Operation of Electrical Coil without Core With Damaged Windings Insulation

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Abstract

Electrical parameters of coil’s open part (not short circuited) with different winding ratio for the both shortened and opened parts are investigated. Coil is foresight to introduce in load circuit of the serial resonant inverter in half-bridge scheme operation with increased circuit frequency and impact of shortening of coil relative to resonance case in the same circuit is investigated.

Keywords
Frequency, coil, windings, ratio, shortening, resistance, inductance, current, resonance

Introduction

In general, in the electrical coil an insulation can be damaged between layers and between closest windings, including in short circuit various parts from coil’s total number of windings W [1].

If we mark the number of short circuited windings with W₂, then here is new parameter - relative short circuited windings ratio:

\[ K = \frac{W_2}{W}. \quad (1) \]

The main aim of the paper is to investigate electrical parameters of coil’s open part (not short circuited) with different K if coil is foresight to examination in resonant circuit [2,3,4].

1. Substitution scheme

According to the substitution scheme on Fig. 1 inductivity of not shortened circuit part is \( L_1 \), resistance \( R_1 \), but inductivity of short circuited part is \( L_2 \) and resistance \( R_2 \). Those parameters can be calculated as:

\[
\begin{align*}
L_1 &= (W - W_2)^2 L_v, \\
R_1 &= (W - W_2) R_v, \\
L_2 &= W_2^2 L_v, \\
R_2 &= W_2 R_v,
\end{align*}
\]

where \( L_v \) and \( R_v \) are respectively inductivity and resistance of one winding:

\[
R_v = \frac{R_{kop}}{W}, \quad L_v = \frac{L_{kop}}{W}.
\]

The coil’s overall inductivity \( L_{kop} = L_1 + L_2 + 2M \), where for coil with dense winding mutual inductance for the both parts can be accepted as

\[
M = \sqrt{L_1 L_2}.
\]

Using ratio \( K \), parameters of the coil’s parts are

\[
\begin{align*}
R_1 &= (1 - k) R_{kop}, \\
L_1 &= (1 - k)^2 L_{kop}, \\
R_2 &= k R_{kop}, \\
L_2 &= k^2 L_{kop},
\end{align*}
\]

2. Parameters’ connections

For the scheme on Fig. 1 we can write, that

\[
U_i = \frac{R_1 R_2 + R_1 j \omega L_2 + j \omega L_1}{R_1 + j \omega L_1}.
\]

The real part of the complex impedance for not shortened circuit part – its resistance can be calculated as

\[
R_e = \frac{R_{kop} (1 - k) + R_{kop} k (1 - k) \omega^2 \tau_{kop}^2}{1 + \omega^2 \tau_{kop}^2 k^2}, \quad (4)
\]

where \( \omega \) is angular frequency of supply voltage, \( \tau_{kop} \) - time constant:

\[
\tau_{kop} = W \tau_v = W \frac{L_v}{R_v}. \quad (5)
\]
But the imaginary part of the complex impedance characterizes inductive reactance of the not shortened circuit part

$$\text{Im} = \frac{\omega L_{kop} (1 - k)^2}{1 + \omega^2 k^2 \tau_{kop}^2}.$$

The coil’s operation can be characterized by relationship between open part inductive reactance, its active resistance and respectively coil’s overall inductive reactance and active resistance in normal regime:

$$X^* = \frac{X_m}{X_{kop}} = \frac{L_{kop}}{\omega L_{kop}} = \frac{(1 - k)^2}{1 + \omega^2 k^2 \tau_{kop}^2};$$

$$R^* = \frac{R_c}{R_{kop}} = \frac{(1 - k)(1 + k\omega^2 \tau_{kop}^2)}{1 + \omega^2 \tau_{kop}^2 k^2}.$$  \hspace{1cm} (7)

In the Fig. 2 are shown curves $R^* = f(k)$ with different $\omega$ and two coil’s time constants 0.1 s and 0.01 s.

The first time constant 0.1 s accords to higher power coils, the second – to lower power coils. As it’s shown, if coil operation is realized with kilohertz angular frequency $\omega$, then with low K (<0.1) resistance of the open part increase very much, it reaches 100 and 1000 times increase with $K=0.001$ in respect to coil’s overall $R_{kop}$, which have been measured with DC.

Furthermore, when $K$ increase, relation $R^*$ decreases lower and lower, and in case, when $K=0.1$ (10% of coil windings are in short circuit), it decrease to 10 and continues to decrease to values lower than 1, when K is almost 1. In addition, increase of $R^*$ with low K is much higher to coil with higher time constant $\tau_{kop}$.

But, if coil with higher time constant operate in short circuit regime with relative lower frequency voltage (lower than kHz) and also coils with lower time constant in regime with very high voltage frequency, the increase of $R^*$ reaches only 20-30 times and the maximum is with $K=0.01...0.05$. With very low K, the increase of open part resistance doesn’t reaches 10.

In figure 3 are shown curves $L^*(X^*) = f(K)$ with different K and time constants $\tau_{kop} = 0.1$ and 0.01 s. As it’s shown, this relation as well at increase of K very fast decreases to very low values but ratios in all range of K are smaller as 1.

The lower $L^*$ values are for higher power coil’s and with higher $\omega$ values. With $K=0.001$ relation $L^*$ is in limits between 0.02 and 1. The lowest value is with $\omega=62800$ 1/s, the highest - with $\omega=314$ 1/s and lower.

