X_L}{Z_L} \right) \). Thus, the excitation current \( I_m \) can be expressed as:

\[ I_m = \sqrt { \left( \frac{I_1}{N_2} \right)^2 - \left( \frac{I_2 R_0}{Z_0} \right)^2 - \left( \frac{I_2 X_0}{Z_0} \right)^2 } \]  

(6)

According to (6), the secondary side induced voltage \( E_2 \) can be expressed as:

\[ E_2 = \frac{\omega N_1 I_1 Z_0}{(R_L Z_0^2 + 2 \omega R_L X_0 N_2^2 + \omega^2 N_2^4)^{1/2}} \]  

(7)

According to (7), the secondary side output power \( P \) can be expressed as:

\[ P = \frac{(\omega N_1 I_1)^2 R_0}{(R_L Z_0^2 + 2 \omega R_L X_0 N_2^2 + \omega^2 N_2^4)^{1/2}} \]  

(8)

According to (8), the output power \( P \) is related to the angular frequency of the transmission line, the number of secondary side turns, the iron core parameters and the secondary side impedance. Thus, Figure 4 and Figure 5 can be drawn.

![Figure 4. Output characteristics of impedance regulator.](image)

![Figure 5. CT secondary side output power when \( I_1 = 20 \) A.](image)

Through analyzing Figure 4, we can notice that:

1. Comparing with the condition without impedance regulator \( Z_L \), \( Z_L \) can be adjusted in a certain range to enhance or weaken \( E_2 \).

2. When the primary side current is small, in order to increase the output power of the secondary side, \( Z_i \) becomes capacitive to reduce the shunting action of the excitation inductance \( L_m \). When \( Z_i = - \frac{\omega N_2^2}{R_0} \), the \( L_m \) and the \( Z_L \) reach the parallel resonance state. Thus, the CT obtain the maximum output power.

3. When the primary side current is too large that the iron core is saturation. In this time the peak waveform of secondary side voltage is distortion, causing the secondary side voltage of the CT is too large and the electric circuit may be damaged. To avoid the iron core saturation, the secondary side voltage \( E_2 \) should meet \( E_2 \leq E_{2\text{m}} = 4.44f N_2 B_{\text{m}} S \) (\( B_{\text{m}} \) is the iron core saturation flux density). In order to make the CT work in the linear region, the impedance regulator can be adjusted to inductive load, and it can increase the shunting action to reduce the excitation current \( I_m \).

Through the above analysis, two working states of impedance regulator are obtained:

1. When the primary side current is too small, in order to obtain sufficient output power of the CT’s secondary side, the impedance regulator is adjusted to be capacitive load to increase output power of the secondary side.

2. When the primary side current is too large, in order to avoid iron core saturation, the impedance regulator is adjusted to be inductive so that the iron core can work in the linear region to
provide stable output power for the secondary side load. According to the above analysis, when the primary side current measured by the Rogowski coil, the exact value of impedance regulator can be calculated.

4. Simulation of impedance regulator

The basic structure of a single-phase voltage source PWM rectifier (VSR) is shown in Figure 6:

![Figure 6. Schematic diagram of rectifier circuit.](image)

The single-phase VSR uses unipolar sinusoidal pulse width modulation (SPWM) to reduce the content of harmonic making the secondary side voltage of the CT to achieve high quality output waveform. The single-phase VSR circuit has four switching modes and can be described by a three-valued logic switching function $\beta$. The three-valued logic switching function $\beta$ can be expressed as:

$$\beta = \begin{cases} 
1, & V_1 \text{ or } V_4 \text{ on} \\
0, & V_1 \text{ or } V_3 \text{ or } V_2 \text{ or } V_4 \text{ on} \\
-1, & V_2 \text{ or } V_3 \text{ on} 
\end{cases}$$

The single-phase VSR modulation switch mode in Table 1.

| Switch mode | 1 | 2 | 3 | 4 |
|-------------|---|---|---|---|
| Conduction device | $V_1 V_4$ | $V_2 V_3$ | $V_1 V_3$ | $V_2 V_4$ |
| $\beta$ | 1 | -1 | 0 | 0 |

The single-phase VSR control method uses a double closed loop control: a voltage outer loop and a current inner loop. The double closed loop control has the characteristics: simple structure and excellent control performance. The control block diagram of the impedance regulator is shown in Figure 7. The output voltage $U_{dc}$ and the input current $I_{ac}$ is collected to be controlled objects. The stable voltage output is realized by the voltage outer loop, and the tracking of reference current is achieved by the current inner loop. The voltage outer loop is controlled by PI controller, the voltage error signal is sent to the PI controller. Thus, no static error tracking of DC reference voltage can be achieved by using PI controller. The PLL realizes the function of simulating the target impedance by controlling the phase of the reference current.

