RIGA TECHNICAL UNIVERSITY

Faculty of Power and Electrical Engineering

Institute of Industrial Electronics and Electrical Engineering

EDGARS DREIMANIS

Doctoral program „Computer control of electro technologies” PhD

ELECTRICAL INDUCTOR COIL WINDINGS INSULATION HIGH-FREQUENCY DIAGNOSTIC METHODS INVESTIGATION AND CREATION

Dissertation summary

Scientific supervisor:
Dr.habil.sc.ing., prof.
I.RANKIS

RTU Publishing House
Riga 2011

UDK 621.314.21(043)
Dr 288 e

Dreimanis E. Electrical inductor coil windings insulation high-frequency diagnostic methods investigation and creation. Dissertation summary.-R: RTU, 2011.-31 pages.

Printed according to IEEI 28.06.2011. minute N.57

ISBN 978-9934-10-183-0

DOCTORATE PROMOTION WORK
PRESENTED TO OBTAIN ENGINEERING DOCTOR DEGREE IN RIGA TECHNICAL UNIVERSITY

Dissertation paper for engineering doctor degree will be public presented and defended on ………..of 2011 at 14:00 in Riga Technical University Faculty of Power and Electrical Engineering Kronvalda boul. 1, 117.room.

OFFICIAL REVIEWERS

Professor, Academic, Dr.habil.sc.ing., prof. Leonids Ribickis
Riga Technical University

Associated Professor, Dr.sc.ing. Leonards Latkovskis
Latvian Science Academy Physical Energetic institute

Professor, Dr.habil.sc.ing. Andris Sniders
Latvian Agriculture University Technical Faculty Energetic institute

CONFIRMATION

I confirm that I developed this promotion paper, which is submitted in Riga Technical University for engineering doctoral degree. Promotion paper isn't submitted in any other University for obtaining the scientific degree.

Edgars Dreimanis…………………………………(Signature)

Date……………

Promotion paper is in Latvian, consists from introduction, 4 paragraphs, conclusions, literature, appendix, 104 figures and illustrations, together 131 pages.
Literature consists from 114 sources.

PAPER GENERAL CHARACTERISTIC

ACTUALITY OF PAPER

Reliability of electrical supply is really important in energetic. Annual rise of number of electrical energy consumers and consumed volume of electrical energy take place. Due to previously mentioned factors, also raise losses to consumers and suppliers in cases when electrical energy supply is being suspended. Electrical supply reliability largely depends on equipment reliability, which is in its order influence transmission reliability from generator to consumer. Equipment reliability mainly depends on equipment insulation.

Ones of the main system elements are electrical devices with electrical windings. The most important from them are transformers. For safe operation must be provided normal operation conditions for their windings - quality of insulation, count of windings in operation, windings power losses in different regimes. According to these requirements is being done periodical control of windings quality. This control can be made with different methods.

Insulation is important part of equipment. It defines equipment lifetime, economical aspects and quality of electrical supply. So, it is important to evaluate insulation condition. To make this, it is necessary to acquire precise information about insulation. So, there is need for really precise and qualitative methods of diagnose.

Reliable information can be get from that diagnostic method, which gives a lot of dates of insulations. Here need to be information about main processes in insulation. There is need for new diagnostic methods in fact that the old ones have disadvantages. Analyze of traditional methods allows not only to determine their disadvantages, but also got positive facts, which need to be involved in new methods. The new methods development can’t be realized without good theoretical and technical basis.

Equipment insulation testing generally can be made when this equipment is switched off from electricity. Due to this fact, higher-voltage and mid-voltage equipment insulation testing can be made much less than low-voltage equipment. Evaluation of insulation, which is based only on one or two parameters, is related with high possibility to made wrong conclusions. Possible mistakes in measurements and measured parameters dependence on several factors shows the disadvantage, which is in diagnostic with small amount of information. This also shows that in high and mid-voltage equipment diagnostic must be acquired maximum information about insulation. To this information must be strong attention, because it is strongly connected to system economical and technical aspects. Formal attitude to diagnostic of insulation indirectly reduces reliability of system, but lower reliability is connected with higher loses for suppliers.

Furthermore equipment diagnostic is kind of product, which is being offered electrical suppliers for testing their equipment insulation. Economical situation makes not only prolong equipment durability, but also increase their load and decrease expenses. That is fact that in Latvia yearly increases equipment general aging. Large part of equipment was made in 60ties, 70ties. They are being used for 25-40 years.

Also must be mentioned, that real durability depends on load, cooling system, defense etc. That shows that the same age equipment, which operated in different conditions, remaining durability can be different. It is also in fact that equipment, which was made in 60ties still works, but some new substations in Latvia, Sweden and other countries had explosions.

This experience makes two possibilities:

1. Trust in equipment and don’t make diagnostics;
2. Make diagnostics, acquire information about equipment before beginning of operation and at the end of operation.

In the first case must be realized equipment change, when their operation time ends. Otherwise will be high risk situation in fact that durability time will end and nobody can guaranty further operation time.

So, the first case we can choose only if equipment operation level is high, which in Latvia’s conditions can’t be realized. Furthermore, if this case is accepted, must underline that equipment after operation time can be used further.

AIM OF PAPER

To develop and invent new insulation diagnostic method for coreless inductor coils, which is based on resonant inverter.

SCIENTIFIC NOVELTY

Scientific novelty is:

- in reason, that low frequency coil layers and windings diagnostic can be realized in high frequency resonant inverter chain. In this case achieves high-voltage, which is connected to coil. Here is small current in this chain and it gives advantage that source power can be low level.
- in reason, that coil’s voltage amplitude in resonance half bridge scheme can be acquired by fundamental harmonic influence to coil resistance, which define chain current amplitude, but it, in turn, multiplied with angular frequency and inductance- voltage amplitude.
- in reason, that, if parallel with investigated coil put etalon coil with stationary from frequency resistance, then possible partly limit coil’s current fast reduction in case of frequency rise. It helps to obtain higher level voltages on coil with the same frequency.
- in reason, that in case of coil windings inter-shortening sharply reduces voltage on coil, because undamaged part resistance influenced by inter-shortening sharply increases, but inductance - decreases. As result chain isn’t more in resonant regime.

THE PRACTICAL VALUE

The developed method can be practically used in electrical coil (drives and transformers) overhauls, when coil is taken from core.

This method can be used also in process of producing new electrical drives and transformers.

Have been obtained analytical methods, which can be used for equipment calculation.

Is invented methodology for chain element determination.

IS PRESENTED FOR PROMOTION

1. Method of windings and layers insulation diagnostic with high frequency high-voltage.
2. Methodology for element determination due to investigated coil’s parameters.

PAPER STRUCTURE AND EXTENT

Promotion paper consists from introduction, 4 paragraphs, conclusions and literature. Paper extent is 131 pages, 104 figures and illustrations, 1 table and literature with 114 sources.

PAPER APPROBATION AND PUBLICATIONS

Promotion paper results reported and discussed in scientific international conferences:

1. Riga, RTU, 49.scientific international conference, 2008. „Spoļu starpvijumu izolācijas pārbaude ar augstfrekvences sprieguma signāliem" (Examination of coil inter-winding insulation with high frequency signals) .
2. Kuresare, Eesti, 5.International Symposium. Topical Problems in The Field of Electrical and Power Engineering, 2008. Development of the Impulse Method for Testing High-Voltage Coil Inter-shortening Insulation// 5.International Symposium. Topical Problems in The Field of Electrical and Power Engineering 2008. 17-19p.
3. Kuresare, Eesti, 6.International Symposium. Topical Problems in The Field of Electrical and Power Engineering 2009. Determination of High-Voltage Windings Monitoring Voltage in Scheme with Resonant Inverter// 6.International Symposium. Topical Problems in the Field of Electrical and Power Engineering 2009. 22-25p.
4. Parnu, Eesti, 8.International Symposium. Topical Problems in The Field of Electrical and Power Engineering 2010. Resonant Inverter Operation with Over-frequency of Load Circuit// 8.International Symposium. Topical Problems in The Field of Electrical and Power Engineering 2010. 221-224p.
5. Parnu, Eesti, 9.International Symposium. Topical Problems in The Field of Electrical and Power Engineering 2010. Calculation of voltage resonance circuit with coreless electrical coil// 9.International Symposium. Topical Problems in The Field of Electrical and Power Engineering 2010. 190-192p.
6. Parnu, Eesti, 10.International Symposium. Topical Problems in The Field of Electrical and Power Engineering 2011. Operation of Electrical Coil with damaged windings insulation// 10.International Symposium. Topical Problems in The Field of Electrical and Power Engineering 2011. 13-16p.

Promotion paper results reported in 9 publications.

PAPER CONTENT

1. ELECTRICAL COILS AS INVESTIGATION OBJECTS

In the first paragraph is investigated electrical coil with its main electrical parameters.

As it is known, electrical coil inductance can be calculated:

$$L = \frac{0.32 r^2 w^2}{(6r + 9l + 10d)10^4} \text{ H}, \qquad (1)$$

where r – coil's average radius (Fig.1), l – it's length, d – layer thickness, w- windings count.

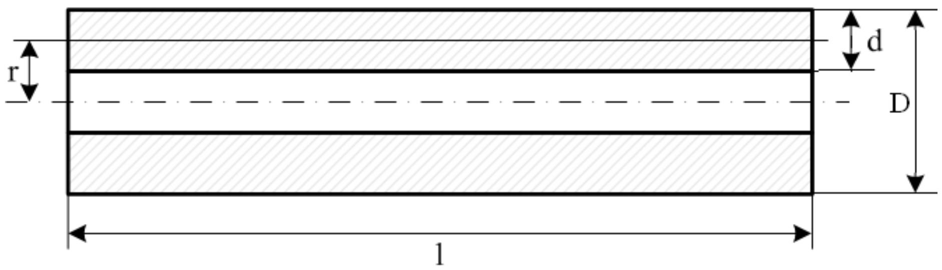


Fig.1 Coil's geometric parameters

One of the most important parameters is coil resistance, which depends on the effective coil current, as well as geometric parameters.

In DC case:

$$R_0 = \rho \cdot w \cdot \frac{l_{vid}}{S_v}, \qquad (2)$$

where $\rho = 0.02 \cdot 10^{-6} \Omega \cdot m$ is specific resistance of copper wire, $l_{vid} = 2\pi \cdot r$ is average length of winding.

Current density must be such that the coil doesn't overheat at the calculated current I_{efa}, as well as be fully loaded. If coil outer surface load indicator $q > 1200 \, {}^{W}\!/_{m^2}$, then current density in coil calculations must be decreased, because coil will overheat; if $q < 1100 \, {}^{W}\!/_{m^2}$, then density j must be increased, because coil haven't loaded.

Is possible large parameters r, d, l variation multiplicity, who by given L and I_{efa} can provide necessary criteria. However, for this paper, according to transformers constructions, can accept d=r and l=12r, i.e., that kind of coil is 4 times longer than the outer diameter. Then coil main parameters, using given expressions, can be calculated and they are in Fig.2. There is connection R_0=f(L) at different effective currents.

