Research on an Improved Induction Power-taking Method for Smart Grid Monitoring Equipment

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Abstract: The development of smart cities is inseparable from the support of smart grids. Transmission lines are the bloodstream of the smart grid. Due to the geographical environment and insulation conditions of the transmission lines, the power supply of its monitoring equipment cannot directly transfer electrical energy from the cable. The low-pressure end is transferred to the high-pressure end. In order to ensure the smooth operation of the smart grid, the development of an online monitoring device that can continue to work reliably in different environments is a prerequisite to ensure the effective operation of the transmission line\textsuperscript{(1)}. Aiming at the technical bottleneck of monitoring equipment, this article improves the conventional induction power extraction method, and proposes an induction power extraction method based on parallel resonance, by matching the capacitor in the secondary winding of the magnetic core with the corresponding excitation inductance, parallel resonance occurs, thereby increasing the equivalent impedance of the damping branch where the magnetic core is located, so that the load can obtain more power through another branch. Finally, an electromagnetic core electromagnetic simulation experiment was carried out by using Ansoft Maxwell simulation software to verify the effectiveness of the method.

1. Introduction
With the rapid development of smart grids, people are paying more and more attention to the safety of power transmission systems, and it is more difficult to monitor and diagnose the operating conditions of high-voltage transmission lines. Therefore, online monitoring equipment plays an important role here. It can carry out real-time monitoring of the temperature, icing and other parameters of the transmission line, and issue an early warning of abnormal conditions to provide a basis for line maintenance. However, the on-site power supply conditions of the monitoring equipment are limited, so the convenience and reliability of the power supply mode of the monitoring equipment are very high. Because most of the transmission lines are erected in remote areas, the traditional power supply method is not only troublesome to replace the power supply material of the monitoring equipment, but also the maintenance work of the power supply device is also very heavy. Aiming at the technical bottleneck of the above monitoring equipment in terms of power supply, this paper adopts the method of inductive power extraction based on parallel resonance, and obtains more power through the establishment of a power model and parameter optimization. This method of obtaining electricity not only breaks through the shortcomings of conventional power supply methods such as cumbersome replacement of electricity...
and low energy output, but also has the advantages of low cost and high power. Therefore, the research of this project has important theoretical value and practical significance.

2. Principle of inductive power extraction based on parallel resonance

The inductive power taking system is composed of two parts, the damping branch and the power taking branch, as shown in Figure 1 below. Among them, the damping branch includes transmission cables and damping magnetic cores; and the power-taking branch includes shunt wires, transformers, rectifier circuits, DC-DC circuits, and power loads.

In this design, a secondary winding is wound on the damping core, and a matching capacitor C is added to the winding at the same time, so that the capacitor and the magnetizing inductance of the core will resonate in parallel, which can greatly increase the equivalent impedance of the damping branch\cite{2}; When parallel resonance occurs, the damping impedance theoretically tends to infinity, at this time all the load current will flow into the power branch circuit. In this case, all load currents will flow into the power-taking branch. However, it is actually restricted by the excitation resistance, and the damping impedance is a finite maximum value at resonance.

In the power-taking branch, if the input impedance is less than the damping impedance, then the bus current on the transmission cable can be shunted to the power-taking branch more. Therefore, the partial load current flowing on the transmission cable is led to it can take power on the load, so as to realize high-power inductive power output.

3. The equivalent circuit model of the induced resistance Ni branch

From the above analysis, it can be seen that the damping branch can provide the damping impedance $Z_d$ for the transmission cable, thereby shunting more load currents to the power-taking branch. Therefore, it is necessary to optimize the design of the components and parameters related to the damping branch to obtain sufficient large load current.

3.1. Equivalent circuit model construction

The damping branch can be regarded as a transformer structure with a single-turn coil on the primary side and a capacitive load on the secondary side. Therefore, the equivalent circuit of the damping branch can be derived according to the transformer T-shaped model \cite{3} as shown in Figure 2.

Among them, $R_{2}$, $L_{1k2}$ are the resistance and leakage inductance of the secondary winding converted to the primary side; $C'$, $R_C$ are the capacitance value and internal resistance of the secondary side matching capacitor converted to the primary side. When the number of turns of the secondary winding is $N$ is large, because the resistance and leakage inductance of the secondary winding are small, and the internal resistance of the capacitor is also small, $R_{2}$, $L_{1k2}$ and $R_C$ are equivalent can be ignored in the circuit. Therefore, Figure 2 can be simplified into the equivalent circuit shown in Figure 3 below.

