High Frequency Characteristic of Rogowski Coil

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Abstract
According to the transfer impedance getting from distributed parameter model, we analyse the influences of magnetic conductivity, the number of turns, capacitance to the shield and interturn capacitance on the high frequency characteristic of Rogowski coil through theories and simulations. Simulation shows that there are a series of zeros in high frequency band, but on the whole, the high frequency response does not change with the increase of frequency. The magnetic conductivity, number of turns and capacitance to the shield can influence the frequency at which zero appears, but the high frequency characteristic of Rogowski coil can’t be influenced. Considering the interturn capacitance, the curve of high-frequency response characteristic presents a “V” shape, and this leads to the reduction of higher cut-off frequency. So we should try to decrease the interturn capacitance to reduce the influence on the high frequency characteristic.

Keywords: Rogowski coil, distributed parameter, high-frequency, simulation

1. Introduction
In power system, PD signals of electrical equipment is ns-grade pulse, it’s rise time is very short, the upper frequency limit can range up to several GHz. At present, the frequency band of current sensor (i.e. Rogowski coil) to measure PD pulse current signals is narrow[1], which leads to lots of information contained in PD signals losted. So current sensor with wide band is needed to meet pragmatic needs.

The previous analysis of Rogowski coil is based on the concentrated parameter model, the cut-off frequency of coil can be estimated accurately by this model[2]. But when frequency is higher, the electromagnetic wave in the propagation of the coil should be considered, and Rogowski coil should be equivalent to distributed parameter model[3].

In this paper, we analyse the influences of the number of turns, capacitance to the shield and interturn capacitance on the high frequency characteristic of Rogowski coil according to the distributed parameter model through the simulation.

2. The distributed parameter model
According to reference [3], Rogowski coil can is equivalent to the distributed parameter model, as shown in Figure 1. In Figure 1, \( Z_{load} \) is the impedance of the cable load; \( M \) is the distributed mutual inductance; \( L \) is the distributed inductance; \( Z_{skin} \) is the distributed skin-effect resistance; \( C \) is the distributed capacitance to the shield; \( C_{int} \) is the distributed interturn capacitance; \( Z_w = R_m + jωL_m \) is the integral impedance; \( l_w \) is the length of the windings.

According to reference [3], the transfer impedance of Rogowski coil is shown as (1).

\[
Z_t = \frac{1}{\frac{Z_s}{jωM} \left( \cosh(\gamma l_w) + \frac{1}{Z_w} \right) + \frac{1}{Z_w}}
\]

Where

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Figure 1. The distributed parameter model of Rogoswki coil

Distributed impedance:
\[ Z_s = \frac{(Z_{skin} + joL)}{j\omega C_{str}} - Z_{skin} + j\omega L + \frac{1}{j\omega C_{str}} + \omega \sigma C \cdot Z_{skin} \] (2)

Propagation constant:
\[ \gamma = \frac{(Z_{skin} + j\omega L)}{Z_{skin} + j\omega L + \frac{1}{j\omega C_{str}}} \] (3)

Wave impedance:
\[ Z_0 = \frac{Z_{skin} + j\omega L}{j\omega C \cdot (Z_{skin} + j\omega L + \frac{1}{j\omega C_{str}})} \] (4)

When the interturn capacitance and skin-effect resistance are relatively small, and they can be neglected, then (1) can be simplified as
\[ Z_t = \frac{M'}{L} \cdot Z_m \] \[ 1 - j \frac{Z_m}{Z_0} \cdot \text{ctg} \left( \omega \sqrt{L/C} \right) \] (5)

From (5) we know that \( Z_t \) periodically get to zero when \( \text{ctg} \left( \omega \sqrt{L/C} \right) \) periodically get to \( \pm \infty \), but on the whole, \( Z_t \) does not change with the increase of frequency. The maximum is shown as (6), and this is consistent with the integral parameter model.
\[ Z_{t-max} = \frac{M'}{L} \times Z_m = \frac{Z_m}{N} \] (6)

If the skin-effect resistance can be neglected, but the interturn capacitance increases significantly, and it can’t be neglected, then the high frequency characteristic of Rogowski coil...
will change a lot. First, when \( \frac{1}{j\omega C_{mr}} = j\omega L \), the output voltage of the coil gets to zero, but in fact, due to the skin effect of resistance, the output voltage won't drop to zero totally. Secondly, when \( \frac{1}{j\omega C_{mr}} \ll j\omega L \), (1) can be simplified as

\[
Z_r = \frac{\omega^2 M C_{mr} \cosh(l_p \sqrt{C_{mr}/C})}{j\omega \sqrt{C_{mr} Z} \sinh(l_p \sqrt{C_{mr}/C})} - \frac{1}{Z_m}
\]  

(7)

According to (7), we conclude that when \( \frac{1}{j\omega C_{mr}} \ll j\omega L \), the transfer impedance of coil increases, and increases linearly with the increase of frequency eventually.