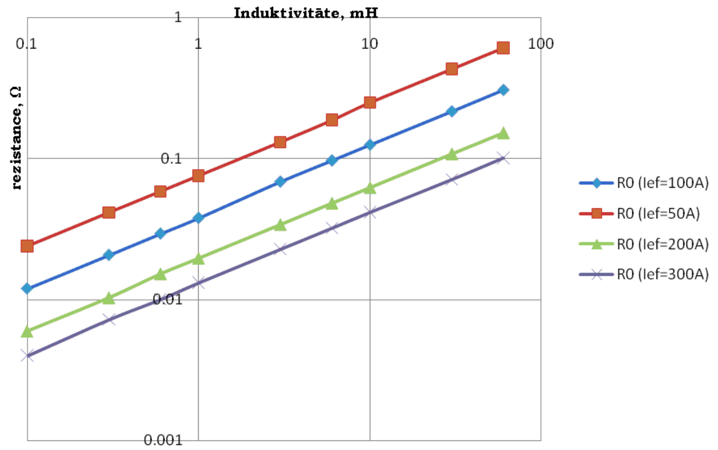


Fig.2 Connections R_0=f(L) at different I_{efa} values; L given in mH, R_0 – ohms, l/d=4

As it seen, resistance increases, if the coil inductance increases, furthermore at smaller I_{efa} are higher resistance R_0. By calculations, coils with configuration (4:1) resistance R_0 can be calculated (furthermore in text ld=l/D)

$$R_0 = \frac{86.\sqrt[4]{ld}\,\sqrt{L}}{I_{efa}}. \qquad (3)$$

Coil average radius

$$r = \frac{0.045.\sqrt[4]{L}\,\sqrt{I_{efa}}}{\sqrt[4]{ld}}. \qquad (4)$$

Current density

$$j = \frac{1.6 * 10^6 \sqrt[10]{ld}}{\sqrt[6]{L}.\sqrt[5]{I_{efa}}} \qquad (5)$$

When current frequency rises, skin effect starts, which influence can be described by electromagnetic wave penetration depth:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}, \qquad (6)$$

where $\omega = 2\pi f$ - current change angular frequency, μ - permeability, which for non-magnetic materials is equal $4\pi \cdot 10^{-7}\ {}^{H}\!/_{m}$.

Therefore, with frequency increase, dramatically increases wire resistance. If $\delta < r_v$, where r_v is radius of wire ($r_v = \sqrt{{}^{I_{efa}}\!/_{\pi \cdot j}}$), then wire resistance at higher frequency

$$R_\delta = R_0 \cdot \frac{r_v^2}{2 \cdot r_v\delta - \delta^2} \qquad (7)$$

and attitude between wire resistance at higher frequency R_δ and at resistance R_0 can be described as

$$\frac{R_\delta}{R_0} = \frac{r_v^2}{2r_v\delta - \delta^2} = \frac{1}{\sqrt{\frac{0,32 \cdot 10^6.\sqrt[10]{ld}}{\pi \cdot f \cdot I_{ef}\sqrt[6]{L}\sqrt[5]{I_{ef}}}} - \frac{0,08 \cdot 10^6.\sqrt[10]{ld}}{\pi \cdot f \cdot I_{ef}\sqrt[6]{L}\sqrt[5]{I_{ef}}}}; \qquad (8)$$

As δ by frequency increase, decreases, then attitude ${}^{R_\delta}\!/_{R_0}$ increases, this can be seen in Fig.3.

As it is in Fig.3, at equal effective current, resistance increase is higher, if coil inductance is higher. But, if case when inductances are equal, then increase is higher at higher current. Furthermore from 100Hz till 1kH increases aren’t so high, but if frequency is higher, increase is more higher.

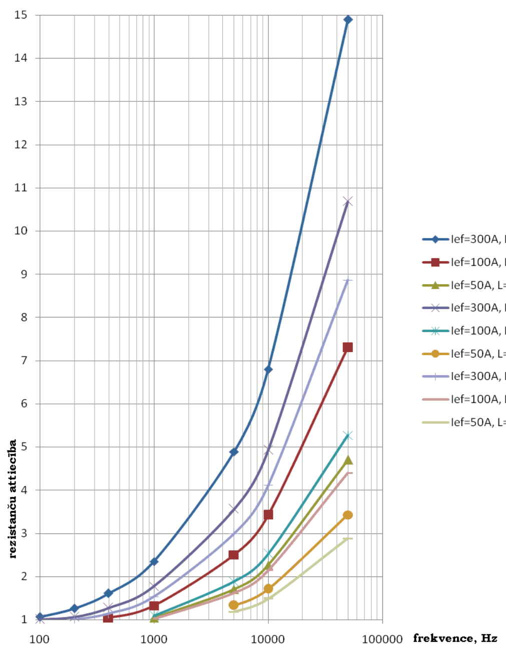


Fig.3 R_δ / R_0 dependence from I_{ef} and L values at different frequencies; l/d=4

To simulate coil's operation at internal inter-shortening must use scheme like autotransformer (Fig.4), where load voltage is zero.

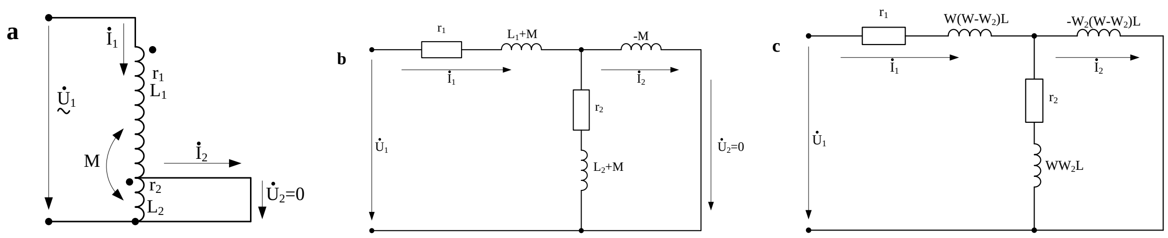


Fig.4. Inter-shortening in coil a-scheme, b, c- substitution schemes

According to scheme (4.a) circuit equations can describe

$$\dot{U}_1 = [r_1 + j\omega(L_1 + M)]\dot{I}_1 + [r_2 + j\omega(L_2 + M)](\dot{I}_1 - \dot{I}_2), \tag{9}$$

$$0 = \dot{I}_2\, j\omega M + (\dot{I}_1 - \dot{I}_2)[r_2 + j\omega(L_2 + M)] \tag{10}$$

This equation real part of impendence:

$$\mathrm{Re} = \frac{r_1 r_2^2 + r_1\omega^2 L_2^2 + r_2\omega^2 M^2}{r_2^2 + \omega^2 L_2^2} \tag{11}$$

Imaginary part:

$$\mathrm{Im} = \frac{\omega L_1 r_2^2 + \omega^3 L_1 L_2 - \omega^3 M^2 L_2}{r_2^2 + \omega^2 L_2^2} \tag{12}$$

As it is from non-shortened coil part inductance's equation, at rise of frequency this inductance sharply decreases. For example, $w_1 = 100$, $L = 10\mu H$, $r = 1m\Omega$, than shortened part inductance dependence from voltage angular frequency ω is in Fig.5.

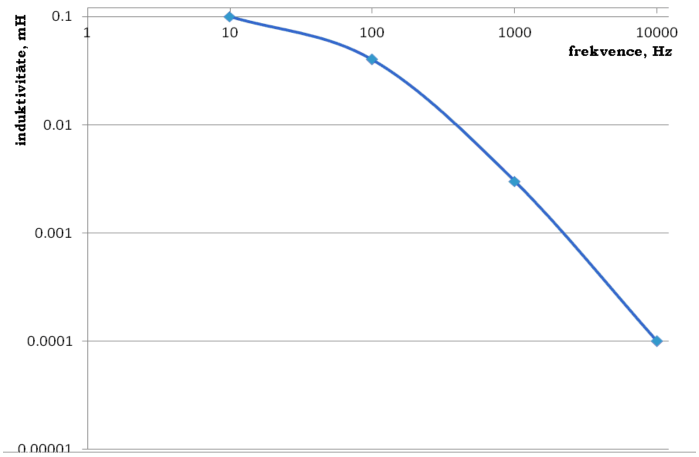
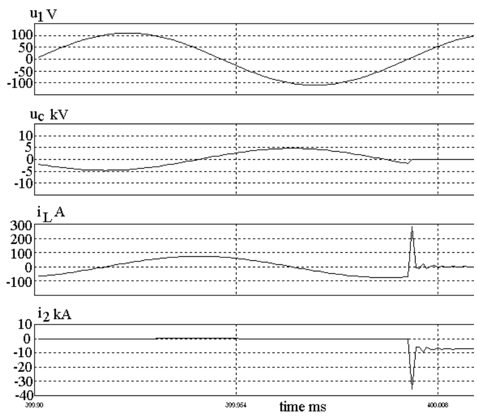


Fig.5. Shortened coil non-shortened part inductance dependence from voltage angular frequency

To check coil's winding insulation, it must be in resonance chain with capacitor, which capacity is $C = \dfrac{1}{4\pi^2 f^2 L_{sp}}$. (13)

In

and



In moment of inter-shortening resonance regime ends and chain current is practically null. Fig.6. shown inter-shortening moment voltage current diagrams, which have been taken in computer simulation with L_{sp}=1mH, R_{sp}=5mΩ, w_1=100, C=0,2536 μF at source frequency 10 kHz. As it is, chain current and capacitor voltage decreases after inter-shortening to very small values.

Fig.6. Coil windings in resonant chain current and voltage diagrams

In general, electrical coil can be insulation inter-shortening between layers and between windings, what can include in this shortened part different count of all windings W of coil.

If mark shortened part windings count with W_2, and then can mark new parameter- relative shortened windings count to all windings count in coil:

$$K = \frac{W_2}{W} . \qquad (14)$$

The aim is to investigate electrical parameters at different K of opened part.

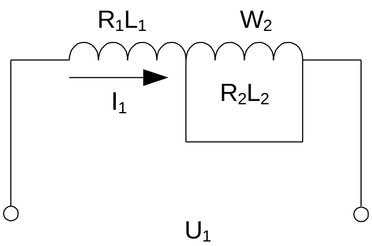


Fig.7. Coil's replacement scheme for non-shortened part investigation

For Pic.7. can write

$$U_1 = I_1 \frac{R_1 R_2 + R_1 j\omega L_2 + j\omega L_1 R_2 - \omega^2 L_1 L_2 + \omega^2 M^2}{R_2 + j\omega L_2} \tag{15}$$

Complex resistance real part – not shortened part resistance- can be calculated

$$\mathrm{Re} = \frac{R_{kop}(1-k) + R_{kop}k(1-k)\omega^2\tau_{kop}^2}{1+\omega^2\tau_{kop}^2 k_2}\ , \tag{16}$$

where ω is voltage angular frequency, τ_{kop} is time constant.