3. Calculation of current

The acquired $R^*$ and $L^*$ relations allow to evaluate current $I_1$ in the open part circuit of coil. In situation when voltage of coil doesn’t change, current can be calculated as

$$I_1 = \frac{U_1}{\sqrt{(R_{kop} \bullet R^*)^2 + (\omega \bullet L_{kop} \bullet L^*)^2}}.$$  \hspace{1cm} (9)

In the Figure 4 are shown coil’s open part current’s dependence from $\omega$ and coefficient K. The inductivities of two examined coils are $L_{kop}=5$ mH and $L_{kop}=50$ mH, resistance of the both coils in DC condition are $R_{kop}=0.5$ $\Omega$, i.e., $\tau_{kop}=0.01$ s and 0.1 s respectively. Voltage of supply is $U_1=200$ V.
Fig. 4. Calculated characteristics of current in circuit of open part of shortened coils with common inductance $L_{kop} = 5 \, \text{mH}$ ($\tau = 0.01 \, \text{s}$) and 50 mH, resistance 0.5 $\Omega$, supply voltage 20 V on dependance of ratio of shortened windings

As it shown, lower currents are with lower values of relation $K$. If $K$ rises, currents rises also, as well become more close their values. With $K = 0.8$ their get practically the same values with all frequencies and both $\tau$. In the same time with very low $K$, the higher currents are with low $\omega$ and $\tau$, therefore difference between values is very high.

4. Shortening of coil in resonance circuit

If coil is operating in resonance circuit in series with capacitor then current is resonance case is determined only on resistance of coil [2,3]:

$$I_{1res} = \frac{U_1}{R_{kop}} \quad \text{(10)}$$

and this current provides necessary voltage across the examined coil

$$U_{resL} = I_{1res} \omega L_{kop} = U_1 \omega \tau_{kop} \quad \text{(11)}$$

In case of internal shortening of part of coil’s windings take changes as resistance of open part $R_1$ (at $K < 0.8$ it’s raising in respect to the common resistance of coil $R_{kop}$) as also inductance $L_1$ (decreasing in all cases). As result current in open part circuit of coil would decrease because reactance of circuit $(1/\omega C - \omega L^*_{kop})$ is raising and common impedance of circuit $L_1C$ stands as

$$z_k = \sqrt{(R^* R_{kop})^2 + (\frac{1}{\omega C} - \omega L^*_{kop})^2} \quad \text{(12)}$$

Current in circuit of supply will be

$$I_k = \frac{U_1}{z_k}$$

but voltage across coil

$$U_{Lk} = \frac{U_1}{z_k} \omega L^*_{kop} \quad \text{(13)}$$

Correct analytical calculation of this voltage at all possible cases is hard task but simplify expressions for $L^*$ and $R^*$ as

$$L^* \approx \frac{(1-k)^2}{\omega^2 k^2 + \frac{1}{\tau_{kop}^2}} \quad \text{and} \quad R^* \approx \frac{1-k}{k}$$

it’s possible obtain simplified expression for calculation of voltage across the partially shortened coil

$$U_{Lk} = \frac{U_1 (1-k)^2}{\sqrt{\omega^2 k^2 + \frac{1}{\tau_{kop}^2} k^2 (1-k)^2 + (1-k)^4}} \quad \text{(14)}$$

Using this expression some calculations have been done at different values of $\omega$ and $\tau = 0.1$ s and 0.01 s and in range of $K$ from 0.001 up to 1 (Fig. 5).

Fig. 5. Dependence of ratio of voltage across coil in respect to supply one at shortening of coil’s windings

As can be seen from figure at all shortenings inside coil ratio of voltage across coil is much smaller as it is at resonance. If for example $\tau = 0.1$ s then ratio of voltage at resonance is 0.1. At $\omega = 314 \, \text{1/s}$ ratio will be 31.4 but at shortenings ratio at every case will be 1 or smaller. At that bigger values of $U_{Lk*}$ will be at smaller meanings of ratio of shortened windings. If $K$ is bigger then $U_{Lk*}$ is very small.

In the case when time constant is very small the ratio of voltage at resonance also will be small and then at small ratio of shortened windings the both voltage relations should be very close. As example if $\omega = 314 \, \text{1/s}$ and $\tau = 0.01$ s then $U_{Lres*} = 3.14$ but at shortening with $k = 0.1$ ratio of coil’s voltage will be 1.38, i.e., very close to the resonance case.

5. Conclusions

1. At shortening one part of coil resistance of not shortened part in electrical circuit is rising above common resistance of coil in normally condition. Bigger values of rise ratio take place at higher frequencies of supply source voltage and bigger time constants of coil’s winding at normally condition.

2. At inside shortening of coil inductance of not shortened part is decreasing in large extent in respect to the normally inductance of coil. Bigger decreasing take place at higher frequencies and bigger time constants of coil’s winding.
3. If coil is operating in AC normally circuit then at internal shortenings current in open operating part and circuit of supply is rising but biggest values of current will be at smaller time constants and smaller frequencies too.

4. If coil is operating in resonant circuit in series with capacitor then at internal shortening of coil impedance of circuit is rising and as result current s decreasing and voltage across coil – too.

5. In resonant operation case largest decrease of voltage across coil take places at bigger time constants and bigger ratio of numbers of shortened winding and usually ratio of voltage across coil in respect to supply is equal or smaller as 1.

References