General procedure for Design of Resonance Inverters with electrical application

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Annotation: **This study presents generalized methodology for design of resonance inverters with electro technological application. The presented technology was achieved as a result of investigations and analyses of different types and working regimes of resonance inverters, made by the authors. Authenticity of achieved results is confirmed by simulating research work.**

Keywords: **Autonomous Resonance Inverters, Design, Electro technologies, Complicated output circuits**.

I. INTRODUCTION

Autonomous Resonance Inverters (ARI) are one of the most widely spread converters of electric energy. Their advantages are known in comparison to other types of autonomous inverters [1, 2, 5, 6, 7, 8, 9].

Questions related to their analysis, design and development are subject to much research work by many Bulgarian and foreign authors [1, 2, 5, 6]. Various approaches and related to them basic parameters of analyses are offered [1, 2, 5, 6]. By this study authors propose on the basis of suggested by them unified approach for analysis of ARI, a generalized methodology for design of resonance inverters with and without reverse diodes, working at different correlation between own and controlling frequency. Methodologies are for resonance inverters, used as supply source for realization of various electro technologies. In many of these applications work is carried out by complex load with large quality factor of the parallel circuit Q [1, 4, 7].

Basic parameters used for analysis and design are the coefficient of hesitation k of the consecutive / serial / resonance circuit and the frequency coefficient ν, which are в used at analyses of autonomous resonance inverters.

II. BASIC CORRELATIONS

As per classification introduced by authors for the unified approach for analysis of resonance inverters, they are divided into resonance inverters with and without reverse diodes, beside that these circuits also discern by the way of work – with control frequency under or above their own resonance frequency.

II.1. CORRELATIONS AT RESONANCE INVERTERS WITHOUT REVERSE DIODES

Analysis of resonance inverters without reverse diodes begins with analysis of work with compulsory commutation of appliances (regime of discontinued electrical current, work with control frequency above the resonance) because it is most common and from it could be taken expressions for inverters current in case of work in under resonance frequency. [1, 2, 5, 6]. In order to work in resonance regime in the equivalent duplicating serial, following conditions for resonance processes must be fulfilled:

$$R_{\text{екv}} < 2\sqrt{\frac{L_{\text{екv}}}{C_{\text{екv}}}}\text{, where}$$

$R_{\text{екv}} = R_{(1)} = R$ at parallel compensated load;

$L_{\text{екv}} = L_k = L$ at capacity disorder of the parallel compensated load;

$L_{\text{екv}} = L_k + L_{(1)}$ at inductive disorder of the parallel compensated load;

$C = C_{\text{екv}} = C_k$ at inductive disorder of parallel compensated load;

$C_{\text{екv}} = C_k \,||\, C_{(1)}$ at capacity disorder of parallel compensated load.

The case of electro technical applications is worked out by load parameters as per first harmonic $R_{(1)} = R_e \cos^2\gamma$ и $X_{(1)} = R_e \cos\gamma\sin\gamma$, where R_e is resonance resistance, end γ – angle of disorder of the parallel loading circle. This way, without any significant break of accuracy, analysis and design of these inverters is simplified.

Taking into consideration the equivalent duplicating circuit in operative mode, shown on fig. 1 and conditions for periodicity $i(0)=i\left(\frac{\pi}{\omega}\right)$ of inverters electrical current $i(\theta)$ и $u_C(0) = -u_C\left(\frac{\pi}{\omega}\right)$ of voltage of equivalent commutating capacitor $u_C(\theta)$ following expressions came out:

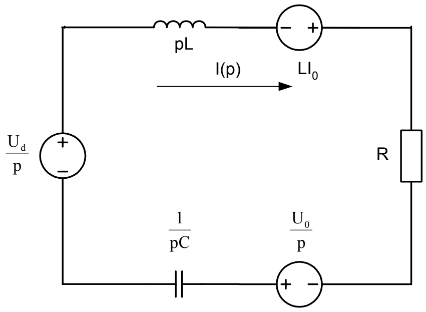

Fig. 1 Unified equivalent circuit

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$$i(t) = I_m e^{-\delta t}\left(\left(1 - a\frac{\delta}{\omega_0}\right)\sin\omega_0 t + a\cos\omega_0 t\right) \qquad (1)$$

$$u_C(t) = U_d - 2k_I U_d e^{-\delta t}\left(A\sin\omega_0 t + a\cos\omega_0 t\right) \qquad (2)$$