Coil operation is being characterized by open part attitude of inductive resistance and resistance to attitude of coil complex inductive resistance and resistance in normal case:

$$X^* = \frac{X_{val}}{X_{kop}} = \frac{\mathrm{Im}}{\omega L_{kop}} = \frac{(1-k)^2}{1+\omega^2 k^2 \tau_{kop}^2}\ ; \tag{17}$$

$$R^* = \frac{R_{val}}{R_{kop}} = \frac{\mathrm{Re}}{R_{kop}} = \frac{(1-k)(1+k\omega^2\tau_{kop}^2)}{1+\omega^2\tau_{kop}^2 k^2}. \tag{18}$$

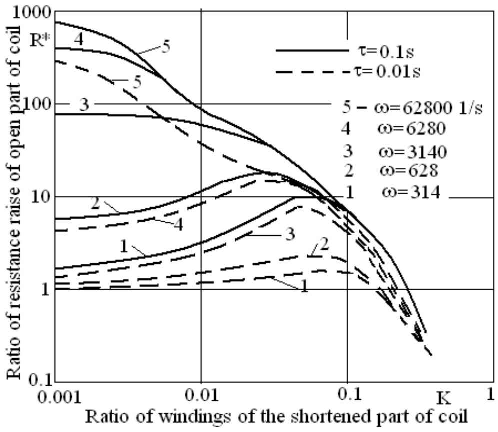


Fig.8 Calculated values $R^*=f(K)$ at ω=314, 628, 3140, 6280, 62800 1/s ad two time constants 0.1 and 0.01 s

In Fig.8. given curves $R^* = f(k)$ at different ω and two time constants 0.1s and 0.01s. The first time constant confirm higher power coils, the second- for lower. As it seen, if coil operation is at 1kHz ω, then at small K (<0.1) opened part resistance sharply increases and reaches at k=0.001 100 and 1000 times increase against coil complex R_{kop}, which is measured at DC.

Furthermore, if k increases, attitude R^* comes smaller, and at k=0.1 (10% from coil's all windings is in shortened part) decreases to 10 and continues decreasing to less than 1 at k close to 1. And increase of R^* at small k is much higher for coil with higher time constant τ_{kop}.

While, if coil with higher time constant operates in inter-shortening regime with relative lower voltage frequency (smaller than kHz), and coils with smaller time constant at very high voltage frequency, R^* increase reaches only 20-30 times and maximum is at k=0.01…0.05. At very small k increase of opened part resistance don't reaches 10.

If coil operates in resonance scheme with capacitor, then current in resonance is being determined by coil resistance:

$$I_{1res} = \frac{U_1}{R_{kop}} \qquad (19)$$

and this current provides necessary voltage for investigated coil

$$U_{Lres} = I_{1res}\omega L_{kop} = U_1\omega\tau_{kop} \text{ or } U^*_{Lres} = \omega\tau_{kop}. \qquad (20)$$

In case when is being shortened coil's windings part, influence is for opened part R_1 (at K<0.8 it increases to coil total resistance R_{kop}), and inductivity L_1 (decreases in all cases). As a result opened part current decreases in fact that chain resistance $(1/\omega C - \omega L^* L_{kop})$ increases and L_1C chain total resistance now describes as

$$Z_k = \sqrt{(R^* R_{kop})^2 + (\frac{1}{\omega C} - \omega L^* L_{kop})^2}\ . \qquad (21)$$

This is maximal simplified expression for shortened part voltage:

$$U_{Lk} \approx \frac{U_1(1-k)^2}{\sqrt{\omega^4\tau^4_{kop}k^4 - \omega^2\tau^2_{kop}k^2(1-k)^2 + (1-k)^4}}\ . \qquad (22)$$

Were made calculation at different ω values and τ=0.1 s and 0.01s at condition, that K is in limits from 0.001 till 1 (Fig.9.). In Fig.9 curves $U^*_{LK} = {U_{LK}}/{U_1} = f(k)$.

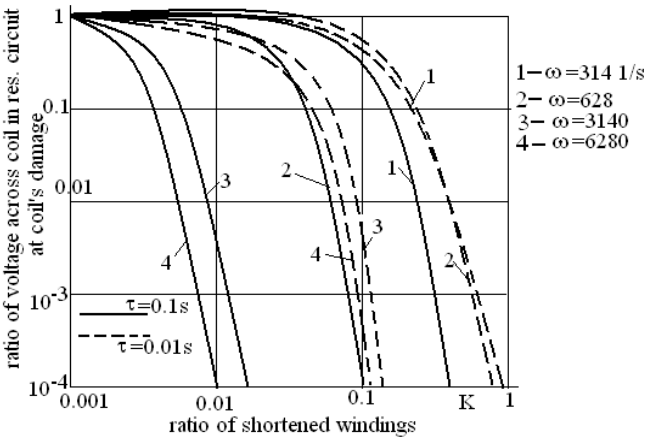


Fig.9. Coil voltage relative proportion to source voltage attitudes to count of shortened windings

In case, when time constant is very small, voltage value at resonance will be small and as result at small proportion of shortened windings, both values will be pretty close. For example ω=314 1/s and τ=0.01 s, then U_{Lres}^*=3.14, but at shortened with k=0.1 proportion U_{Lk}^* will be 1.38, i.e., pretty close resonance, and then is hard to recognize coil windings or layers inter-shortening.

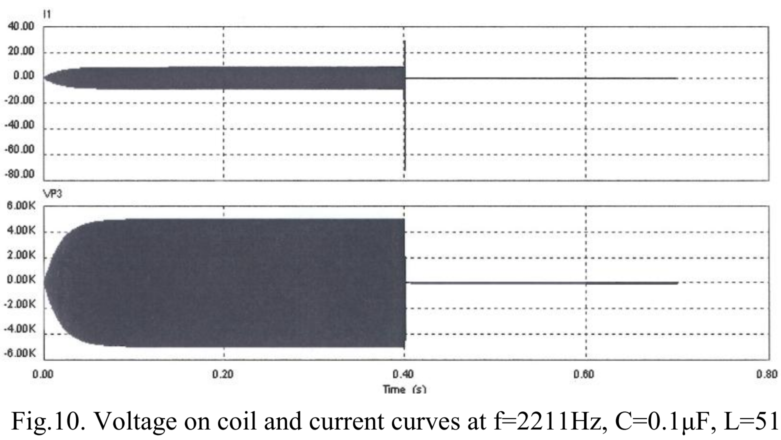


Fig.10. Voltage on coil and current curves at f=2211Hz, C=0.1μF, L=51.86mH, K=0.1818, R_1=4.5Ω, R_2 =1Ω, L_1=35mH, L_2 =1.66mH, M=7.6mH.

Voltage on coil and current changes at inter-shortening of coil part depending on frequency was made computer simulation with coil parameters L_1=35 mH, L_2=1,66 mH, M=7,6 mH, R_1=4,5 ohms and R_2=1 ohms. Here k=0,1818.

In Fig.10. is shown, that voltage amplitude reaches ~5kV at frequency 2211Hz and C=0.1μF.

But, if we look inter-shortening, then is situation that the higher is the frequency, the relative smaller are coil's currents and voltages. But must be mentioned that in inter-shortening is high current increase in small time moment, and this increase is linear with increase of frequency. This fact is important for creation of resonance inverter schemes.

In moment, when happens coils inter-shortening in resonance chain, is essential current increase (Fig.11.). It can be seen in Fig.10.

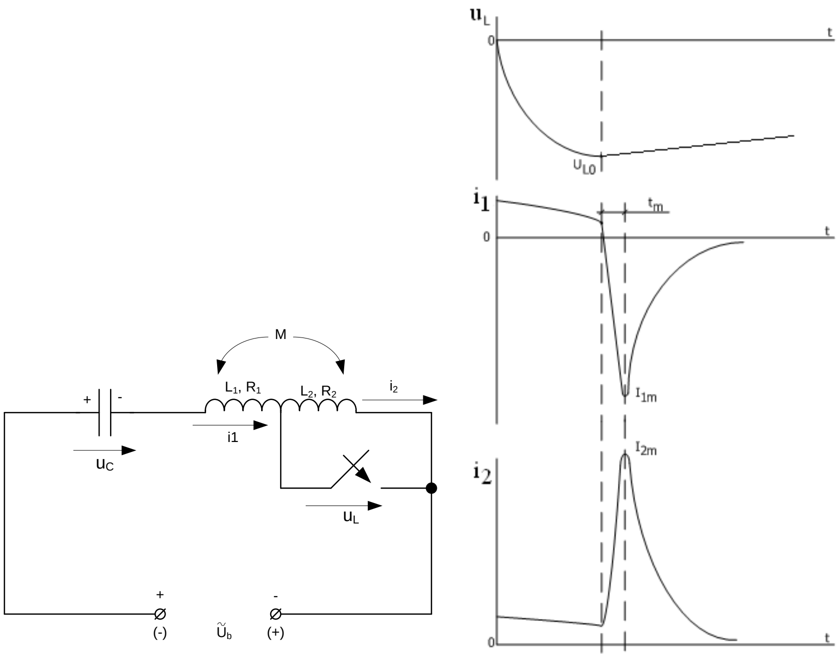


Fig.11. Transition process substitution scheme and inter-shortening process in current and voltage curves

This current increase can influence operation of resonant inverter, specially, transistors. This is the fact, why it's important to evaluate this increase.

In computer simulations was made experiment and results I_{1m}=-22A, I_{2m}=129A, U_{Lm}=-694V, t_m=19μs are acceptable, in fact, that was made major approximations in calculations.

2. RESONANT INVERTER AND ITS OPERATION INVESTIGATION

For investigation of coil's insulation, resonance inverter must realize:

1. reliable scheme operation at different frequencies, which is higher or lower than chain resonance frequency f_r, $(\omega_r = 2\pi f_r)$;
2. small voltage on switches in all their operational time, and voltage fall on turned switch must be near null;
3. minimal power from source. It can be realized with source voltage regulation for different regimes of coil current;
4. source with reverse current;
5. coil chain current measure with non-contact electronic equipment;
6. some milliseconds huge currents in inter-shortening with electronic protection.

Due to the fact that thyristors are more reliable than transistors, vantage would be to thyristors. One of the most effective would be parallel resonance inverter, in which load chain is parallel to capacitor, which provides resonance process as well as makes safe commutation of thyristors.

But, as thyristors schemes have problems with safe closing of thyristors and practically hard realize of sinusoidal current regime at resonance frequency, these schemes we can't use in these investigations. Only modern transistors allow provide qualitative resonance regime with minimal source power and limited voltages on switches. The most effective is half-bridge scheme with non-divided capacitors (Fig.12) in fact that in this scheme high level output voltage van be reached without transformer, which complicate processes in scheme and makes additional losses.

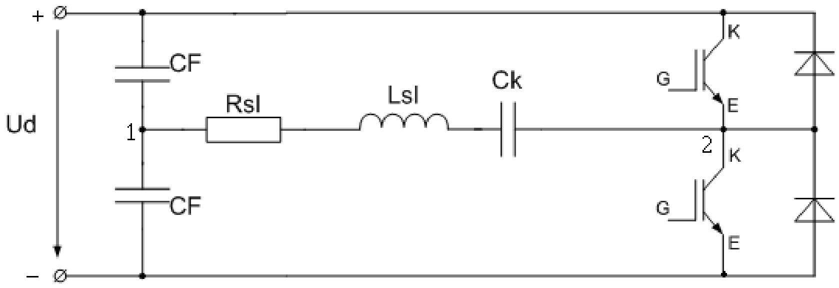


Fig.12. Series resonance inverter in half-bridge scheme with non-divided capacitors

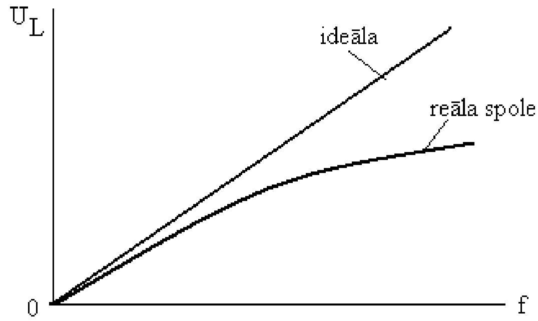


Fig.13. Voltage on investigated coil depending on frequency

As it is shown in the first paragraph, in simple series resonance inverter frequency rises causes current. The reason is that investigated coil active resistance rises in influence of skin effect and proximity effect. If coil at different frequencies would be with unchanged resistance, then voltage on coil increased linearly with frequency rise (Fig.13.). In reality, by rise of frequency, rises also resistance of coil, current amplitude decreases and voltage on coil- also decreases.

