Winding distribution influence of some current limiting devices certain parameters

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Abstract: This report presents a study of connection between winding distribution and some current limiting devices parameters. Influence of separation coefficient on the variation of the mass parameters and the active resistance of an air coil is examined. The results of the simulation study are presented and a critical analysis is performed.

1. Introduction
In the technical literature, the design issues for current-limiting devices (CLD) are well known [1], [2], [3]. In the last years, the group of CLD equipment also includes devices of a new type - the so-called "Fault Current Limiters" (FCL) [4], [5]. FCLs are an alternative to traditional CLD - current-limiting reactors, chokes, dampers. In general, they can be divided into two groups [4]: FCL using superconducting materials [5], [6] and FCL made of conventional materials [6], [7], [8]. In the second group are included semiconductor type [6], FCL with submerging [7], transformer type FCL [8], electromagnetic type FCL [9], resistive type FCL [9].

It is necessary to know the distribution of the magnetic field created by the coil sequentially incorporated into the protected circuit in order to design an FCL with conventional materials.

There are some assumptions and simplifications in the engineering methodology designing current-limiting devices [1], [3], [10]. When designing a new type of CLD, these assumptions and simplifications may lead to a deterioration in their characteristics - increased losses, insufficient efficiency, higher end product costs. One of the main parameters for CLD improving efficiency is the coefficient of winding distribution [1].

The report aim is to investigate influence of the coil distribution coefficient on CLDs basic parameters - active resistance and change of the magnetic induction in the coil bright hole. Some dependencies have been used in the engineering methodology for calculating CLDs designed to operate in a particular power system (PPS) [10], [11]. A simulation study was conducted using the Finite Element Method (FEM).

2. CLD input parameters
In the design of the CLD, input parameters are assumed to be those that depend on the placement of the device and the type of PPS [12]. One of the input parameters is the admissible value of the paid-in inductance from the CLD [12].

In order to evaluate effect of the winding distribution coefficient on the bright hole winding volume field, the parameters of a specific PPS [13] are given in Table 1.
Table 1

| Xbr [Ω] | Lbp [H] | I2n[A] | Q[mm²] | σ[A/mm²] | k3 |
|---------|---------|--------|--------|---------|----|
| 0,519   | 0,01    | 577,35 | 300    | 2,3     | 0,25 |

With Xbr the induced resistance in the system is indicated, while residual network voltage is maintained in short circuit (SC) - 70%. Lbp is the inductance of the winding; I2n is the nominal operating current in the system; q is the cross section of the conductor with which the winding of the current limiter is wound; torque density; kz - winding load coefficient [12].

3. CLD output parameters

When calculating the output parameters of the device, the mean radius of the winding Rbp is determined by the expressions [3], [10], [14]:

$$R_{bp} = \left[ \frac{L_{bp}.(6 + 19.k).I_{2n}}{32.10^{-6}.k1^2.k3^2.γ^2} \right]^{0.2}, m$$

(1)

In (1) the distribution coefficient denoted by k1 is unknown. Winding distribution coefficient choice depends on the constructor's considerations. In this study it is assumed that its value is in the range of k1 = 0.33 to k1 = 0.71. The values of k1 are shown in Table 2.

The geometric dimensions a (winding package height) and b (winding package width) are calculated from the dependencies [3], [10]:

$$b = k.R_{bp}, m$$

(2)

$$a = \frac{2.R_{bp} + b}{2}, a.m$$

(3)

The number of Wbp windings, outer diameter D2bp and inner diameter D1bp are calculated with the following dependencies:

$$D_{1bp} = 2.R_{bp} - a, m$$

(4)

$$D_{2bp} = 2.R_{bp} + a, m$$

(5)

$$Wbp = k_2.k^2.\frac{R_{bp}^2}{q.10^{-6}}$$

(6)

The results of the expressions (1), (2), (3), (4), (5), (6) are given in Table 2

Table 2

| K1 | Rbp[m] | a[m] | b[m] | D1bp[m] | D2bp[m] | Wbp[num.] |
|----|--------|------|------|--------|--------|-----------|
| 0,33| 0,517  | 0,602| 0,171| 0,863  | 1,205  | 25        |
| 0,42| 0,482  | 0,583| 0,202| 0,761  | 1,166  | 34        |
| 0,54| 0,449  | 0,570| 0,243| 0,656  | 1,141  | 49        |
| 0,66| 0,426  | 0,566| 0,281| 0,570  | 1,132  | 66        |
| 0,71| 0,417  | 0,566| 0,296| 0,539  | 1,131  | 73        |

The variation of the coil distribution coefficient k1 results in a change of average radius Rbp (Fig. 1) and the other output parameters (figure 2) – the coil windings number Wbp, the bright hole coil diameter D1bp. Increasing the coefficient k1 reduces the geometric dimensions – mean coil radius
Rbp, winding height a, internal and external diameters (figure 1); the winding width b and the number of windings are increas. (figure 2).

