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DETERMINATION OF HIGH-VOLTAGE WINDINGS MONITORING VOLTAGE IN SCHEME WITH RESONANT INVERTER

STARPVIJUMU IZOLĀCIJAS KONTROLĒJOŠĀ SPRIEGUMA NOTEIKŠANAS APRĒĶINI REZONANSES INVERTORA SHĒMĀ

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Introduction

Investigation of coil's insulation must be realized at impact of high voltage stresses. Such a voltage can be generated in load circuit of resonance inverter operating at supply from rather low level DC voltage [1, 2]. Therefore it is essential to calculate appropriate values of voltage applied to the investigated coil. Calculations are connected with investigation of resonant converter operation regimes. Normal operation of resonance inverter can be provided only in case when parameters of load circuit accord to the oscillating processes in load circuit, i.e., in accordance with relation

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

where δ- damping parameter.

Frequency of self oscillations for circuit

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

Correct calculation of resonance inverters is difficult task because oscillation process is developing from one switching cycle to the next one and in the steady-state condition of converter magnitude value of capacitor's voltage is much bigger than voltage of the DC supply [2]. Therefore in this article is presented a simplified method for calculations which allows calculate processes with rather good approximation assuming that shape of current in load of inverter is close to the sinus mode.

Operation cases

In scheme of resonance inverter (Fig.2) must be applied semiconductor switches (usually transistor with reverse diode) with bidirectional conductivity (only with such switches it's possible operate with large voltage across the reactive elements of load without dangerous voltage stresses on switches at discontinuous current of load). In such case there are possible three operation cases [2,3].

The first case is at $\omega_v = \omega$, where $\omega_v = 2\pi/T$ is angular switching frequency comprising in the full switching cycle a two situations – when in half cycle continuously is conducting switch S1 and in other half cycle – switch S2. In the first case control frequency is equal to the self oscillation frequency of load and current of the load is practically sinus shaped with instantaneous values in the end and beginning of each half cycle equal to zero. Voltages across reactive elements of the load are maximal large, because current is limited only with resistance of load. This case is rated one for investigation of the coil and is accepted as calculation example in this article.

The second case will be at decreasing of inductivity of coil at shortening of any turn of coil when its inductivity is decreasing and self oscillation frequency – rising. In this case control frequency ω_v is smaller than ω. Current passing through load is not sinus shaped (Fig.1) and as result magnitude of capacitors voltage U_C is much smaller as for resonance case. Instantaneous values of current through load at end and beginning of half cycles are not equal zero that hardening operational conditions of

switches

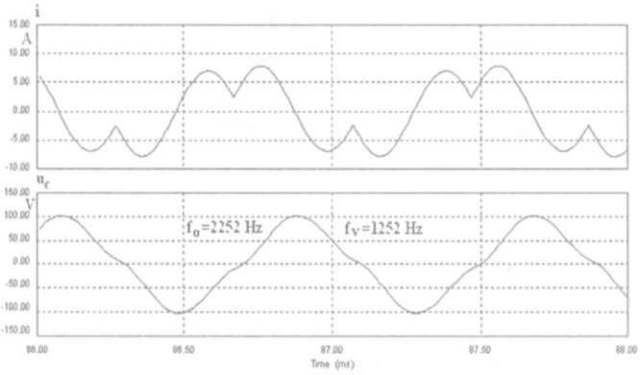

Fig.1. Diagrams of load current and voltage across capacitor at $\omega_v<\omega$ (R=0.5Ω, C=10μF, L=0.5 mH)

The third case is at $\omega_v > \omega$ and take place switching of load in part of its oscillation half cycle. Also in this case magnitude of voltage across capacitor will be smaller than at resonance case. This case can be applied only in duration of inverter tuning for resonance case.

