

An On-Line Energy Acquisition Method for Transmission Lines Based on Impedance Matching

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Abstract. Aiming at the shortcomings of large starting current and small output power for induction energy acquisition methods of conventional current transformers, an on-line energy acquisition method for transmission lines based on impedance matching is proposed in this paper. In this method, parallel resonance is generated by matching the secondary winding of the open gap magnetic core with its excitation impedance, thus the equivalent impedance of the damping branch of the magnetic core is increased. So that the load can get more electric energy by more current separated by the other branch. The experiments show that the on-line energy acquisition method of power transmission line based on impedance matching can achieve more power than the conventional current transformer induction energy acquisition method at the same bus current and the same magnetic core.

1. Introduction

Taking into account the importance of transmission line operation safety and the increasing accident safety hazards, researchers have focused on transmission line status parameter monitoring and fault diagnosis[1,2], which has made rapid progress in real-time monitoring systems for high-voltage transmission lines. However, the power supply for real-time monitoring equipment is not easy to obtain, and that has always been an important issue that restricts the widespread application of online real-time monitoring equipment for transmission lines.

This paper improves the conventional method of absorbing power via current transformers, proposing an on-line power-receiving method for transmission lines based on impedance matching, and establishing an energy-harvesting model, then, deducing the relationship between circuit model parameters and acquired power.

2. Energy harvesting method based on matching impedance

2.1. The energy harvesting theory

The on-line energy harvesting device structure based on impedance matching is shown in Fig. 1. A damped branch, an energy-stripping branch and a backup energy storage power supply are included in the energy harvesting system. The transmission line, a current transformer with an air gap and the capacitors concatenated on the current transformer secondary side are included in the damped branch circuit; A shunt wire, a transformer, a rectifier circuit, a DC-DC circuit and a load are included in the



energy-stripping branch circuit; A lithium battery and a charge and discharge management circuit are included in the backup power source.

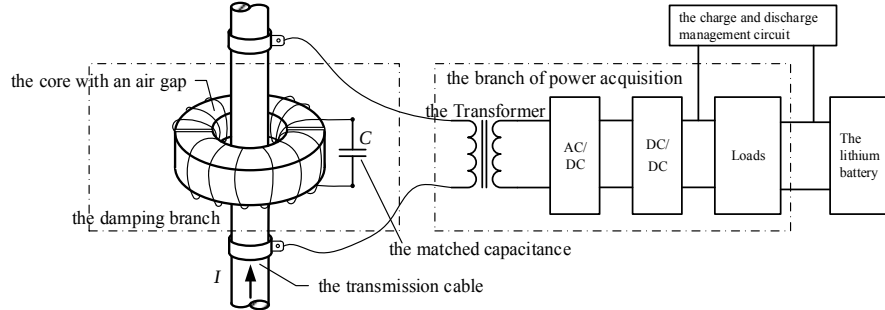


Figure 1. The structure of on-line energy acquisition device

If the transformer, the rectifier circuit, the DC-DC circuit, and the energy loading are viewed as a whole, the input impedance and the impedance of the damping branch constitute a parallel relationship. By adjusting the capacitance value of the secondary branch of the damping branch, it can make parallel resonance with the equivalent excitation inductance of the core, increasing the equivalent impedance of the damping branch, and matching the impedance of the damping branch with the load impedance.

2.2. Power acquisition circuit model

According to the law of electromagnetic induction and the principle of transformer, the model of the circuit for taking power shown in Fig. 2a can be established. The simplified model of the on-line power-collection circuit for transmission lines based on impedance matching is shown in Figure 2b.