To fix this problem, I decided for my investigations use improved resonance scheme with MOSFET transistors (Fig.14.). In this scheme are parallel switched two coils- one with wire for 50Hz, the second - made from high frequency multi-core wire, which resistance don't depends on frequency. As one coil is with unchangeable resistance from frequency, then both coils together have less frequency influence to resistance and have stabile operation and resonance parameters.

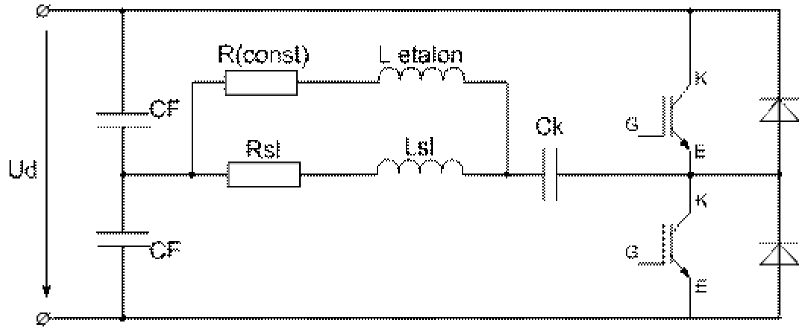


Fig.14. Scheme of resonance inverter with decreased resistance influence from frequency

Operation of resonance inverter can be normal only if chain parameters provide fluctuation process, must be

$$\frac{1}{LC} > \left(\frac{R}{2L}\right)^2 = \delta^2, \qquad (23)$$

where δ- damping coefficient.

Chain self-oscillation frequency

$$\omega_r = \sqrt{\frac{1}{LC} - \delta^2}\,. \qquad (24)$$

Precise resonant inverter calculations is very complicated, because it develops from one switching cycle to next one and voltage on condenser reaches much higher amplitude than in DC source.

Generally resonance inverter operation divides in three regimes. The first is $\omega_V = \omega_r$, when control angular frequency $\omega_v = 2\pi/T$ is equal to chain self-oscillation frequency $\omega_r = \sqrt{\frac{1}{LC} - \delta^2}$. In this case we get border-regime, when current is continuous and practically sinus. This is also the preferred operation regime.

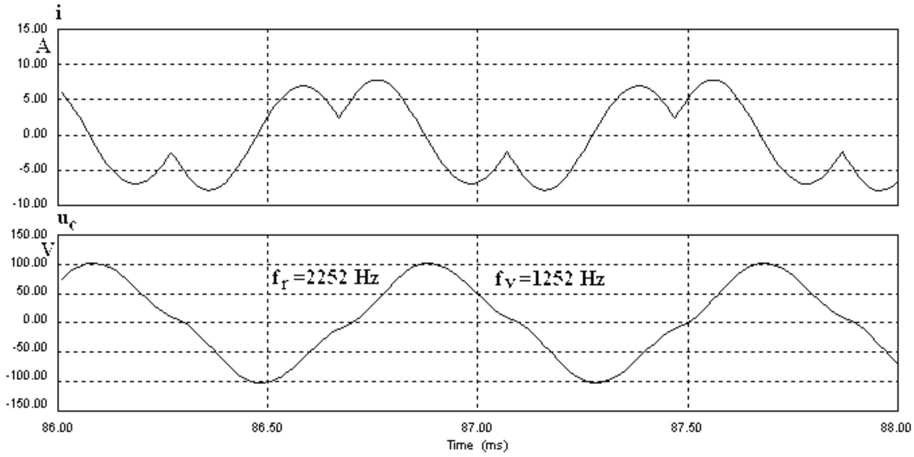


Fig.15. Currents and voltage on capacitor curves at $\omega_V < \omega_r$ (R=0.5Ω, C=10μF, L=0.5mH)

The second regime is when control angular frequency ω_v is smaller than ω_r, then we get non-sinus current). In this case, current is with small amplitude and as result it gives influence to voltage U_C, which is in Fig.15.

The third case is $\omega_V > \omega_r$, then load voltage effective value decreases against evaluated value in resonance regime. In this scheme isn't possible to operate at $\omega_v > \omega$, if transistor isn't shunted with diode, otherwise in transistor starting moment current value of load always will be with opposite direction to transistor control, and this is against principles of switching. To make normal operation of scheme, each transistor must be shunted with reverse diode and source need to be in two-directions.

Resonance chain element voltages in stationary regime have been calculated at border-regime, when $\omega_V = \omega_r$. Calculation scheme is in Fig.16.

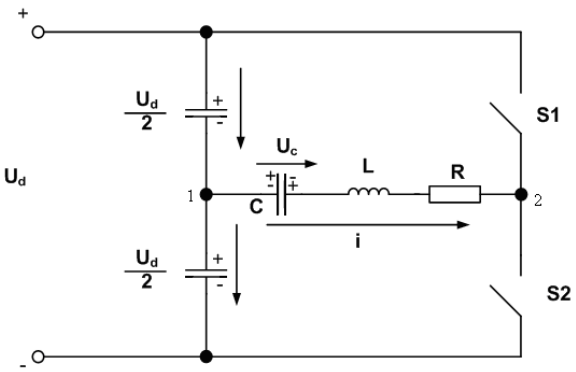


Fig.16 Calculation scheme

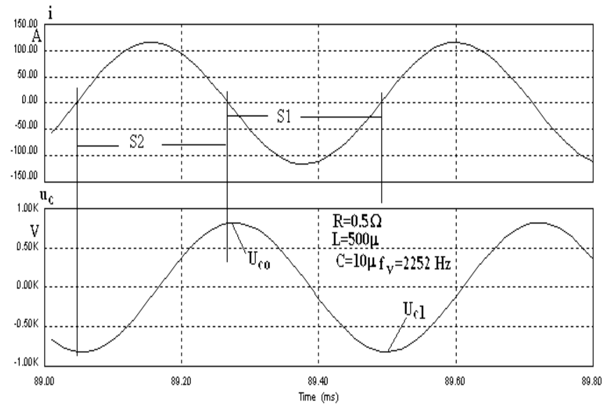


Fig.17. Resonance chain current and capacitor voltage curves in resonance regime

Switches S1 and S2 is being switched periodically and control signals to their switching lasts half period. Source voltage is being divided in dynamic regime with capacitors chain and to resonance chain is being provided one and the other polarity half voltage.
In the first half period is switched switch S1. Switch S2 is off. Curves of voltages and currents are in Fig.17.

At the beginning t=0, $i = 0$, but $u_c = U_{c0}$, which is from rule, that chain is in resonance and current curve is in fuse with switching voltage u_{12} . Thus moment values of current can be described as:

$$i = e^{-\delta t}(A\sin\omega t + B\cos\omega t)\,, \tag{25}$$

what, due to start rules, transforms in

$$i = -e^{-\delta t}\,\frac{0{,}5U_d + U_{c0}}{\omega_r L}\sin\omega_r t\ , \tag{26}$$

where $\omega_r = \dfrac{1}{\sqrt{LC}}$ (self-oscillation angular frequency, which period is $T = 2\pi\sqrt{LC}$. Practical it is resonance frequency).

Voltage on inductance

$$u_L = L\frac{di}{dt} = -e^{-\delta t}(0{,}5U_d + U_{c0})(\cos\omega_r t - \frac{\delta}{\omega_r}\sin\omega_r t)\,. \tag{27}$$

When $\omega_r t = \pi$, then

$$u_{L(\pi)} = e^{-\delta\frac{\pi}{\omega_r}}(0{,}5U_d + U_{c0})\,, \tag{28}$$

while capacitor voltage maximal value at switched S1 is

$$U_{c1} = -0{,}5U_d - e^{-\delta\frac{\pi}{\omega_r}}(0{,}5U_d + U_{c0})\,, \tag{29}$$

which obligatory is negative value.
In the second half period switch S2 is turned on. S1 is switched off. At the beginning of half period current $i = 0$.

As capacitor current average value is null, then making integration of current equations, and taking equation of U_{C1}, we can get:

$$U_{c0} = \frac{0{,}5U_d + U_d e^{-\delta\frac{\pi}{\omega_r}} + 0{,}5U_d e^{-2\delta\frac{\pi}{\omega_r}}}{1 - e^{-2\delta\frac{\pi}{\omega_r}}} \quad . \tag{30}$$

These equations (29) and (30) allow calculating necessary parameters (voltages on capacitor and coil) in resonance regime. But, here is also another solution, which is based on calculation of switching voltage u_{12} fundamental harmonic influence to resonance chain element voltages. Fundamental harmonic voltage amplitude is:

$$U_{LD(f)m} = \frac{2U_d}{\pi} . \tag{31}$$

Then load current amplitude in resonance regime is $U_{LD(f)m}/R$ and capacitor voltage amplitude is

$$U_{C0} = \frac{2U_d}{\pi R \omega_r C} . \tag{32}$$

From acquired equations can be calculated average value of source current I_d. Assuming that in semiconductors and capacitors don't have active power loses, we can write

$$I_d = \frac{I_{mo}^2 . R}{2U_d} , \tag{33}$$

where I_{m0} is resonance current amplitude. So, we can write

$$I_d = \frac{2U_d}{\pi^2 R} . \tag{34}$$

As it been mentioned before, if frequency rises, coil's resistance also rises, as result decreases resonance chain current, but it makes decreasing of chain elements voltage amplitudes at resonance (Fig.18). In result awaited increase of voltage isn't reached (Fig.19).

To partly resolve this effect, was invented scheme in Fig.20. Here parallel to investigated coil is etalon coil, which resistance doesn't dependents from frequency. Overall resonance regime will be determined by etalon coil, on which will be suitable voltage for resonance regime, but this voltage at the same time will be put on investigated coil. It allows to make coil's insulation investigations.

For investigation was made scheme (Fig.20).