where $\delta = \frac{R}{2L}$ is coefficient (decrement) of damping of the equivalent consecutive (serial) resonance circuit; $\omega_0 = \sqrt{\frac{1}{CL} - \delta^2}$ is resonance frequency of the equivalent serial circuit $\nu = \frac{\omega}{\omega_0}$ - frequency coefficient, ω – control frequency, $I_m = \frac{2k_I U_d}{\omega_0 L}$, $A = \frac{\delta}{\omega_0} - a - a\left(\frac{\delta}{\omega_0}\right)^2$, $I_0 = I_m a$ and $U_0=(2k_I-1)U_d$ reflect the initial conditions in circuit, R is the equivalent loading resistance, L and C are equivalent commutating inductivity and capacity, U_d is feeding voltage,and I(p) is the image of the total current in circuit

$$a = \frac{\sin\frac{\pi}{\nu}}{\frac{1}{\pi}\ln\left(\frac{k}{k-1}\right)\sin\frac{\pi}{\nu} - \cos\frac{\pi}{\nu} + \left(\frac{k}{k-1}\right)^{\frac{1}{\nu}}},$$

$$k_I = \frac{1}{1 + e^{-\delta\frac{\pi}{\omega}}\left(\left(\frac{\delta}{\omega_0} - a - a\left(\frac{\delta}{\omega_0}\right)^2\right)\sin\frac{\pi}{\nu} + \cos\frac{\pi}{\nu}\right)}$$

is quantity characterizing resonance process in the fluctuation (oscillation) circuit, analogy to coefficient of hesitation $k = \frac{1}{1 - e^{-\frac{\delta\pi}{\omega_0}}}$, introduced at resonance inverters without reverse diodes in regime with natural commutation, called coefficient of hesitation of electric inverters [1, 2, 5].

For community of results and for evaluation of inverter's behavior at change of load and control frequency normalizing of expressions towards control frequency ω is used:

$$i(\vartheta) = I_m P e^{-\delta\frac{\vartheta}{\omega}}\sin\frac{\pi}{\lambda}(\vartheta + \psi) \qquad (3)$$

$$u_C(\vartheta) = U_d - 2k_I U_d\sqrt{1 + A^2}\, e^{-\delta\frac{\vartheta}{\omega}}\sin\frac{\pi}{\lambda}(\vartheta + \varphi_I), \qquad (4)$$

where: $P = \sqrt{\left(1 - a\frac{\delta}{\omega_0}\right)^2 + a^2}$,

$\psi = \frac{\lambda}{\pi}\psi' = \frac{\lambda}{\pi}\operatorname{arctg}\frac{a}{1 - a\frac{\delta}{\omega_0}}$,

$\varphi_I = \frac{\lambda}{\pi}\varphi'_I = \frac{\lambda}{\pi}\operatorname{arctg}\frac{1}{\frac{\delta}{\omega_0} - a - a\left(\frac{\delta}{\omega_0}\right)^2}$ reflect initial phases respectively to inverted current and to voltage of equivalent commutating capacitor.

By using these expressions we determine basic values which are used for design:

1. Average value of used current is determined by the integral:

$$I_d = \frac{1}{\pi}\int_0^{\pi} i(\vartheta)d\vartheta = \frac{1}{\pi}\int_0^{\pi} I_m e^{-\delta\frac{\vartheta}{\omega}}\sin\frac{\pi}{\lambda}(\vartheta + \psi)\, d\vartheta,$$

and after it is solved is:

$$I_d = \frac{H_I}{\pi F} I_m, \qquad (5)$$

where $F = \sqrt{\left(\frac{\delta}{\omega}\right)^2 + \left(\frac{\pi}{\lambda}\right)^2}$, $\alpha = \operatorname{arctg}\frac{\frac{\pi}{\lambda}}{\frac{\delta}{\omega}}$,

$$H_I = -\left(e^{-\frac{\delta\pi}{\omega}}\sin\left(\frac{\pi}{\lambda}(\pi + \psi) + \alpha\right) - \sin\left(\frac{\pi}{\lambda}\psi + \alpha\right)\right)$$