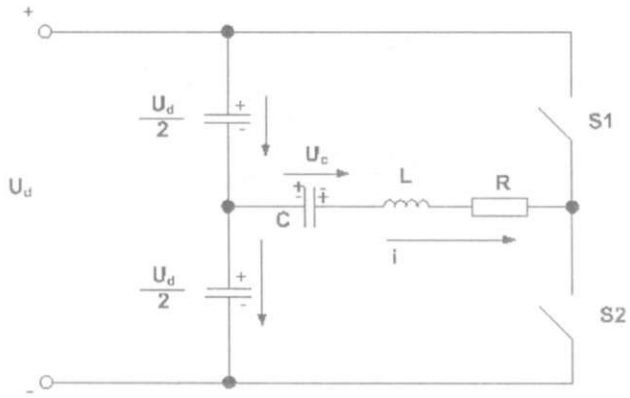

Fig.2. Substitution scheme for investigated resonance inverter

Analytical calculations

In the substitution scheme there are 2 operation intervals. In the first interval is on-switched **S1** but switch **S2** is in off position. Diagrams of load current and capacitor voltage at resonance steady-state case are presented on Fig.3. At beginning of switching half cycle current of load is at t=0 $i = 0$, but $u_c = U_{c0}$. Therefore after turn-on of switch S1 changes of current can be described with differential equation

$$i = e^{-\delta t}(A\sin\omega t + B\cos\omega t), \quad (3)$$

solution of which is

$$i = -e^{-\delta t}\frac{0{,}5U_d + U_{c0}}{\omega L}\sin\omega t \ . \quad (4)$$

Voltage across the coil can be described as

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

When $\omega t = \pi$, voltage of coil is

$$u_{L(\pi)} = e^{-\delta\frac{\pi}{\omega}}(0{,}5U_d + U_{c0}), \quad (6)$$

but end value of capacitor's voltage for switched position of S1 is

$$U_{c(1)} = -0{,}5U_d - e^{-\delta\frac{\pi}{\omega}}(0{,}5U_d + U_{c0}), \quad (7)$$

valuated as negative signed voltage.

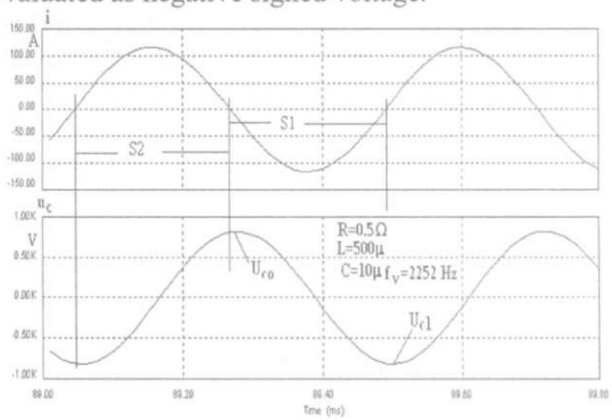

Fig.3. Diagrams of current and capacitor voltage of load at resonance

In the other half cycle is turned-on switch **S2** but **S1** is in off position. Also at beginning of this half cycle instantaneous meaning of current is $i = 0$.

Therefore instantaneous meanings of current change as

$$i = e^{-\delta t}\frac{0{,}5U_d - U_{c(1)}}{\omega L}\sin\omega t \quad (9)$$

(i.e., meanings of current are same as in the first situation only positive signed).

Averaged value of capacitor's current in full cycle is zero. Therefore integrating the both equations for current and taking into account meaning of U_{C1} is possible to get

$$U_{c0} = 0{,}5U_d + e^{-\delta\frac{\pi}{\omega}}(0{,}5U_d - U_{c(1)}) \quad ;$$

From here

$$U_{c0} = 0{,}5U_d + e^{-\delta\frac{\pi}{\omega}}\left[0{,}5U_d + 0{,}5U_d + e^{-\delta\frac{\pi}{\omega}}(0{,}5U_d + U_{c0})\right] \quad (10)$$

Equations above mentioned allow to calculate parameters of scheme at resonance. But there is possible to apply another approach based on assumption of influence of fundamental harmonic of inverted voltage across load's circuit magnitude of which is equal

$$U_{LD(f)m} = \frac{2U_d}{\pi} \quad . \quad (11)$$

Then magnitude of load current at resonance is $U_{LD(f)m}/R$ and magnitude of capacitors voltage is

$$U_{C0} = \frac{2U_d}{\pi R\omega C} \quad . \quad (12)$$

Evaluation of results

For estimation of above given equations a numerical calculations and modeling in program package PSIM was done.