![Figure 1 The structure of the induction power taking system based on parallel resonance](image-url)
If the damping core is selected, the values of $R_v$, $L_{lk1}$, $R_m$, and $L_m$ in the above figure are basically constant under certain conditions. At this time, the equivalent impedance $Z_d$ of the damping branch can be changed by changing the secondary capacitor $C$. If the influence of $R_v$ and $L_{lk1}$ is ignored, it is obvious that matching $C$, make $L_m$ and $C'$ just at the point of power frequency resonance, then the equivalent impedance $Z_d$ at this time is the largest. Let $Z_d$ be the input impedance of the RLC parallel resonant tank, then:

$$
|Z'_d| = \frac{1}{|Y'_d|} = \frac{1}{\sqrt{(\frac{R_n}{R_n^2 + \omega^2 L_n^2})^2 + (\frac{\omega C'}{R_n^2 + \omega^2 L_n^2})^2}}
$$

In the above formula, $Y'_d$ is the input admittance of the parallel resonant circuit. Obviously, when the capacitor $C$ satisfies the following formula (2), the modulus value of $Z'_d$ is the largest.

$$
N^2 C = C' = \frac{L_m}{R_n^2 + \omega^2 L_n^2}
$$

And at this time, the relationship between the modulus of $Z'_d$ and the quality factor $Q$ is:

$$
|Z'_d| = \frac{R_n^2 + \omega^2 L_n^2}{R_n} = R_n(1 + Q^2)
$$

Therefore, the equivalent impedance $Z_d$ of the damping branch is proportional to the square of the quality factor $Q$ of the damping core. So, when designing a damping magnetic core, the quality factor of the magnetic core should be increased as much as possible in order to increase the equivalent impedance of the damping branch.

3.2 Analysis of the output power of inductive power extraction

From the analysis in section 3.1, when the magnetizing inductance $L_m$ and the secondary capacitor $C$ have parallel resonance, the damping impedance $Z_d \approx R_v + Z'_d = R_v + R_m(1 + Q^2)$. $Z_d$ can be regarded as a pure resistive load, so the input impedance $R_L$ of the electric branch can be used to analyze the output power. Because the current on the high-voltage transmission line can be equivalent to a strong current source, if $Z_d$ is regarded as the internal resistance of the current source $I_1$, after resonance occurs, for the purely resistive branch, according to the maximum power transmission theorem, when the input impedance $R_L$ of the power-taking branch is equal to the damping impedance $Z_d$, the output power obtained by the power-taking branch is the largest. That is, the maximum power is obtained when $R_L = Z_d = R_m(1 + Q^2)$. The maximum power at this time is:

$$
P_{\text{max}} = \frac{I_1^2}{4} \times Z_d = \frac{I_1^2}{4} \times R_m(1 + Q^2)
$$

Therefore, in order to obtain greater output power, the most critical method is to design a damping core with a sufficiently high $Q$ value. And it is necessary to control the input impedance $R_L$ of the power-taking branch to match the equivalent impedance $Z_d$ of the damping branch to ensure the maximum power output from the transmission cable.
3.3 Optimized design of magnetic core structure

It can be seen from the designed equivalent circuit that increasing $R_m$ and $L_m$ can increase the current drawn by the load, and the output power obtained will also increase. However, when the magnetic core is not saturated, $R_m$ is constant, so $L_m$ can only be increased. Because the primary side of the transformer T-shaped model is the power transmission bus, that is, $N = 1$, and the vacuum permeability $\mu_0$ is a fixed value, therefore, the optimized design is firstly developed from the material and shape of the magnetic core.

Nowadays, the transformers and inductors are more commonly used in the design of silicon steel sheets, permalloy and nanocrystalline materials. Their magnetic parameters are different, as shown in Table 1 below. After parameter comparison and analysis, the initial permeability and magnetization curve comparison chart shown in Figure 4 below can be obtained. Obviously, the saturation magnetic induction intensity of silicon steel sheet is the highest among the three, but it is not easy to saturate, its initial permeability and maximum permeability are lower, and the iron loss is the largest; Permalloy Except for the larger maximum permeability, other basic magnetic parameters have no advantages; while nanocrystalline combines the advantages of silicon steel sheet and permalloy, with higher magnetic saturation induction intensity (1.2T), and its iron loss is very low, only 1/3~1/6 of silicon steel sheet. And because the magnetic core of nanocrystalline material can induce greater power when the bus current is small; at the same time, it will not saturate at a large bus current, so it is very suitable for application in the power supply system of the transmission line, so it is used in the design Nanocrystals with a relative permeability of approximately 300000 H/m in the linear region are used as the magnetic core material.