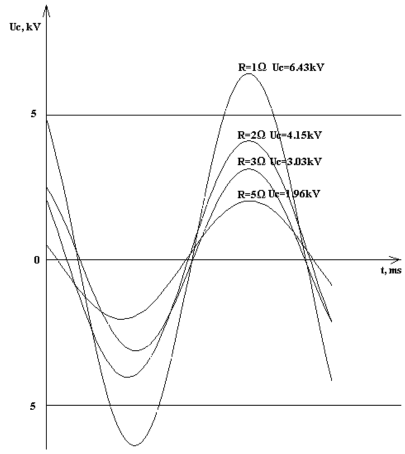


Fig.18. Capacitor voltage curves at non-changeable control frequency and different coil's resistances

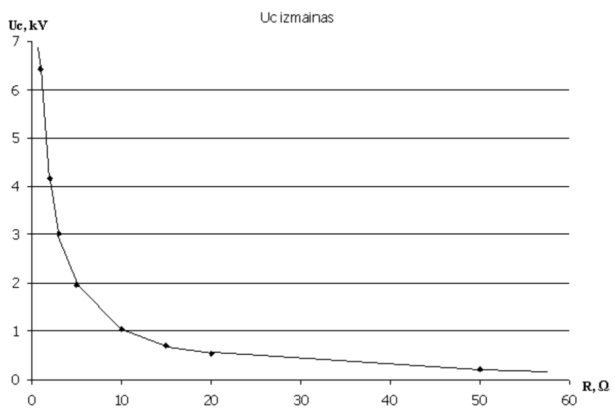


Fig.19. Capacitor voltage amplitude changes from coil resistance in resonance chain

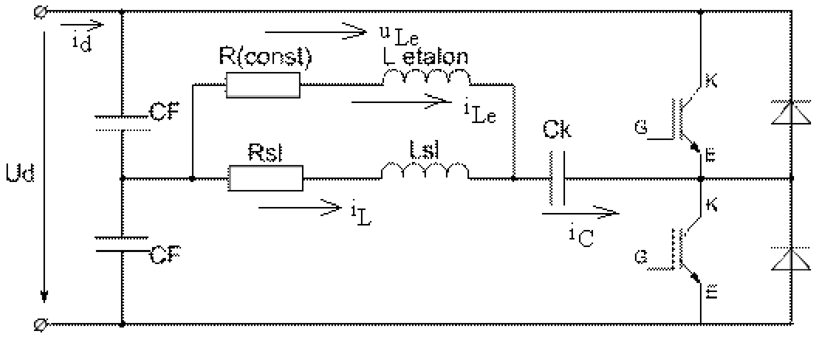


Fig.20. Scheme for improved method

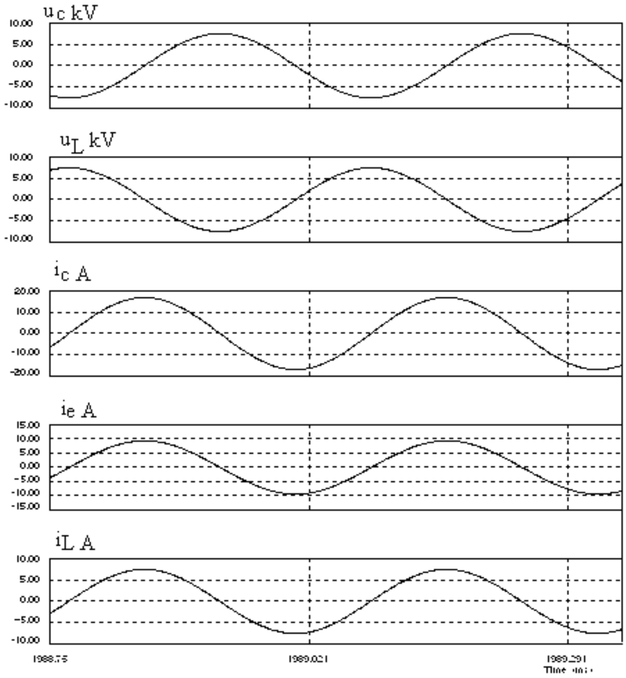


Fig.21. Coils and capacitor voltage curves, and each coil and capacitor current curves

Process illustration is in Fig.21, where are shown capacitor and coil voltage curves as well as current curves in coil, etalon coil and capacitor. Curves are taken in computer simulation at L=50mH, L_e=40mH, C=0,1125μF, f=3173Hz, U_d =100V, R=12Ω, R_e=0.1 Ω. As it is, all three currents is in phase, but voltages u_c and u_L is in anti-phase.

To check effectiveness of improved scheme, in computer simulation were made curves U_{Lm}=f(R), as well as in traditional scheme. Results are in Fig.22. Coil's resistance have been changed from 1 to 15 ohms, in traditional scheme coil voltage amplitude changes more than 10 times, but in improved scheme only 1.5 times. This shows the effectiveness of improved scheme for investigation of coil with different resonance frequencies.

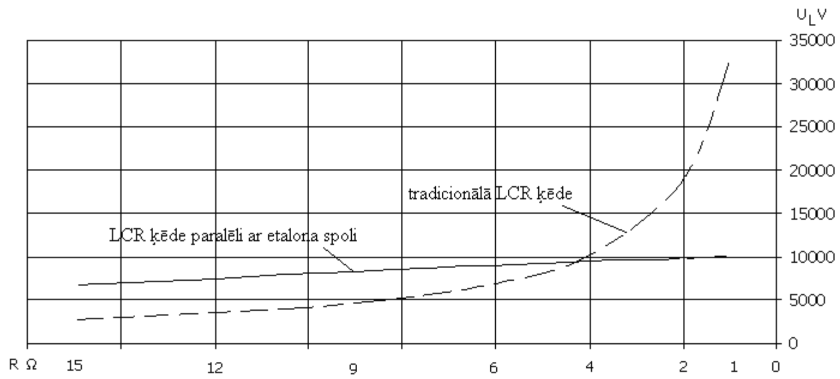


Fig.22. Resonance voltages on in traditional scheme (---) and in scheme with etalon coil

3. COIL RESONANCE SYSTEM PARAMETERS CHOICE

For resonance system parameter calculations at constant investigated coil resistance can be used simplified equation (32). If chain goodness is high, this resonance frequency can be calculated as $\omega_r = \sqrt{\dfrac{1}{LC}}$.

Source and resonance chain active powers are equal in fact that loses in transistors and reactive elements can be ignored. Then source current can be calculated using another equation (34).

Putting equation 32 in 34 and take, that $U_{c0}/U_d=k_u$ – voltage increasing coefficient, can calculate curves $C=f(k_u)$ at different attitude of L/R^2. These curves are in Fig.23.

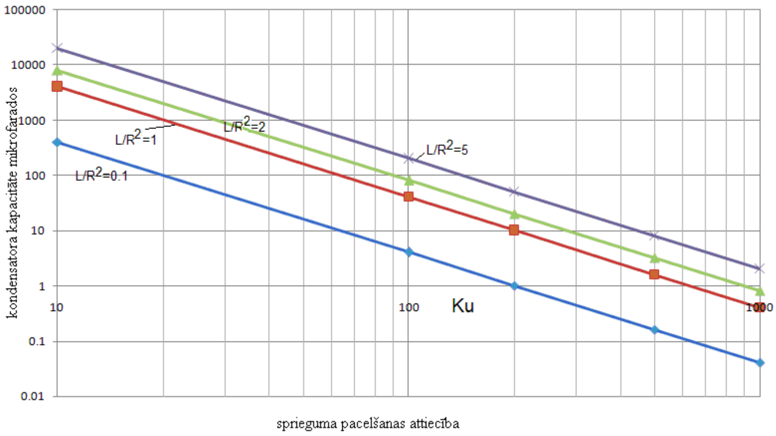


Fig.23. Calculated curves for choose of capacitor values depending on voltage increase factor

As it is in Fig.23, the higher is voltage increase coefficient, the capacitor value is less at the same indicator L/R^2. If attitude L/R^2 rises, proportional to it raises also capacitor.

For example, if L=10mH and R=0,1 ohm, at voltage increase factor 100 in chain must be capacitor with value 40,57 µF. Verifying in computer simulation PSIM confirms correctness of results, furthermore resonance frequency was 1569,86 1/s.

When is acquired necessary capacitor values, we can calculate necessary inverter transistor control frequency. Using C equation $C = \dfrac{4L}{k_u^2 \pi^2 R^2}$, frequency can be calculated as

$$f = \frac{k_u R}{4L} \quad . \tag{35}$$

If voltage increase indicator increases, frequency increases linearly in logarithm scale. Furthermore, the attitude L/R is smaller, the necessary frequency proportionally higher.

It is important to determine DC source power. If we don't count loses in switches and reactive elements, power can be calculated as

$$P = I_{ef}^2 .R \ ,$$

where I_{ef} is resonance chain effective current, R – coil's resistance.

Chain effective current can be determined using rule, that in resonance voltages on coil and capacitor are equal and all AC in it's fundamental harmonic way is set to resistance:

$$I_{ef} = \frac{U_{(1)ef}}{R} \quad , \tag{36}$$

where $U_{(1)ef}$ can been calculated

$$U_{(1)ef} = \frac{U_d 4}{2\sqrt{2}\pi} \quad . \qquad (37)$$

So

$$P = \frac{U_d^2 2}{\pi^2 R} \quad . \qquad (38)$$

While source current

$$I_d = \frac{P}{U_d} = \frac{2U_d}{\pi^2 R} \quad . \qquad (39)$$

As it is in previous equations, source power and current in source don't depend on resonance chain reactive parameters and frequency, but only form source voltage and resistance. In Fig.24 are relevance between source power and voltage increase factor $k_u = U_{cm}/U_d$ at constant U_{cm}=10 kV. When indicator k_u rises, source power sharply decreases. It is higher at smaller coil's resistances, what is characteristic for high-power coils with big cross-section wires.

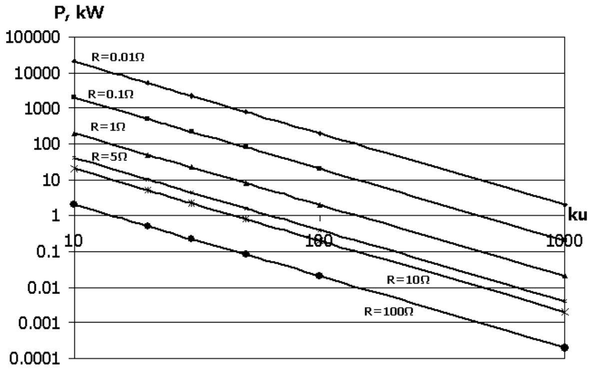


Fig.24. Source power curves as function P=f(ku) at different coil R, Ω and coil's voltage amplitude 10kV

Given curves allows choosing necessary k_u (source voltage) at source power limitedness. For example, maximal power for source is 2 kW, then at R=0,01 ohms for acquisition capacitor or coil's maximal voltage amplitude 10 kV, is necessary to choose k_u=1000, i.e., source voltage must be 10 V.

Source power depends in second grade from necessary coil voltage amplitude. For example, if amplitude is 20kV, and then power will be 4 times higher than in Fig.24.