The three-dimensional simulation model [15], [16], has been formed from the CLD coil parameters. The software product COMSOL [17], [18], [19] was used. The simulation is performed in both modes - nominal mode and SC mode. Some of the results are shown in figure 3 and figure 4.

To verify the simulation model, value of the active resistance of CLDs winding was compared (Table 3). With Re the active resistance obtained by the engineering methodology is indicated, and with Rc - the resistance obtained in the simulation test. The minimum and maximum values of the winding bright hole magnetic induction are determined. The magnitude of magnetic induction change in the air gap Kp is a disproportionate coefficient. It is accepted to evaluate the uniformity of the field [1]:

\[ K_p = \frac{B_{\text{max}}}{B_{\text{min}}} \]  

(7)

Table 3 shows the influence of winding distribution coefficient k1 on the minimum and maximum induction in nominal operating mode and in SC mode. The active resistance of the winding Re
determined by the simulation is not different from the value calculated by the engineering methodology $R_c$. At $k_1 = 0.66$ the multiplicity of air gap magnetic induction change is independent of the operating mode of the CLD - nominal or SC.

Table 3

| $k_1$ | $Re$ | $Rc$ | $B_{min}^n$ | $B_{max}^n$ | $B_{min}^f$ | $B_{max}^f$ | $Kpn$ | $Kpf$ |
|-------|------|------|-------------|-------------|-------------|-------------|-------|-------|
| 0.33  | 0.0048 | 0.0048 | 0.433      | 0.741       | 0.97        | 1.68        | 1.74  | 1.73  |
| 0.42  | 0.0061 | 0.0061 | 1          | 1.68        | 0.95        | 1.62        | 1.68  | 1.71  |
| 0.54  | 0.0082 | 0.0082 | 2.6        | 4.3         | 0.91        | 1.52        | 1.65  | 1.67  |
| 0.66  | 0.0105 | 0.0105 | 5.64       | 9.12        | 0.84        | 1.36        | 1.62  | 1.62  |
| 0.71  | 0.0114 | 0.0114 | 7.32       | 11.36       | 0.8         | 1.27        | 1.55  | 1.59  |

Figure 5 shows the geometric size variation and the coil distribution coefficient variation $k_1$. It also shows the active resistance change. By increasing the coil distribution coefficient value $k_1$, the dimension $a$ decreases and the resistance of the coil increases. The intersection in the characteristics of the active resistance and the characteristic of the geometric dimensions is found at winding distribution coefficient $k_1 = 0.66$.

Figure 5. Physical parameters change and winding active resistance depending on the distribution coefficient

Figure 6. Multiplicity magnetic induction change in the winding bright hole depending on the coil distribution coefficient

Figure 6 gives the dependence of the magnetic inductance multiplication variation and the resistance variation depending on the coil distribution coefficient. In both the geometric dimensions and the winding bright hole induction multiplicity, the intersection of the characteristics is found at $k_1 = 0.66$.

4. Conclusions

From the results presented in figure 5 and figure 6, the following conclusions can be made:
- The winding output current of the CLD depends on the coil distribution coefficient.
- The increase in the coil distribution coefficient results in the designed coil geometric dimensions change.
- For values of $k_1$ greater than 0.5 the relative dimensional change decreases.
The increase in coil distribution coefficient results in a more even magnetic field distribution in the designed coil bright hole. This is essential in the case of conventional materials made FCLs coil.

The increase in coil distribution coefficient leads to an increase in the active resistance, hence the designed coil losses.

For coil distribution coefficient \( k_1 = 0.66 \) the multiplication factor of the magnetic induction in the winding bright hole does not depend on the operating mode.

At coil distribution coefficient \( k_1 = 0.66 \) good weight-to-gauge ratio is achieved with comparatively low added active resistance.

5. Inference

Winding distribution coefficient has a significant effect on current limiter output parameters.

The report demonstrates that if the coil distribution coefficient is \( k_1 = 0.66 \) the weight-to-gauge ratio and coil losses will be acceptable; multiplicity magnetic induction coefficient in the bright hole coil bore does not depend on the mode of operation of the CLD.

This will allow for a even distribution of the magnet field of the coil when designing conventional materials FCL and hence limiting the inductance of the scattering of the CLD.

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