In terms of shape design, the cross-sectional area of the magnetic core can be increased and the length of the magnetic circuit can be shortened, so that the current transformer can be more closely fitted to the transmission bus [4]. However, in actual situations, due to restrictions on the volume and weight of the power-taking device, the cross-sectional area and volume of the magnetic core cannot be increased without limitation. Under comprehensive consideration, the open air gap magnetic core structure is selected.

| Basic magnetic parameters | Silicon steel sheets | Permalloy | Nanocrystalline |
|---------------------------|----------------------|-----------|-----------------|
| Saturation magnetic induction (B/T) | 2.1 | 0.7 | 1.2 |
| Initial permeability (H/m) | 1500 | 100000 | 100000 |
| Maximum permeability (H/m) | 40000 | >450000 | >400000 |
| Lamination factor | 0.95 | 0.9 | 0.7 |
| Iron loss 50Hz (W/kg) | 1.2 | 0.5 | 0.18 |

Figure 4 Magnetization curve of silicon steel sheet and nanocrystallin
4. Magnetic core electromagnetic simulation experiment

This part will use Ansoft Maxwell simulation software to carry out the magnetic core electromagnetic simulation experiment [5] to verify whether the magnetic saturation state of the selected magnetic core material is normal.

In order to verify the rationality of the above-mentioned analysis and deduction results and the design of the magnetic core structure, this paper carried out a simulation experiment on the selected nanocrystalline magnetic core. According to the magnetization curve of the nanocrystalline core provided by the manufacturer, first establish the core model in the simulation software [5], then add the nanocrystalline material, and finally set the boundary conditions, then the excitation source can be added to the wire passing through the middle of the magnetic core to start electromagnetic simulation. When the experimental bus current is 50A, the simulation results obtained are shown in Figure 5 below:

It can be seen from Figure 5 that when the wire current passing through the magnetic core is 50A, the magnetic induction intensity $B_1$ of non-open air gap nanocrystalline core is 1.1T, which is already in the deep saturation zone; and the magnetic induction of the magnetic core with an air gap length of 0.2mm the maximum intensity of $B_2$ is only 0.6T, which is still in the linear working area. This phenomenon is because the equivalent relative permeability of the nanocrystalline magnetic core is greatly reduced after the air gap is opened, so the magnetic induction intensity will also decrease under the same excitation current, therefore, the magnetic core is not easy to saturate.

![Magnetic induction intensity diagram of two magnetic cores at current 50A](image)

5. Conclusion

This paper studies the induction power extraction method of smart grid monitoring equipment, and proposes an improved induction power extraction method. The equivalent circuit model of the damping branch is built first, and then the maximum power that can be obtained under a given bus current is analyzed to determine the relationship between the output power and the relevant parameters of the damping core, which provides a basis for the optimal design of the magnetic core. After comparing and analyzing several commonly used magnetic core materials, this paper selects nanocrystals with higher saturation magnetic induction and permeability as the magnetic core material, and then uses Ansoft Maxwell simulation software to set the bus current as at 50A, electromagnetic simulations were performed on the non-open air gap and open air gap nanocrystalline cores. The simulation experiment results verified that the selected open air gap nanocrystalline cores are not easy to saturate. Therefore, applying this kind of magnetic core to the induction power extraction method enables the monitoring equipment to obtain a sufficiently large power output.

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References
[1] Yao, L. (2015) Research on the technology of coupling energy extraction power supply system based on overhead ground wire. Electrical application, 34(S2): 32–37.
[2] Bai, Y.C, Wu,G.P, Xiao,H, et al. (2010) Parameter matching method for induction power taking device of transmission line. Automation of Electric Power Systems, 34(21): 75–80.
[3] Jian L, Zhen S, Cheng H, et al.  (2010) A current transformer feeding power supply for distribution automation systems. In: International Conference on Power Electronics and Intelligent Transportation System. Nanjing, China. pp. 105-109.
[4] Du L, Wang C, Li X, et al. (2010) A Novel Power Supply of Online Monitoring Systems for Power Transmission Lines. Transactions on Industrial Electronics, 57(8):2889-2895.
[5] Liu G.Q, Zhao L.Z, et al. (2005) Ansoft Engineering Electromagnetic Field Finite Element Analysis. Electronic Industry Publishing, Beijing, China.