In all previous figures we can see, that resonance inverter must operate with maximal k_u, for effective use of this system in economical and technical ways. We can conclude that this scheme must work with maximal k_u, and then also resonance frequency is high and capacitor value is small. The in scheme will be smaller power loses. This is also positive for switches, in fact that at higher voltage is higher current, which must be commuted by switches in each half-period. For example, if source voltage is 10 V and coil's resistance 0,01 ohms, then resonance current amplitude is

$$I_{cm} = \frac{U_d .4}{2\pi R} = 637A \ .$$

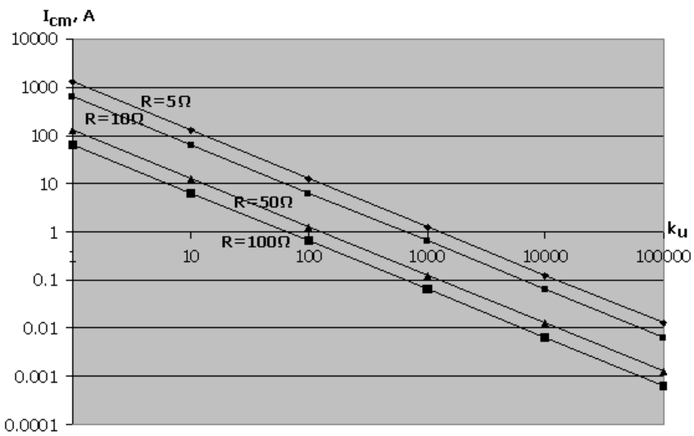


Fig.25. Relation between switches current amplitude and k_u and coil resistance R

It, of course, is huge current, but it could be more higher in case when k_u would be smaller and U_d higher. In Fig.25 shown curves I_{cm} , k_u and coil R, in case if capacitor and coil voltage amplitude at resonance is 10 kV. The higher is k_u , the current thru switches at the same R will be smaller. In the same way it will decrease at resistance increase.

For stabile scheme operation, capacitors CF (Fig.20) values must be as high as possible in replacement scheme. It, of course, would be ideal. If these values will be high, then U_d would be constant and here wouldn't be pulsations in source. The second preferred case is when in source is ideal DC voltage and then here wouldn't be pulsations.

Due to these facts is necessary CF>>C for constant U_d. Furthermore, both CF must be equal, another way here will be pulsations in each half period and output for each half period will be different. Necessary value for each CF can be calculated if current and frequency is taken as constant values and is limited minimal pulsation level, which is acceptable for operation. As from each capacitor in half period is taken sinus half-wave current with amplitude $I_{cm} = \dfrac{4U_d}{2\pi R}$, which can be replace with rectangle signal with amplitude $0{,}9I_{cm} / \sqrt{2}$, then capacitor voltage fall in half period is

$$\Delta U_{CF} = \frac{0.9 I_{cm}}{\sqrt{2}.2f.C_F} = \frac{0.9.U_d}{\sqrt{2}.\pi f R C_F} \quad . \tag{40}$$

If we take voltage decrease attitude to U_d low (around 0,05), we can obtain capacitor CF necessary value. For example, if attitude is 0,05, but R=0,1 ohms, frequency 3kHz, then capacitor values is 13456 μF.

Coreless coil resonance voltage can be calculated due to fact that in resonance chain resistance depends from frequencies. In this chapter are given parameters for real coil, when is necessary to obtain maximal voltage on coil at different resonance frequencies. If coil resistance wouldn't depend from frequency, then such calculations can be made as in previous paragraphs. But in realty resistance depends on frequency- it increases if frequency increases and that make calculations more complicated.

In previous calculations is that resonance inverter voltages attitude in half-bridge scheme with good resonance parameter and DC source voltage U_d can be calculated

$$k_u = \frac{U_{cm}}{U_d} = \frac{4Lf}{R} \quad , \tag{41}$$

where L is coil inductivity, R- resistance, f – inverter switching frequency. But $R=\beta.R_0$, where R_0- coil's resistance at DC, β- resistance increase factor from frequency.

For result's verifying is necessary to determine R_0 values in dependence from coil inductance I_{ef} and attitude between coil winding length and its outer diameter ld. Due to done computer simulations, in coil with copper windings, with defined loses in surface cooling process, R_0 can be described

$$R_o = 86\sqrt[4]{ld}\,\frac{\sqrt{L}}{I_{ef}} .$$

Voltage increase value is

$$k_u = \frac{4\sqrt{L}\,f I_{ef}}{86\beta\sqrt[4]{ld}} \quad . \tag{42}$$

But also is necessary to enquire coherences between β and f, L, I_{ef}, ld. It is known, that coil winding resistance rises, if rises frequency, in fact that is electromagnet field influence. In computer simulations and figures is shown, that frequency, in which electromagnetic wave penetration depth is equal with wire radius, can be calculated

$$f_\delta = \frac{8.10^4}{\pi I_{ef}\sqrt[6]{L}.\sqrt[5]{I_{ef}}} \qquad (43)$$

and it don't depends from attitude ld. As result

$$\beta = \frac{1}{\sqrt{\frac{f_\delta}{f}(2-\sqrt{\frac{f_\delta}{f}})}} \quad . \qquad (44)$$

Equations is valid, if $f > f_\delta$. In Fig.26 showed curves $f_\delta = \varphi(L, I_{ef})$.

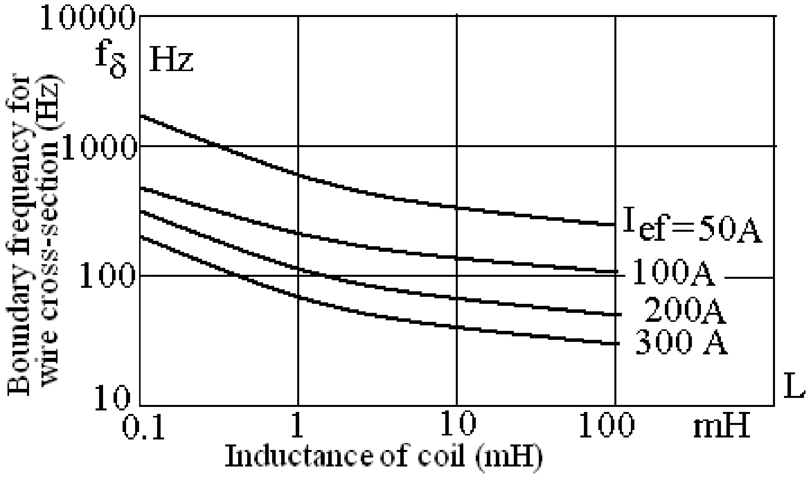


Fig.26. Boundary frequency dependence from I_{ef} and coil inductivity

As it is in figure, at smaller inductivities and current values, boundary frequency f_δ values is higher. If is given f_δ values, then can get resistance increase factor β values in dependence from coil inductivity and current values. These curves are in Fig.27.

The faster β increase is at higher inductivities and higher coil currents.

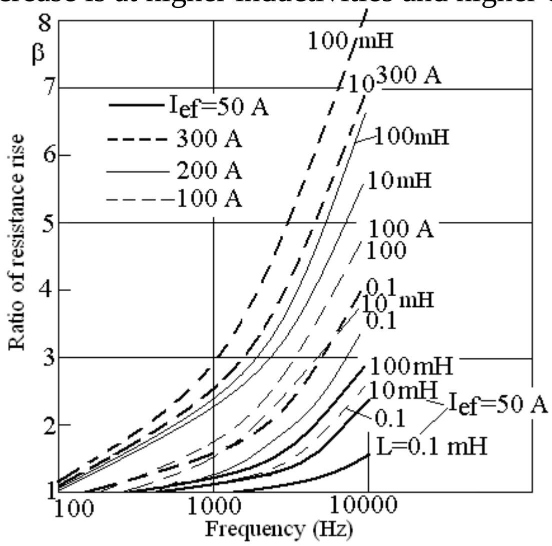


Fig.27. Resistance increase factor β dependence on frequency at different coils with inductance L and current value

As it is in Fig.27, coils with small inductivity have harder to obtain high voltage increase factor. It can be explainable with small inductance coil quality decrease.

As it has been mentioned in the second paragraph, more qualitative resonance regime can be obtained if in parallel to investigated coil is connected etalon coil with non-changeable resistance from frequency (Fig.28.). In figure L_e is etalon coil with resistance R_e and inductivity L_e , but investigated coil is replaced by resistance R and inductivity L.

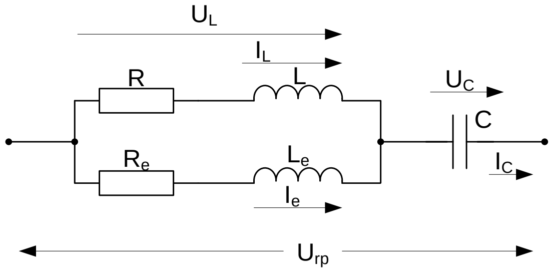


Fig.28. Resonance chain with parallel coils

In Fig.28 showed resonance chain currents and voltage positive directions. To chain has been connected voltage with fundamental harmonic effective values

$$U_{rp} = \frac{U_d \cdot 4}{2 \cdot \pi \cdot \sqrt{2}} = \frac{\sqrt{2} \cdot U_d}{\pi} . \tag{45}$$

This voltage makes effective current I_c, which divides I_L and I_e. As R<<ωL un R_e<<ωL_e, then I_L and I_e is in phases, and from it

$I_c=I_L+I_e$, $I_L = \frac{U_L}{\omega L}$, $I_e = \frac{U_L}{\omega L_e}$, then $\frac{I_L}{I_e} = \frac{L_e}{L}$ and $I_L = I_c \frac{L_e}{L + L_e}$.

From previous parts and computer simulations is known that voltages U_L and U_c at resonance is equal. So, at resonance

$$I_c = \frac{\sqrt{2} \cdot U_d}{\pi \cdot R_v} = U_L \omega C , \tag{46}$$

where R_v – virtual all system resistance at resonance, U_L- coil's voltage effective value at resonance, $P = I_C^2 \cdot R_v$ - power loses in resonance chain.

Power loses in chain is $P = \frac{U_L^2}{\omega^2}\left(\frac{R}{L^2} + \frac{R_e}{L_e^2}\right)$, and $\omega^2 = \frac{L_e + L}{L_e LC}$

So, power loses

$$P = \frac{U_L^2 L_e LC}{L_e + L} \cdot \frac{RL_e^2 + RL^2}{L^2 L_L^2} . \tag{47}$$

If accept $k_u = \frac{U_{Lm}}{U_d} = \frac{\sqrt{2} U_L}{U_d}$, then

$$P = \frac{k_u^2 U_d^2 C(RL_L^2 + R_e L^2)}{2(L_e + L)LL_e} . \tag{48}$$

Putting I_c^2 , we get that virtual resistance

$$R_v = \frac{P}{I_c^2} = \frac{k_u^2 U_d^2 C(RL_e^2 + R_e L^2)2}{2(L_e + L)LL_e U_L^2 \omega^2 C^2} . \tag{49}$$

Using this $R_{v,}$ can obtain another equation for necessary angular frequency ω calculation

$$U_L \omega C = \frac{k_u U_d}{\sqrt{2}} \omega C = \frac{\sqrt{2} U_d (L_e + L) L L_e \omega^2 C}{\pi (R L_e^2 + R_e L^2)}.$$

From here

$$\omega = \frac{k_u \pi (R L_e^2 + R_e L^2)}{2(L_e + L) L L_e}. \qquad (50)$$

This ω depends only from parameters R, L_e, R_e, L and k_u. If compare both ω, can obtain necessary capacitor value

$$C = \frac{4(L_e + L)^3 L L_e}{k_u^2 \pi^2 (R L_e^2 + R_e L^2)^2}.$$

Equation examples:

1. R=5Ω, R_e=0.5Ω, k_u=100, L=50mH, L_e=5mH.

$$C = \frac{4(0.005 + 0.05)^3 0.05 \cdot 0.005}{100^2 \pi^2 (5 \cdot 0.005^2 + 0.5 \cdot 0.05^2)^2} = 0.8925 \mu F$$

; for resonance regime it is necessary apply an angular frequency 15700 1/s, or comuttation frequency f=2500 Hz.