Example Nr 1 where resistance is rather big – R=19Ω, U_d=220 V, L=0.22 H, C=0.1 μF.

$$\omega = \sqrt{\frac{1}{LC}} = \sqrt{\frac{1}{0.22*0.1*10^{-6}}} = \sqrt{\frac{10^6}{0.022}} = 6741.99 \ 1/s$$

$$\delta = \frac{R}{2L} = \frac{19}{2*0.22} = 43.18$$

$$f_v = \frac{\omega}{2\pi} = \frac{6741.99}{2*3.14} = 1073.56Hz$$

$$\delta\frac{\pi}{\omega} = -\frac{R*\pi}{2*L*\omega} = -\frac{19*3{,}14}{2*0.22*6741.99} = 0.0201$$

According to the equations

$$U_{c0} = \frac{0{,}5U_d + U_d e^{-\delta\frac{\pi}{\omega}} + 0{,}5U_d e^{-2\delta\frac{\pi}{\omega}}}{1 - e^{-2\delta\frac{\pi}{\omega}}} =$$

$$= \frac{0{,}5*220 + 220e^{-0.0201} + 0{,}5*220e^{-0{,}0402}}{1 - e^{-0.0402}} = 10946.4 = 10.9464kV$$

$$U_{c1} = -0.5U_d - e^{-\delta\frac{\pi}{\omega}}(0.5U_d + U_{C0}) =$$

$$= -0.5*220 - e^{-0.0201}(0.5*220 + 10946.4) =$$

$$= -10946.37V = -10.94637kV$$

Modeling gives U_{co}=-U_{c1}=9.81 kV. Calculation applying simplified equations gives U_{C0}=10.49kV.

Example Nr2 investigates load circuit with rather small resistance – R=0.5 Ω, L=0.5 mH, C=10 μF, U_d=100V.

$$\omega = \sqrt{\frac{1}{LC}} = \sqrt{\frac{10^{12}}{500*10}} = \sqrt{\frac{10^6}{70.71}} = 14142 \ 1/s \quad ;$$

$$\delta = \frac{R}{2L} = \frac{0.5}{2*500*10^{-6}} = 500 \ 1/s$$

$$\delta\frac{\pi}{\omega} = -\frac{R*\pi}{2*L*\omega} = -\frac{0.5*3{,}14}{2*500*10^{-6}*14142} = 0.111$$

$$f_v = \frac{\omega}{2\pi} = \frac{14142}{2*3.14} = 2252Hz$$

Calculated extreme voltages of capacitor

$$U_{c0} = \frac{0{,}5U_d + U_d e^{-\delta\frac{\pi}{\omega}} + 0{,}5U_d e^{-2\delta\frac{\pi}{\omega}}}{1 - e^{-2\delta\frac{\pi}{\omega}}} =$$

$$= \frac{0{,}5*100 + 100e^{-0.111} + 0{,}5*100e^{-0{,}222}}{1 - e^{-0.222}} =$$

$$= 902.26V$$

$$U_{c1} = -0.5U_d - e^{-\delta\frac{\pi}{\omega}}(0.5U_d + U_{C0}) =$$

$$= -0.5*100 - e^{-0.111}(0.5*100 + 902.26)$$

$$= -900.25V$$

Computer simulation at same parameters gives (Fig.3) U_{co}=850 V; U_{c1}=-850 V, but calculations using simplified equation – U_{c0}=900.78V. As it's seen simplified equation gives practically same result as calculation by differential equation but

experimental values are close enough to the calculated, especially taking into account complexity of processes.

Simplified equation can be used for calculation of necessary capacitance of circuit for obtaining preset values of extreme voltages at given parameters of coil (L,R):

$$C = \frac{4L}{k_u^2 \pi^2 R^2} \quad , \qquad (13)$$

where k_u is relation between U_{C0} and U_d . How it can be seen volume of capacitance is reverse proportional to the factor k_u in the second power. Volume must be bigger at bigger relations between L and resistance of coil R. For example, if supply voltage is 100 V, necessary amplitude of voltage across capacitor – 10,000V (k_u=100), L=10mH, R=0.1Ω, then calculated value of capacitance is C=40.6μF. Modeling shows that obtained amplitude is 9.5kV,i.e., quiet close to the preset value.

Conclusions

1.Equations obtained for calculation of steady-state voltage extremes across capacitor plates in load's circuit of resonance inverter converge sufficient well with obtained from modeling.

2.It is possible for calculations apply simplified method based on influence to load's circuit of fundamental harmonic of inverted voltage.

3.Simplified method for calculation of amplitude value of voltage across capacitor in load's circuit of inverter can be applied for choice of necessary capacitance at preset value of the amplitude of voltage.