3. The influence of different parameters on frequency characteristic of Rogowski coil

There are many factors which influence the amplitude frequency characteristic of Rogowski coil, below we consider the influences which exercised by magnetic conductivity, the number of turns, capacitance to the shield and interturn capacitance respectively. We assume that NiZn ferrite core is used as the skeleton, and its model is NXO-100, its dimension is D×d×h (60 × 38 × 10) mm.

3.1 The influence of magnetic conductivity of ferrite core

The magnetic conductivity of real NiZn ferrite core is not constant, it changes with frequency, and it’s “f-\(\mu\)” shape is shown in Figure 2. There are two cases to consider: that of neglecting the change of magnetic conductivity (ideal ferrite core), and that of considering the change of magnetic conductivity (real ferrite core).

![Figure 2. The magnetic conductivity of NiZn ferrite core](image_url)
But the difference is that the frequency at which zeros of ideal ferrite core appears is evenly spaced, and the frequency of real ferrite core at which zeros appears is not evenly spaced. This is because inductance changes with the change of magnetic conductivity, and further lead to the change of period when \( \frac{\lambda \omega}{L} = \pm \infty \).

3.2. The influence of the number of turns.

When the distance from the core to the shield H is 7mm, magnetic conductivity of the magnetic core \( \mu \) is 100, the number of turns N is respectively 20, 40, 60, and the interturn capacitance is neglected, simulation is shown in Figure 4.

According to Figure 4, the maximum of amplitude frequency characteristic decreases with the increase of N, and this is consistent with the integral parameter model. At the same time, when N increases, the frequency when \( \frac{\lambda \omega}{L} = \pm \infty \) will decrease, that is the frequency at which zero appears will decrease.
3.3. The influence of capacitance to the shield.

When the number of turns N is 60, magnetic conductivity of the magnetic core μ is 100, distance from the core to the shield H is respectively 7mm and 1mm, and the interturn capacitance is neglected, simulation is shown in Figure 5.

According to Figure 5, the maximum of amplitude frequency characteristic doesn't change with the increase of H, this is because from (6), the maximum has nothing to do with the capacitance to the shield. At the same time, when H decreases, the frequency when \( \omega \sqrt{LC} = \pm \infty \) will decrease, that is the frequency at which zero appears will decrease.

3.4. The influence of interturn capacitance.

When the number of turns N is 60, magnetic conductivity of the magnetic core μ is 100, distance from the core to the shield H is 7mm, simulation(with interturn capacitance and without interturn capacitance) is shown in Figure 6.
According to Figure 6, we can see that when considering the influence of interturn capacitance, the maximum of low frequency characteristic won’t change. But the high frequency characteristic of coil will drop to zero nearly, and then increase linearly, that is to say, the curve of high-frequency response characteristic presents a “V” shape. So when considering the influence of interturn capacitance, the higher cut-off frequency will reduce, that is the high frequency characteristic of coil will become worse.

4. Conclusion
1. A series of zeros appear in high frequency band of the amplitude frequency response, this is the inherent characteristic of the coil, and it has nothing to do with the integral impedance, so this phenomenon won’t disappear with the change of integral impedance.
2. The magnetic conductivity of ferrite core influences the frequency at which zero appears, but it doesn’t influence the high frequency characteristic of coil, that is to say, the amplitude frequency characteristic of coil is irrelevant to the band of ferrite core.
3. The frequency at which zero appears decreases with the increase of N or C, but they don’t influence the high frequency characteristic of coil. At the same time, N exercises influence on the maximum and low frequency characteristic of coil, and the influence is contrary.
4. When considering the influence of interturn capacitance, the curve of high-frequency response characteristic presents a “V” shape. In other words, the higher cut-off frequency will reduce, so we should try to decrease the interturn capacitance to reduce the influence on the high frequency characteristic.

References