For the first example was made computer simulation with U_d=100 V and is it is from Fig.29, voltage amplitude is practically 10 kV, i.e., $k_u.U_d$.

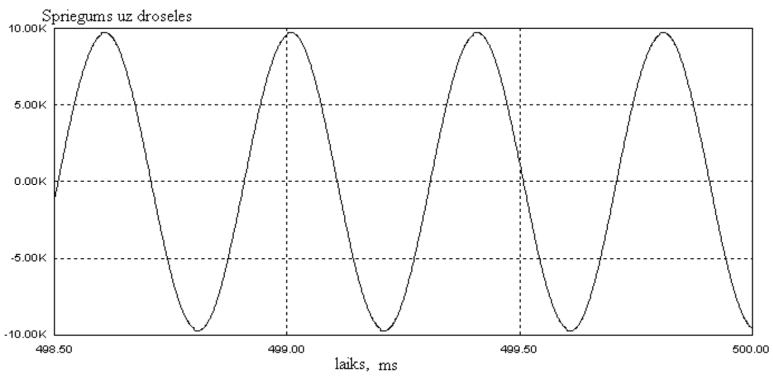


Fig.29. Coil voltage curve in resonance regime with parallel etalon coil

4. EXPERIMENTAL PART

For investigations was made coil (Fig.30.) with technical parameters:

- Coil inductivity 45,1 mH;
- Coil resistance at DC 4,7 ohm;
- Coil resistance at frequency 100 Hz is 5,22 ohm;
- Goodness at 100Hz – Q=5,4;
- Coil resistance at frequency 1kHz – 6,6 ohm (Q=42,7);
- Coil resistance at 10 kHz -100,7 ohm (Q=28,9);
  (resistance measurements have been made with electronic parameters measurement unit)
- Coil windings count – 1019;
- Windings count in one layer – 93;
- Layers count in coil – 11;
- Coil length 26.5cm;
- Outer diameter - 15cm, R=7.5cm;
- wire square 1.0 mm^2 ; S_v=πR^2 ; $R = \sqrt{\frac{S}{\pi}} = \sqrt{\frac{1}{3.14}}$ =0.56mm.

Fig.30. Investigated coil

Fig.31. Investigated coil with capacitors

Investigations were made in chain with series connected high-voltage capacitors with nominal voltage 16kV. Each capacitor capacity is 0,1 μF. In each block are 5 capacitors, which can be connected parallel and in series. Parallel connected overall capacity can be from 0,5μF till 0,1 μF, but in series till 0,02 μF. Choose of capacity allows to work with frequency from f_r=1060,4 Hz till – 5301,9 Hz. Investigated coil with capacitors is in Fig.31.

Made control scheme with resonance inverter is in Fig.32. Power part's source is realized from DC source with voltage 100 V (Fig.32.). In first part of scheme have two voltage dividing capacitors C1 and C2 with capacitors 1500 μF each. There have been made half-bridge inverter scheme with MOSFET transistors VT1 and VT2 with involved reverse diodes. In diagonal of bridge is switched series connected investigated coil and capacitors.

Control is being provided by control system VS, which is connected to block BB3 with voltage 15V. Two exits of control system thru resistors R1 and R2 is connected to transistors drivers DR1 and DR2 optical inputs. Drivers are connected to DC blocks BB1 and BB2.

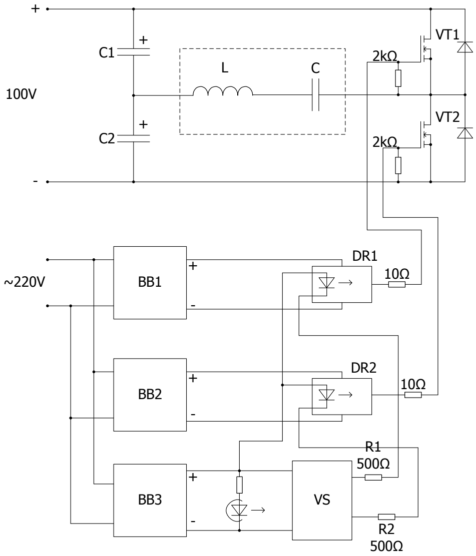


Fig.32. Resonance inverter scheme

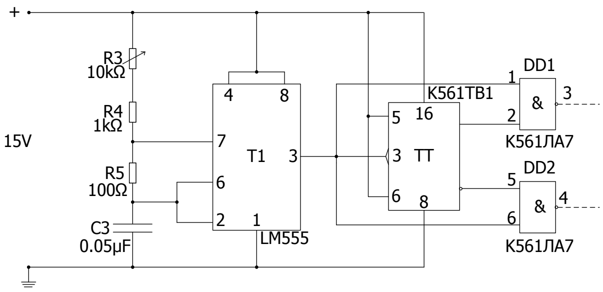


Fig.33 Control scheme

Control scheme (Fig.33.) consists from timer T1 (type LM555) with charge-discharge R-C chain R3-R4-R5-C3, which together with timer, makes rectangular form high level signals with pause between periods. This pause length can be regulated with parameters of R5 and C3. Generator frequency is regulated by resistor R3. Timer exit is connected in trigger TT clock entrance, which is working in T regime. In each exit re-switches trigger's direct and reverse exits with two time smaller frequency than tact generator. Each exit connected to logical element UN-NE, each element second entrance connected to generator exit. As in generator exit periodically is null signal, then UN-NE logical exit's active positions don't overlap and in this way formed temporary signal breaks. As result transistors simultaneous switching isn't possible (Fig.34.).

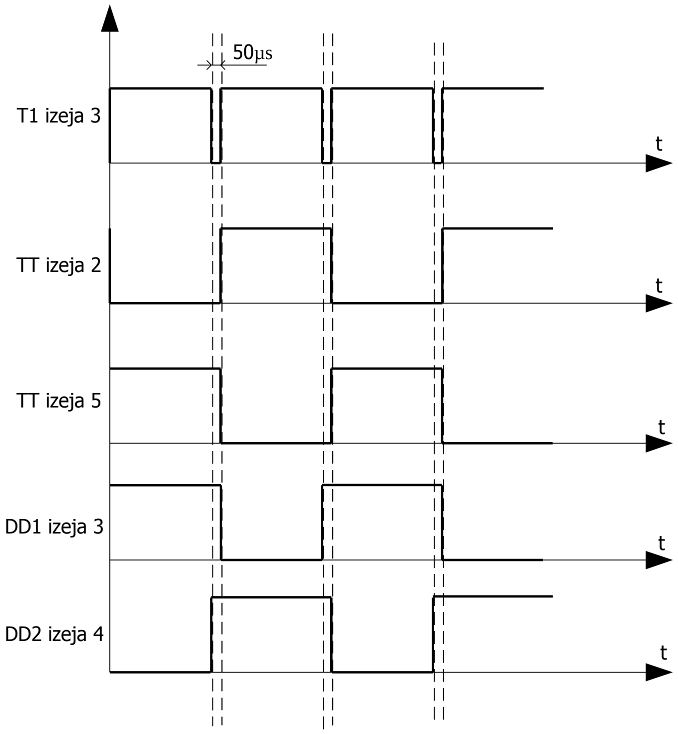


Fig.34. Control scheme signal diagrams

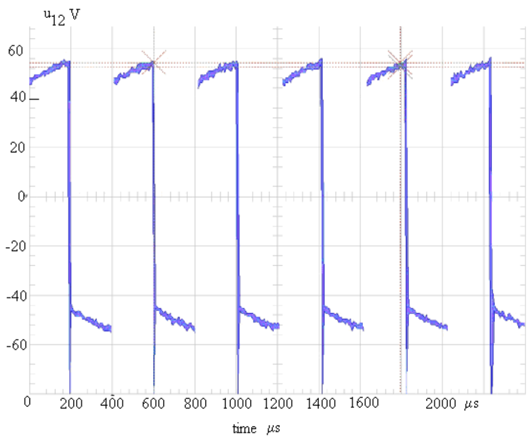


Fig.35. Resonance chain voltage curve at frequency 2,5 kHz

Using created scheme, was made investigations with coil. Resonance voltage instantaneous values are in Fig.35. Here commutation frequency is 2,5 kHz. Chain voltage average values in half period is approx. 50 V, i.e. fundamental harmonic amplitude is 63,7 V.

Changing capacitors were made measurements and oscillogram for chain with investigated coil in resonance inverter scheme. In Fig.36 it is shown current oscillogram.

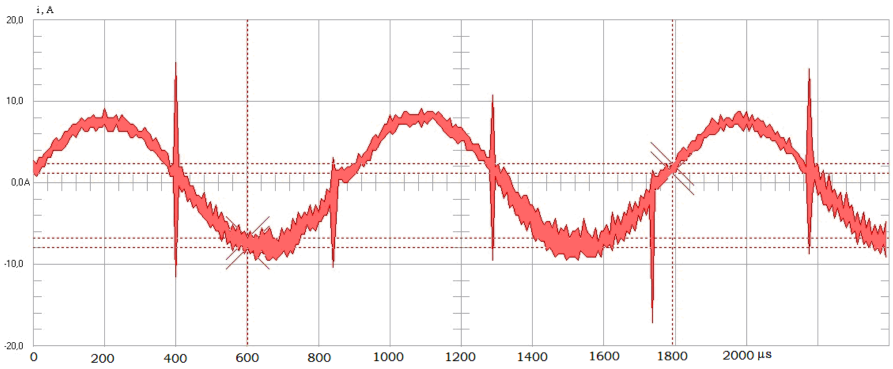


Fig.36. Current curve at frequency f=1061.6Hz, C=0.5µF

As it in oscillogramm, in moments of switching, here creates spikes, which significantly interfere assessment. However, we can find that resistance increases if frequency rises. In Fig.37 shown currents curves dependence from frequency. Here frequency diapason isn't to high- from 1000 to 2500Hz, which is connected to capacitors availability problem. Similar curves were obtained from ammeter, which was connected in resonance chain.

If we know chain voltage fundamental harmonic amplitude or effective value, we can obtain coil resistance's dependence on frequency. These curves are in Fig.38. If frequency rises, sharply rises resistance due to skin effect.