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Rankis I., Dreimanis E. Determination of High-voltage Windings Monitoring Voltage in Scheme with Resonant Inverter

Processes in scheme of resonant inverter with bidirectional conductivity switches in half-bridge connection are described accenting complexity of correct calculation of processes characteristic with development of transient from cycle to cycle. Approximated calculation method based on solution of differential equations is proposed which allows rather correctly calculate extreme voltages of capacitor of resonant circuit at different parameters of circuit in steady-state resonant operation case when control switching frequency is equal to frequency of self-oscillations of circuit. Is given also more approximated calculation method based on influence on circuit a fundamental component of inverted voltage which has square shape. Comparison of obtained results for two different calculation examples with modeling results is done and results are sufficient good. Applying the last proposed calculation method it is

possible find out necessary volume of capacitor for preset value of extreme voltage across capacitor plates and given parameters of investigated coil.

Dreimanis E., Raņķis I. Starpvijumu izolācijas kontrolējošā sprieguma noteikšanas aprēķini rezonanses invertora shēmā

Aplūkotajā rezonanses invertora shēmā ar divvirziena pusvadītāju slēdžiem un pustilta konfigurāciju aplūkoti elektromagnētiskie procesi, pie tam skaidrots, ka procesu korekts aprēķins ir ļoti sarežģīts, jo process attīstas no cikla uz ciklu un reaktīvo elementu spriegums pieaug, līdz sasniedz stacionāru stāvokli, kad to spriegums var daudzkārt pārsniegt barošanas avota. Piedāvāts tuvināts stacionārā procesa sprieguma amplitūdas aprēķins uz slodzes ķēdē virknē ieslēgtā kondensatora platēm, balstīts uz diferenciālvienādojumu pielietošanu. Aprēķini tiek veikti rezonanses režimam, kad slēdžu vadības frekvence sakrīt ar ķēdes pašsvārstību frekvenci, kad arī būs maksimālie spriegumi uz reaktīvajiem elementiem, un kas izvēlēts par spoļu pārbaudes nominālo režīmu. Piedāvāta arī cita vienkāršota aprēķina metode, kas balstīta uz invertētā taisnstūrveida sprieguma pamatharmoniskās ietekmi uz invertora slodzes ķēdes strāvas amplitūdu rezonanses gadījumā. Veicot datormodelēšanu, parādīts, ka abas metodes dod praktiski vienādus rezzultātus plašā slodzes ķēdes parametru izmaiņas diapazonā, pie tam veikto aprēķinu rezultāti labi sakrīt ar datormodelēšanas rezultātiem, kas ļauj pielietot aprēķinu izteiksmes procesu novērtējumam. Ieteiktsr otro tuvināto aprēķinu metodi pielietot rezonanses ķēdes parametru noteikšanai pie uzdotās kondensatora sprieguma amplitūdas un zināmajiem pētāmās spoles nominālajiem parametriem.

Ранькис И., Дрейманис Э. Расчет контролирующего напряжения для исследования межвитковой изоляции катушки в цепи резонансного инвертора

Рассмотрены электромагнитные процессы в схеме резонансного инвертора с полупроводниковыми ключами двухсторонней проводимости и при полумостовой структуре схемы инвертора. Показано,что корректный расчет процессов в стационарном режиме затруднителен ввиду того, что процесс развивается с периода переключения на следующий период и установившееся состояние весьма неопределенно, но при этом напряжение на реактивных элементах цепи нагрузки резонансного инвертора многократно превышает напряжение источника питания постоянного тока. Расчетным принят режим, когда частота переключений ключей инвертора совпадает с частотой собственных колебаний цепи нагрузки и этот режим является основным, поскольку напряжение на реактивных элементах достигает максимальных значений, необходимых для проверки изоляции исследуемой катушки. Предложен упрощенный метод расчета амплитуды напряжения на конденсаторе, основанный на решении дифференциального уравнения с допущениями. Предложен также другой упрощенный метод расчета, учитывающий влияние основной гармоники инвертированного напряжения с прямоугольной формой. Проведены расчеты с использованием обех методов и показано, что результаты расчетов хорошо совпадают с данными, полученными из компютерной модели. Показано, что второй упощенный метод позволяет найти необходимые параметры конденсатора цепи при заданных параметрах катушки и максимального напряжения на конденсаторе.