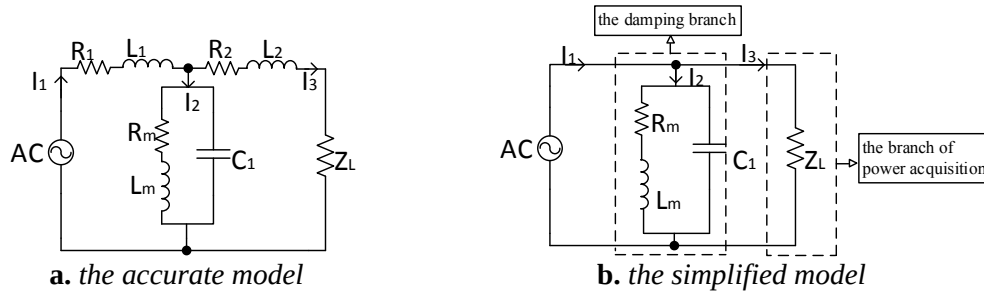


Figure 2. Circuit model of on-line energy acquisition

I_1 is the transmission line current, I_2 is equivalent current in the damping branch, I_3 is equivalent current in the energy-equipping branch; R_1 , L_1 are the core primary resistance, the primary leakage inductance; R_m , L_m , C_1 are the core excitation resistor, magnetizing inductance and matching capacitance; R_2 , L_2 are the secondary resistance of the magnetic core, and the secondary leakage inductance of the magnetic core; R_L is the equivalent input load.

When the core is not saturated, its value is generally constant and can be calculated from the magnetic hysteresis curve of the core material. The excitation inductance L_m is:

$$L_m = \frac{\mu_0 \mu_s N_1^2 S}{l} \quad (1)$$

In the formula (1): μ_0 is the vacuum permeability, μ_s is the relative permeability, N_1 is the number of primary turns, S is the cross-sectional area of the core, and l is the magnetic path length of the core.

The primary side of the magnetic core is the transmission line, mean $N_1=1$; vacuum permeability $\mu_0 = 4\pi \times 10^{-7} \text{ N} \cdot \text{A}^{-2}$, but the vacuum permeability of the core with an air gap is:

$$u_s = \frac{u_{Fe}}{u_{Fe} \frac{\delta}{l} + 1} = \frac{1}{\frac{\delta}{l} + \frac{1}{u_{Fe}}} \approx \frac{l}{\delta} \quad (2)$$

In the formula (2): u_{Fe} is the Magnetic core permeability; δ is the core air gap length.

According to the parameters of the core magnetization curve given by the manufacturer and the iron loss per unit volume of the core material, $R_m \approx 2.5m\Omega$ can be estimated, and the above core parameters can be substituted into equations (1) and (2) to calculate $L_m = 30uH$; Thus, the excitation impedance Z_m of the magnetic core can be calculated from equations (3). Thus, the excitation resistance $|Z_m| = 0.0097$.

$$Z_m = R_m + j\omega L_m \quad (3)$$

3. Analysis of On-Line energy harvesting output power based on impedance matching

In Fig. 2b, if the damping branch has no capacitance C_1 , it is the equivalent circuit model of the conventional current transformer inductive powering method. According to Fig. 2b, when the capacitance C_1 is connected in parallel across the magnetic core, the equivalent admittance Y and equivalent impedance Z of the damped branch can be calculated as:

$$Y = \frac{1}{Z} = \frac{1}{R_m + j\omega L_m} + j\omega C_1 =$$

$$|Z| = \frac{L_m}{C_1} \frac{\sqrt{1 + \left(\frac{R_m}{\omega L_m}\right)^2}}{\sqrt{R_m^2 + \left(\omega L_m - \frac{1}{\omega C_1}\right)^2}} \quad (4)$$

$$\varphi = \arctan \frac{\omega L_m - \frac{1}{\omega C_1} [R_m^2 + (\omega L_m)^2]}{R_m} \quad (5)$$

Ideally, when the phase difference $\varphi = 0$, that is, “parallel resonance” occurs in the damped branch, the entire circuit is resistive, and the equivalent impedance of the damped branch reaches a maximum value. The equivalent capacitor C_1 on the primary side is:

$$\omega L_m - \frac{1}{\omega C_1} [R_m^2 + (\omega L_m)^2] = 0 \quad (6)$$

$$C_1 = \frac{L_m}{[R_m^2 + (\omega L_m)^2]} \quad (7)$$

$R_m = 2.5m\Omega$ and $L_m = 30uH$ are put into formula(7), then calculating the $C_1 = 318.84mF$. And R_m , L_m and C_1 are put into formula(4), then calculating the damping branch equivalent impedance $Z = 0.037\Omega$. According to the principle of maximum power output:

$$P = \left(\frac{I_1}{2}\right)^2 \times R_L = \left(\frac{I_1}{2}\right)^2 \times Z \quad (8)$$

When transmission line current $I_1 = 50A$, the maximum power that the load can obtain is 23W. This is much more than the power obtained by the conventional current transformer inductive powering method in the same situation.