2. Average value of current through appliances is $I_{av} = \frac{I_d}{2}$.

3. Maximum value of current through appliances is determined by current expression (3), at $\vartheta = \frac{\lambda}{\pi}\alpha - \psi$:

$$I_{max} = i\left(\frac{\lambda}{\pi}\alpha - \psi\right) = I_m e^{-\frac{\delta}{\omega}\left(\frac{\lambda}{\pi}\alpha - \psi\right)}\sin\alpha \qquad (6)$$

4. Maximum value of voltage over equivalent commutating capacitor is:

$$U_{Cmax}=(2k_I-1)U_d \qquad (7)$$

5. Voltage expression of commutating inductivity is:

$$u_L(\vartheta) = \omega L\frac{di(\vartheta)}{d\vartheta} = \omega L I_m F e^{-\delta\frac{\vartheta}{\omega}}\sin\left(\alpha - \frac{\pi}{\lambda}(\vartheta + \psi)\right) \qquad (8)$$

6. Appliance voltage, when it is used in reverse direction is described by expression:

$$u_a(\vartheta) = U_d - \omega L I_m F e^{-\delta\frac{\vartheta}{\omega}}\sin\left(\alpha - \frac{\pi}{\lambda}(\vartheta + \psi)\right) \qquad (9)$$

7. Maximum value of reverse current over appliances is used at moment corresponding to $\vartheta = 0$ and is respectively:

$$U_{RRM} = U_d - \omega L I_m F\sin(\alpha - \frac{\pi}{\lambda}\psi) \qquad (10)$$

8. Maximum value of direct current voltage over appliances is calculated for angle $\vartheta = \pi - \alpha$ and is:

$$U_{DRM} = U_d + \omega L I_m F e^{-\frac{\delta}{\omega}\pi\left(\frac{-\psi}{\pi} - \nu\left(1 - \frac{2\alpha}{\pi}\right)\right)}\sin\alpha \qquad (11)$$

9. Value of direct current voltage over appliance at the end of interval of non conduct is close to maximum and is:

$$U_{D(\vartheta=\pi)} = U_d - \omega L I_m F e^{-\frac{\delta}{\omega}\pi} \sin\left(\alpha - \frac{\pi}{\lambda}(\pi + \psi)\right) \tag{12}$$

By marking with β the angle between inverters current and inverters voltage, then, $\mathrm{tg}\beta = \frac{X_{\text{екv}}}{R_{\text{екv}}}$, from where it comes:

$$\mathrm{tg}\beta = \frac{1}{\omega CR} = \frac{\omega_0{}^2 + \delta^2}{2\omega_0 \delta \nu} = \frac{\frac{\omega_0}{\delta} + \frac{\delta}{\omega_0}}{2\nu} \tag{13}$$

Maximum value of first harmonic of inverters current is determined by making a harmonic analysis:

$$I_{(1)\max} = \sqrt{a_{(1)}^2 + b_{(1)}^2} = E_I I_m .$$

Maximum value of inverters voltage could be determined by equation of balance of active power, which under the made limits in analysis is:

$$P_d = U_d I_d = \frac{1}{2} U_{I\max} I_{(1)\max} \cos\beta \tag{14}$$

Maximum value of inverters voltage comes to:

$$U_{I\max} = \frac{2H_I U_d}{\pi F E_I} \frac{1}{\cos\beta} \tag{15}$$

The effective value of inverters voltage, if we accept that it is with sinusoidal form is:

$$U_I = \frac{U_{I\max}}{\sqrt{2}} = \frac{2H_I U_d}{\sqrt{2}\pi F E_I} \frac{1}{\cos\beta} \tag{16}$$

Circuit time for recuperation is determined by the expression: $t_{qc} = \frac{\beta}{\omega}$.

Analyzing ART, working in regime of natural commutation of appliances, same circuits for bridge resonance inverters could be used, as these used for analysis of ART with forced commutation with the difference, that the part of commutating inductivity $L_{K2} = (1-\sigma)L$ which is introduced in alternating side or to anode or cathode of any device (for example by $\frac{L_K}{4}$) is much bigger. Reasoning related to loads and their parameters remain in force under that regime as well.