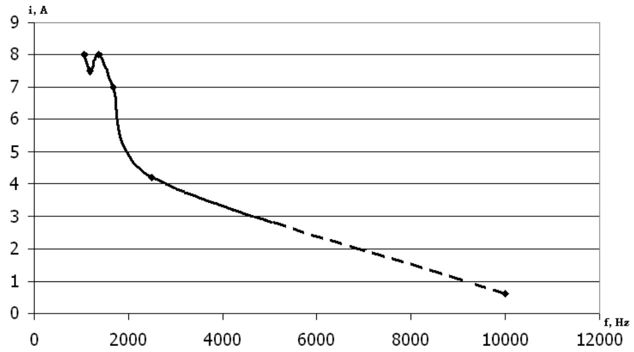


Fig.37. Resonance current's dependence on frequency

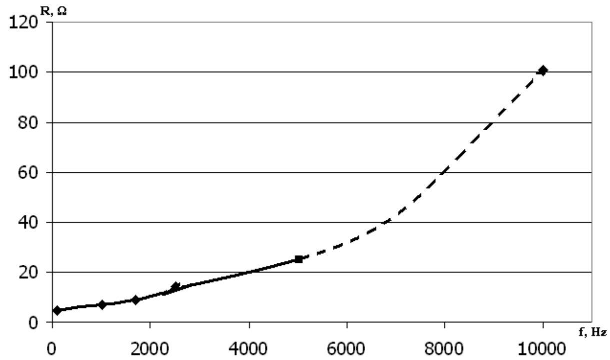


Fig.38 Coil resistance dependence from frequency

As current amplitude due to rise of frequency decreases, then also voltage amplitude also decreases. This curve is in Fig.39, which amplitude is calculated multiplying current amplitude with $2\pi f.L$.

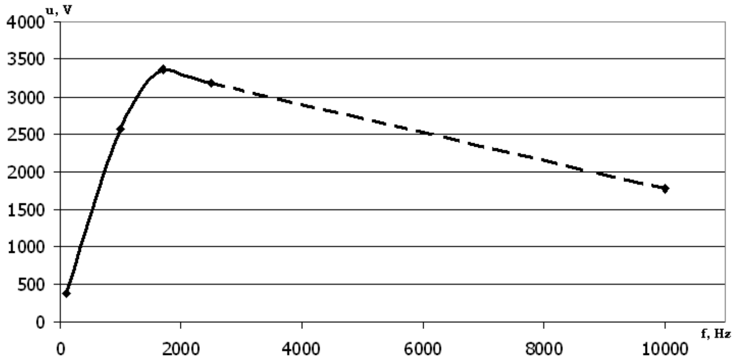


Fig.39. Coil voltage amplitude dependence from frequency

It is important to evaluate real resistance of coil at different frequencies. If we are looking at resistance increase, which was calculated in the first paragraph (here was assumption, that magnetic field penetrates in all layers and windings in the same depth), then we can conclude, that in real experiments rise of resistance is much bigger at the same frequencies. Analyze of results concludes that in the each consecutive layer (counting from outer surface) is smaller and smaller penetration depth, furthermore δ is equal to δ/n, where n is layer number counted from outer surface.

For process investigation in scheme with parallel high-frequency coil was used investigated coil with measured resonance parameters at different frequencies. Taking any frequency and for it measured resistance, we can investigate processes in scheme with parallel etalon coil, which inductivity is 50 mH and resistance 2 ohm. Process investigation was made in PSIM model with source voltage 100V in half-bridge inverter scheme. Frequencies were 100 Hz, 1000 Hz, 1700 Hz, 2500 Hz and 10kHz. Due to these frequencies were calculated voltage increase coefficients and necessary capacities.

Acquired chain currents and voltages curves are in Fig.40.

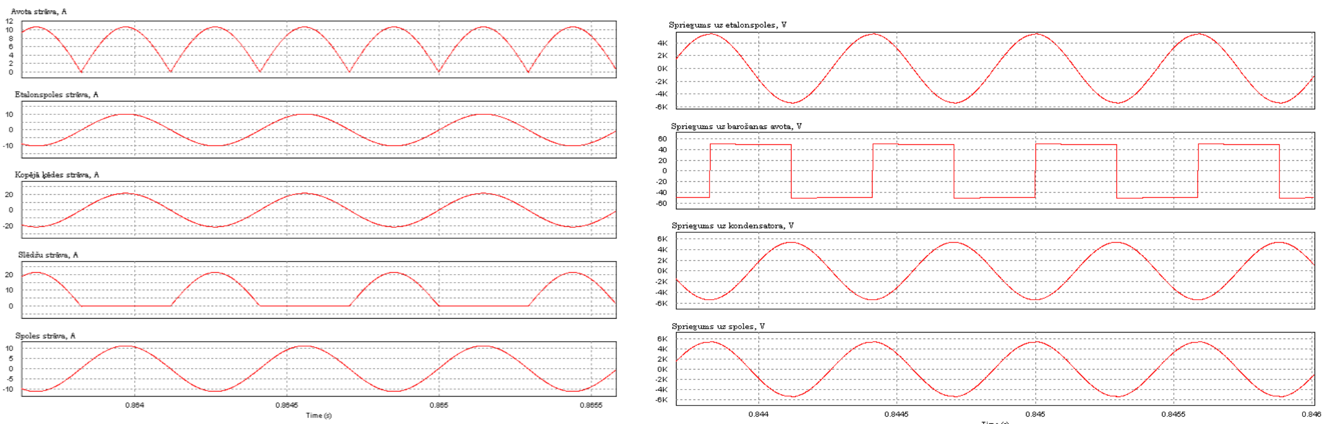


Fig.40. Currents and voltages diagrams at frequencies 1700 Hz; f=1700Hz, C=0.37uF, U_{max}=5423V, investigated coil resistance 9.1 ohms.

As it is in Fig.40 maximal voltage on coil is at frequency 1700 Hz and at higher voltage decreases. Coefficient k_u dependence from frequency is in Fig.41. From here can be conclusion that for higher voltage on coil is need for higher source voltage, furthermore, it must be proportionally to necessary voltage. And here is no need for higher frequency that 1700 Hz, because at this frequency is the largest effectiveness at given etalon coil parameters.

In situation, when frequency is being raised, all parameters' effective values decreases

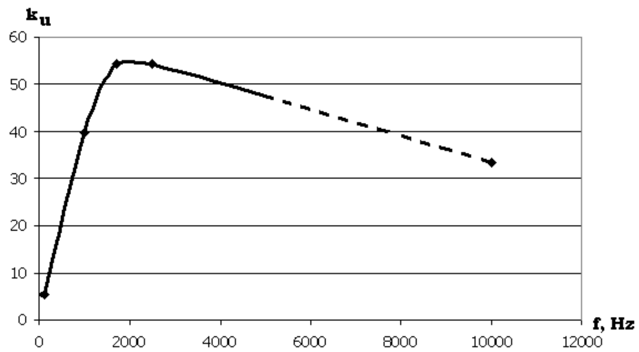


Fig.41. Coefficient k_u dependence on frequency

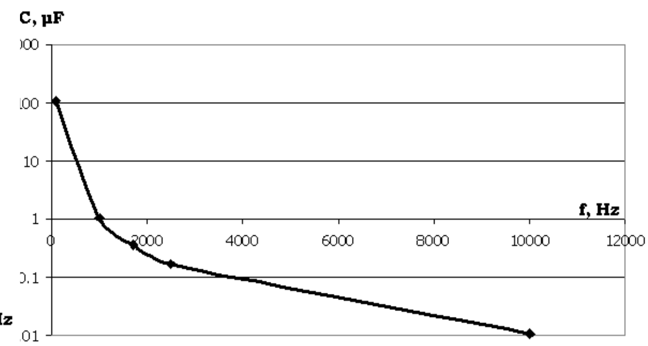


Fig.42. Capacitor values at different frequencies

CONCLUSIONS

1. Low frequency coil layers and windings insulation investigation can be realized in high frequency resonance chain, which is in resonance inverter. As result here can be high voltage with small current, what provides system safe work from low voltage DC source.
2. Making system element parameters calculations need to consider investigated coil resistance's dependence from frequency.
3. From all looked schemes, most seasonable is resonance inverter half bridge scheme, which has minimal switch count and simple control system.
4. Coil voltage amplitude values in resonance regime half bridge inverter scheme can be calculated by resonance voltage fundamental harmonic influence to coil resistance, which determine coil current amplitude, but it, multiplied with angular frequency and inductance- voltage amplitude.
5. In case of simply resonance chain, increase of frequency makes increase of investigated coil resistance, what don't allow getting on coil high level voltages.
6. If in parallel to investigated coil is etalon coil, then is possible to limit current decrease at frequency increase and it gives higher voltages on coil at the same frequencies.
7. Also in scheme with parallel etalon coil is voltage level limit at concrete frequency. This gives conclusion, that here is no point using higher frequency as maximal for this parameters.
8. In coil interrupt sharply decreases voltage on coil, in fact that non-damaged part resistance in interrupt is much higher, but inductance- decreased. This ensure that chain isn't more in resonance.
9. In moment of interrupt are high current impulse, which need to be evaluated in process of projecting equipment.
10. For higher voltages on investigated coil, DC source need to be with regulation possibility.

LISTING OF AUTHOR'S PUBLICATIONS

1. Dreimanis E., Rankis I. Determination of high-voltage windings monitoring voltage in scheme with resonant inverter, 6th International symposium topical problems in the field of electrical and power engineering, Kuressaare, Estonia, 2009, p.22-25.
2. Dreimanis E., Rankis I. Development of the impulse method for testing high-voltage coil inter-shortening insulation, 5th International symposium topical problems in the field of electrical and power engineering, Kuressaare, Estonia, 2008, p.17-19.
3. Dreimanis E., Rankis I. Resonant inverter operation with over-frequency of load circuit, 8th International symposium topical problems in the field of electrical and power engineering, Parnu, Estonia, 2010, p.221-224.
4. Dreimanis E., Ranks I. Determination of high-voltage windings monitoring voltage in scheme with resonant inverter, Enerģētika un Elektrotehnika, series 4, sējums 24, Rīga, RTU, 2010, 94-98 lpp.
5. Dreimanis E., Raņķis I. Elektrisko bezserdes spoļu parametru novērtējums, (Evaluation of parameters of electrical coils) Enerģētika un Elektrotehnika, sērija 4, sējums 26, Rīga, RTU, 2010, 63-66 lpp.
6. Dreimanis E., Raņķis I. Elektriskās spoles darbība vijuma īsslēguma gadījumā, (Operation of electrical coil in case of insulation damaging of winding) Enerģētika un Elektrotehnika, sērija 4, sējums 26, Rīga, RTU, 2010, 58-62 lpp.
7. Dreimanis E., Hramcovs V., Cīmanis V. Augstsprieguma tinumu izolācijas pārbaude ar rezonanses invertora palīdzību, (Examination of coil insulation using high frequency

resonant inverter) Enerģētika un Elektrotehnika, sērija 4, sējums 22, Rīga, RTU, 2008, 94-108 lpp.

8. Dreimanis E., Raņķis I. Calculation of voltage resonance circuit with coreless electrical coil, 9.International Symposium. Topical Problems in The Field of Electrical and Power Engineering 2010. 190-192p.

9. Dreimanis E., Raņķis I. Operation of Electrical Coil with damaged windings insulation// 10.International Symposium. Topical Problems in The Field of Electrical and Power Engineering 2011. 13-16p.

EDGARS DREIMANIS

ELECTRICAL INDUCTOR COIL WINDINGS INSULATION HIGH-FREQUENCY DIAGNOSTIC METHODS INVESTIGATION AND CREATION

Dissertation summary

Registered for printing on 08.08.2011. Registration Certificate No. 2-0282. Format 60x84/16. *Offset* paper. 2,0 printing sheets, 1,38 author's sheets. Calculation 30 copies. Order Nr. 76. Printed and bound at the RTU Printing House, 1 Kalku street, Riga LV- 1658, Latvia.