4. Experimental analysis

4.1. Power model verification experiment

In order to verify the correctness of the theoretical analysis, the nanocrystalline magnetic core with an air gap of 1K107. The inner diameter, outer diameter, and height of the core were 40mm, 120mm, and 60mm, respectively. Its sectional area is 2400mm², the magnetic circuit length is 25.1cm, the secondary side turns N₂ is 18, the air gap length is 0.1mm. In this paper, the no-load experiment is to be tested for the above air-gap current transformer. The voltage and bus current waveforms at both ends of the open air gap of the open-circuit test are shown in Figure 3.

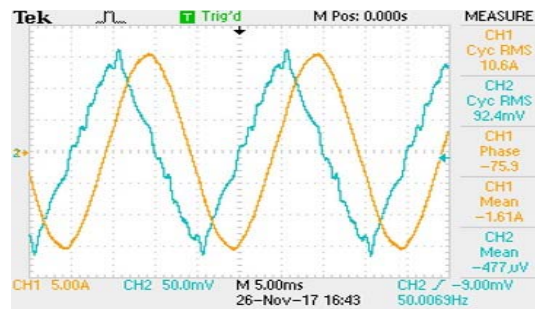


Figure 3. Voltage at both ends of the magnetic core and line current

In Fig. 3, the line current $I_1=10.6\text{A}$, and the voltage at both ends of the core $U = 92.4\text{mV}$. The actual excitation impedance value $|Z_m|$ of the magnetic core, the magnetizing inductance L_m and the magnetizing resistance R_m can be calculated by the equations (9), (10) and (11) :

$$|Z_m| = \left| \frac{U}{I_1} \right| = 0.0087\Omega \quad (9)$$

$$L_m = \frac{U}{\omega I_1} \sin\theta = 27\mu\text{H} \quad (10)$$

$$R_m = \frac{U}{I_1} \cos\theta = 2.1\text{m}\Omega \quad (11)$$

$\theta=76^\circ$ is the difference between voltage and current.

The experimentally measured core excitation impedance is close to the theoretically calculated excitation resistance of $2.5\text{m}\Omega$ and excitation inductance of $30\mu\text{H}$ in the first section. This shows that the online excitation model established in the first section of the theoretical derivation is accurate.

4.2. Energy power experiment

In order to verify the correctness of the output power theoretical derivation of the conventional current transformer inductive method and the on-line power-receiving method based on the impedance matching for transmission lines, we carried out load experiments for two energy-acquisition methods. The experimental system established is shown in Figure 4.

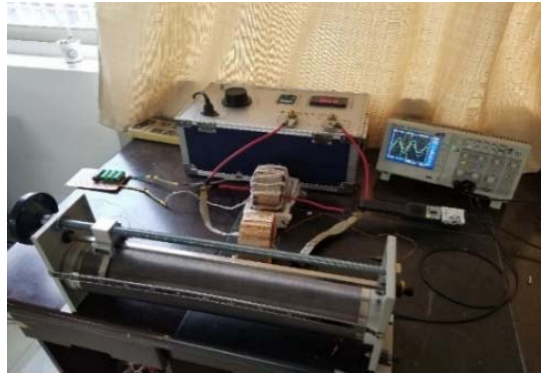


Figure 4. On-line energy acquisition experimental system

The data can be summarized as shown in Table 1, Table 2, and finally plotted according to the measured data. As shown in Figure 5.