Equivalent circuit at Fig.1 is also valid here, but the only difference is, that inverters current is with zero starting value. Here we can use the found out expressions for inverters current (1) and voltage of commutating capacitor (2). As we put $\psi' = 0$ (which reflects the fact, that inverters current is with zero starting value), and from there coefficient a=0 and we assume that work is carried at border regime, i.e. ν=1, coefficient k_i becomes equal to coefficient of hesitation k, characteristic for RI working in regime of natural commutation and expressions for inverters current $i(t)$ and voltage of commutating capacitor $u_C(t)$ take the well known from literature mode:

$$i(t) = \frac{2kU_d}{\omega_0 L} e^{-\delta t} \sin\omega_0 t , \tag{17}$$

$$u_C(t) = U_d - 2kU_d e^{-\delta t}\left(\cos\omega_0 t - \frac{\delta}{\omega_0}\sin\omega_0 t\right) \tag{18}$$

From here comes the conclusion, that analysis of ARI working in regime of natural commutation of appliances, could be considered as exceptional case from analysis of ARI in regime of forced commutation.

Remodeled in analogical way, as in the case of above resonance frequency, these expressions take following form:

$$i(\vartheta) = \frac{2kU_d}{\omega_0 L} e^{-\frac{\delta}{\omega}\vartheta} \sin\frac{\pi}{\lambda}\vartheta = I_m e^{-\frac{\delta}{\omega}\vartheta} \sin\frac{\pi}{\lambda}\vartheta , \tag{19}$$

$$u_C(\vartheta) = U_d - 2kU_d \sqrt{1 + \left(\frac{\delta}{\omega_0}\right)^2} e^{-\delta\frac{\vartheta}{\omega}} \sin\frac{\pi}{\lambda}(\vartheta + \varphi_T) \tag{20}$$

where $\vartheta = \omega t$, $I_m = \frac{2kU_d}{\omega_0 L}$, $\varphi_F = \frac{\lambda}{\pi}.\ \mathrm{arctg}\frac{1}{\frac{\delta}{\omega_0}}$.

Determination of other parameters necessary for design work is analogical to case of uninterrupted current. Difference is in finding out the circuit time for recuperation. For exact determination of circuit time for recuperation of appliances it is necessary to be settled with the help of numerical methods transcendental equation [1]. At [3] it is shown that with satisfactory for engineering practice accuracy, following simplified formula for determination of appliances time for recuperation could be used:

$$t_{qc\Sigma} = t_P + t_{qc} , \tag{21}$$

where $t_{qc\Sigma}$ is total recuperation time, $t_P = \frac{\pi - \lambda}{\omega}$ is interval time and $t_{qc} = \frac{1}{\omega}\left(\frac{\pi}{2} - \mathrm{arctg}\frac{2\delta}{\omega_0}\right)$ is time for appliances recuperation given by the circuit.

Another peculiarity is that because of distribution of commutating inductivity in the alternating and direct current circuit of the inverter, angle β is determined by:

$$\mathrm{tg}\beta = \frac{\frac{\pi}{\ln\frac{k}{k-1}}\left[1 - (1-\rho)\nu^2\right] + \frac{\ln\frac{k}{k-1}}{\pi}}{2\nu} \tag{13a}$$

where $\rho = \frac{L_{k1}}{L_{k1} + L_{k2}}$ is coefficient reflecting distribution of commutating inductivity.

II.2 CORRELATIONS AT RESONANCE INVERTERS WITH REVERSE DIODES

Analysis of RIRD at advanced current towards inverter's voltage (regime in under resonance frequency) is shown in [1, 2]. At [1] are the calculated expressions of inverters current and voltage of commutating capacitor, by their help are calculated the necessary parameters for design of RIOD in this regime.

At work, when inverters current is behind towards inverters voltage (so called regime with above resonance frequency) analysis is made in [3, 4, 5]. There are also the calculated expressions for inverters current and voltage of commutating capacitor, through which necessary design parameters are configured for work in that regime.

Assuming that active and reactive elements are ideal, one and the same equivalent duplicating circuit is valid. Inverters current for discussed cases is described by one and the same unified expression.

From methodology point of view it is more convenient to use analysis of work in settled regime, at work with under resonance frequency, because in first part of half period energy comes from feeding source, but in second it goes back, which is exactly opposite in regime with above resonance frequency.

In order to make generalized design methodology we shall use the possibility that results of analysis of RIOD in regime with under resonance frequency and uninterrupted current to be spread and used also for regime of work with above resonance frequency and uninterrupted current.