![Figure 7. Principle of impedance regulator](image)

The current inner loop uses a quasi-proportional resonant (QPR) controller to achieve no static error tracking of the AC reference current by sending a current error signal to the QPR controller. The output of the QPR controller is used as the modulation wave of the PWM generator. The modulation
wave sent to the SPWM generator to generate four PWM signals. The four signals respectively control the four switching tubes of the VSR circuit to realize the simulation of the target impedance. Transfer function of the QPR controller can be expressed as:

\[ G_R = K_P + \frac{2k_i \omega_c S}{S^2 + 2\omega_c S + \omega^2} \]  \hspace{1cm} (9)

where, \(K_P\) is the proportional coefficient; \(K_i\) is the integral coefficient; \(\omega\) is the resonant frequency of the QPR controller; \(\omega_c\) is the QPR controller Cut-off frequency. Where, \(\omega_c = 4.4\text{rad/s}\), \(K_P = 3\), \(K_i = 2\).

Bode diagram of QPR transfer function can be shown in Figure 8.

![Bode Diagram](image)

Figure 8. The bode diagram of QPR transfer function.

According to Figure 8, the system obtains the maximum gain of the power grid at the angle frequency \(\omega = 100\pi\) and can obtain a large gain in a certain frequency fluctuation range. Figure 8 indicates that the system has a high stability and has an ability to resist the interference of the power grid frequency.

5. **Experimental verification**

According to the above analysis and simulation, the experiment is designed. The field experiment diagram of the energy acquisition system is shown in Figure 9. The iron core size is 50×100×100 mm³. The detailed parameters are shown in Table 2:

| parameter                      | Numerical value |
|--------------------------------|-----------------|
| Air gap \( \delta \)          | 0.28mm          |
| Magnetic path length \( l \)   | 235mm           |
| Iron core cross-sectional area \( S \) | 2500mm³        |
| Number of primary coils \( N_1 \) | 1               |
| Number of secondary coils \( N_2 \) | 70              |
| DC load \( R_L \)              | 44Ω             |

![Table 2](image)

Table 2. Experimental equipment parameters.
The impedance regulator makes the load of secondary side controllable. By simulating various loads, the secondary side current value and power factor can be flexibly set to complete various tests.

Figure 10 shown the experiment results of the energy acquisition system. (a) Simulated inductive load which is equal to 20mH. (b) Simulated capacitive load which is equal to 500μF.

As shown in Figure 11, when the secondary side electromotive force voltage is 35V, the waveform of voltage is distorted and the saturation magnetic flux density $B_m = 0.9T$ can be obtained.

The experimental results of uncontrolled rectifier are shown as Figure 12, $I_1$ is 41.92A, the DC output voltage is 9.43V. When the excitation inductance is fully compensated by impedance regulator, and the result is shown in Figure 13. When $I_1$ is 36.67A, the DC voltage rise up to 20V, which is two times than the condition that there is no impedance regulator, and the output power is rise up to 9W.
Figure 12. The DC voltage of uncontrolled rectifier.

Figure 13. The DC voltage when excitation impedance fully compensated by impedance regulator.

When the primary side current $I_1$ is large, the impedance regulator can be adjusted. The DC output voltage are shown as Figure 14 and Figure 15. In Figure 14, $I_1$ is the 102A and the DC output voltage is 20.414V, impedance regulator simulated inductive load to reduce the output power. In Figure 15, $I_1$ is 173A, the DC output voltage is 21.324V. Through adjust impedance regulator, the CT can provides a stable 9W output power for DC load.

![Figure 14. The DC output voltage when $I_1$ is 102A.](image1)

![Figure 15. The DC output voltage when $I_1$ is 173A.](image2)

6. Conclusion

In this paper, a stable energy acquisition system based on CT is proposed. According to the theoretical analysis, the impedance regulator model is established and its working principle is given. The impedance regulator can according to the required output power dynamically adjusted. When the primary side current is too small, the impedance regulator becomes capacitive load and fully compensates for the excitation inductance to reach the maximum output power; when the primary side current is too large, the impedance regulator becomes inductive load, reducing the output power of the CT’s secondary side.

Simulation and experiment proved that when $30A < I_1 < 200A$, the DC load can be provided stable 20V output voltage and 9W output power.

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