Table 1. Experimental data of induction energy acquisition method based on conventional current transformer

RL LINE CURRENT	0.1Ω	0.5Ω	1Ω	2Ω	5Ω	10Ω
	Load voltage Load power	Load voltage Load power	Load voltage Load power	Load voltage Load power	Load voltage Load power	Load voltage Load power
10A	0.03V 0.01W	0.1V 0.02W	0.15V 0.02W	0.23V 0.03W	0.52V 0.05W	0.95V 0.09W
30A	0.25V 0.63W	0.78V 1.217W	1.23V 1.51W	1.98V 1.96W	2.11V 0.89W	2.51V 0.63W
50A	0.31V 0.96W	1.36V 3.699W	2.05V 4.2W	2.53V 3.2W	3.37V 2.27W	3.81V 1.45W
70A	0.47V 2.21W	1.88V 7.07W	2.78V 7.73W	3.18V 5.06W	4.51V 4.07W	4.98V 2.48W

Table 2. Experimental data of on-line energy acquisition method for transmission lines based on impedance matching

RL LINE CURRENT	30Ω	40Ω	50Ω	60Ω	70Ω	80Ω	90Ω	100Ω	110Ω
	Load voltage Load power	Load voltage Load power	Load voltage Load power	Load voltage Load power	Load voltage Load power	Load voltage Load power	Load voltage Load power	Load voltage Load power	Load voltage Load power
10A	2.4V 0.19W	3.41V 0.29W	3.78V 0.29W	4.32V 0.31W	4.82V 0.33W	5.26V 0.35W	5.56V 0.35W	6.08V 0.37W	6.45V 0.38W
30A	7.42V 1.83W	10.3V 2.65W	12V 2.88W	13.1V 2.89W	14.8V 3.13W	21.2V 5.618W	23.2V 5.98W	27.2V 7.40W	27.8 V 7.03W
50A	12.8V 5.46W	17.8V 7.92W	21.1V 8.90W	23.7V 9.36W	26V 9.66W	31V 12W	32.3V 11.59W	33.2V 11.02W	34V 10.51W
70A	18.6V 11.53 W	24.8V 15.38W	28.5V 16.25W	30.8V 15.8W	32.4V 15W	33.8V 14.2W	35.1V 13.69W	36.7V 13.47W	38.1V 13.1W

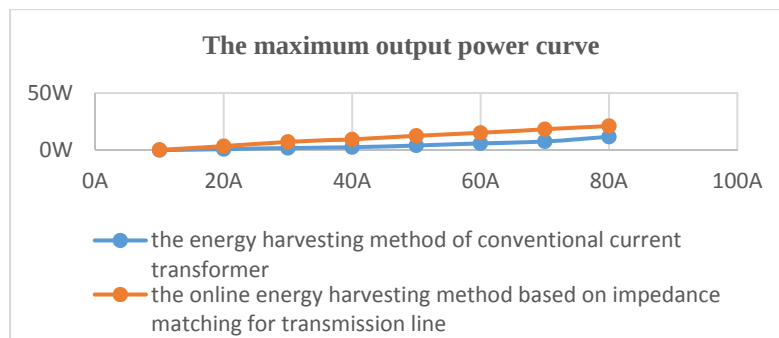


Figure 5. The relation curve of the bus current and the maximum power of the load

it can be seen from Table 1, Table 2 and Fig. 5 that the conventional current transformer induction and power acquisition method achieves a maximum power of 1.96 W at a bus current of 30 A, a maximum power of 4.2 W at a bus current of 50 A, and a maximum power of 11.8 W at a bus current of 80 A. On the other hand, an on-line power-receiving method for transmission lines based on impedance matching achieves a maximum power of 7.4 W at a bus current of 30 A, and a maximum power of 12 W at a bus current of 50 A. This is much larger than the maximum power that a conventional current transformer can draw in the same bus current and the same core. The difference between the load resistances when the two methods obtain the maximum power is larger because the number of turns on the secondary side of the transformer connected to the load is not the same.

5. Conclusion

This paper studies the power supply of on-line monitoring equipment for high-voltage transmission lines. According to the characteristics and defects of the method of inductive sensing of conventional current transformers, an on-line energy-gathering method for transmission lines based on impedance matching is proposed. Compared with the conventional method of inductive sensing of the current transformer, the new method can effectively increase the power harvesting; and when the busbar current change is large, the power energy can be controlled by adjusting the capacitance of the capacitor on the damping branch. This method is an ideal method to solve the power supply problem of the transmission line on-line monitoring device.

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