Analysis of processes in settled regime at work in under resonance frequency [1, 2] and found out on its basis expressions for inverters current and voltage of commutating capacitor are as follows:

$$i(\vartheta) = \frac{2k_{od}U_d}{\omega_0 L} P e^{-\delta\frac{\vartheta}{\omega}} \sin\frac{\pi}{\lambda}(\vartheta + \psi), \tag{22}$$

$$u_C(\vartheta) = U_d - 2k_{od}U_d T e^{-\delta\frac{\vartheta}{\omega}} \sin\frac{\pi}{\lambda}(\vartheta + \varphi) \tag{23}$$

where θ=ωt, ω - control frequency, $R=R_{(1)}$ is equivalent loading resistance, L and C are equivalent commutating inductivity and capacity, U_d is voltage of direct current source, $\omega_0 = \sqrt{\frac{1}{LC} - \delta^2}$ is resonance frequency of serial oscillating circuit, a $\delta = \frac{R}{2L}$ is its damping, $\nu = \frac{\omega}{\omega_0}$ is frequency coefficient, $P = \sqrt{\left(1 - a\frac{\delta}{\omega_0}\right)^2 + a^2}$,

$T = \sqrt{1 + \left(\frac{\delta}{\omega_0} - a - a\left(\frac{\delta}{\omega_0}\right)^2\right)^2}$, $\lambda = \frac{\pi\omega}{\omega_0}$ - standardized to control frequency angle for conducting through of control keys, with h and a are marked:

$$h = \frac{\frac{1}{\pi}\ln\left(\frac{k}{k-1}\right)\sin\frac{\pi}{\nu} + \cos\frac{\pi}{\nu} + \left(\frac{k-1}{k}\right)^{\frac{1}{\nu}}}{\left(\frac{k-1}{k}\right)^{\frac{1}{\nu}}\left(\frac{1}{\pi}\ln\left(\frac{k}{k-1}\right)\sin\frac{\pi}{\nu} - \cos\frac{\pi}{\nu}\right) - 1},$$

$a = \dfrac{\sin\frac{\pi}{\nu}}{\frac{1}{\pi}\ln\left(\frac{k}{k-1}\right)\sin\frac{\pi}{\nu} - \cos\frac{\pi}{\nu} - \left(\frac{k}{k-1}\right)^{\frac{1}{\nu}}}$. Coefficient of hesitation k is from the type $k = \dfrac{1}{1 - e^{-\frac{\delta\pi}{\omega_0}}}$, a

$$\psi' = \operatorname{arctg}\frac{a}{1 - a\frac{\delta}{\omega_0}},$$

$$\varphi' = \operatorname{arctg}\frac{1}{\frac{\delta}{\omega_0} - a - a\left(\frac{\delta}{\omega_0}\right)^2}, \quad \psi = \frac{\lambda}{\pi}\psi', \quad \varphi = \frac{\lambda}{\pi}\varphi'$$

и $k_{od} = \dfrac{1}{1 - h.e^{\frac{-\delta\pi}{\omega}}} = \dfrac{1}{1 - h.\left(\frac{k-1}{k}\right)^{\frac{1}{\nu}}}$ is a parameter characterizing the serial RLC chain, called coefficient of hesitation at RIOD, working in regime with under resonance frequency.

Average current used from feeding source I_d is presented by expression:

$$I_d = -\frac{\frac{4k_{od}\delta U_d}{\omega_0 R}P}{\pi F}\left(e^{-\frac{\delta\pi}{\omega}}\sin\left(\frac{\pi}{\lambda}(\pi + \psi) + \alpha\right) - \sin\left(\frac{\pi}{\lambda}\psi + \alpha\right)\right)$$

where $F = \sqrt{\left(\frac{\delta}{\omega}\right)^2 + \left(\frac{\pi}{\lambda}\right)^2}$ and $\alpha = \operatorname{arctg}\frac{\frac{\pi}{\lambda}}{\frac{\delta}{\omega}}$.

Expression for average current through appliance I_{av} is:

$$I_{av} = \frac{1}{2\pi}\int_0^{\lambda-\psi} i(\vartheta)d\vartheta = \frac{1}{2\pi}\int_0^{\lambda-\psi}\frac{2k_{od}U_d}{\omega_0 L}Pe^{-\delta\frac{\vartheta}{\omega}}\sin\frac{\pi}{\lambda}(\vartheta + \psi)d\vartheta$$

$$I_{av} = \frac{\frac{2k_{od}U_d}{\omega_0 L}P}{2\pi F}\left(e^{-\frac{\delta}{\omega}(\lambda-\psi)}\sin\alpha + \sin\left(\frac{\pi}{\lambda}\psi + \alpha\right)\right),$$

Average current through diodes I_{dav} is determined by expression

$$I_{dav} = I_{av} - \frac{I_d}{2}.$$

For determination of effective value of loading voltage U we use equation for balance of inverters active input / output powers, which for parallel compensated load is:

$$P_d = U_d I_d = UI\cos\gamma = \frac{U^2}{R_{(1)}}\cos^2\gamma.$$

From comparison of expressions, describing currents and voltages in the RIOD's two working regimes, made in [2] it is clear that unified coefficients of hesitation $k_{ОД}$ and $k_{ОДН}$ are one and the same and starting phases of inverters current and voltage of equivalent commutating capacitor are equal by size, but with different signs, which reflects different de-phasing between inverters current and inverters voltage in the two regimes. Same applies to coefficient "a", which reflects starting conditions of inverters current towards inverters voltage in the two cases.

Then from expression (22) for inverters current and voltage of commutating capacitor (23) in regime of under resonance frequency, and change of "Ψ", "φ" and "a" respectively with "-Ψ", "-φ" and "-a" there come their respective expressions in regime with above resonance frequency. That gives us the reason to use results from analysis of RIOD with under resonance frequency also for analysis of processes in RIOD in work with above resonance frequency. For that purpose it is necessary that in all expressions, describing work of RIOD in regime with under resonance frequency, the frequency coefficient "ν" to be with value larger than 1, when it is worked in regime with above resonance frequency.

For determination of average currents values through appliances and diodes it is possible to use their expressions in regime with under resonance frequency, while in integrals for their determination are substituted integrals borders, as per their working regime.

The so made summarized review of processes in RIOD for the two working regimes and discontinued current, allows the use known and widely spread expressions for working regime with under resonance frequency, for evaluation of inverters behavior at change of load or control frequency and for its design.

III. DESIGN OF RESONANCE INVERTERS WITH COMPLICATED OUTPUT CIRCUITS

Further down are presented methodologies for design of resonance inverters, using different output circuits for co-ordination of inverter and load.

III.1 METHODOLOGY FOR DESIGN OF ARI WITH PARALLEL COMPENSATION

On fig.2 is shown most common type of alternating circuit at use of parallel compensation of load.

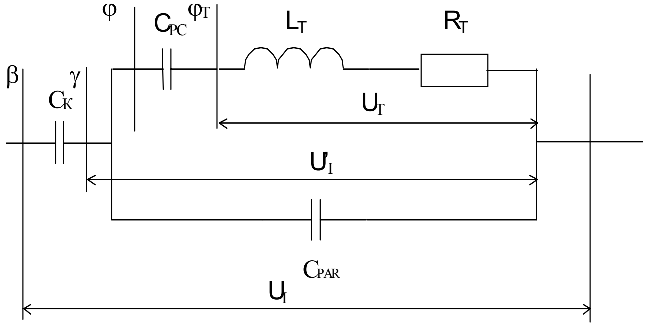

Fig.2 Common circuit of parallel compensated load

Using parallel compensation of load, as in that case, parallel loading circuit is substituted by its active and reactive resistances as per first harmonic – $R_{(1)}$ и $X_{(1)}$ [6].

- determination of hesitance coefficient values κ and frequency coefficient ν, by which is achieved the preset inverted (loading) voltage. This is achieved by using expressions shown in previous chapter. In case the calculated value does not match the preset one, it is necessary to use an inverters transformer.

- finding the phase angle of alternating circuit - β, with the help of expression (13) or (13a):

- determination of own resonance frequency of the in series resonance circuit - ω_0: $\omega_0 = \dfrac{\omega}{\nu}$;

- calculation of active load resonance of parallel duplicating circuit of load - R_e: $R_e = \dfrac{U_T^2}{P_T}$;

- determination of parameters of serial duplicating circuit of load: $R_T = \dfrac{R_e}{1 + tg^2\varphi_T}$, $L_T = \dfrac{R_T tg\varphi_T}{\omega}$;

- finding our of first harmonics of active - $R_{(1)}$ and reactive - $X_{(1)}$ components of serial duplicating circuit of alternating inverters circuit (in that case the parallel loading circuit):

$R_{(1)} = R_e\cos^2\beta$, $X_{(1)} = R_e\cos\beta\sin\beta$;

- determination of damping of serial resonance circuit - δ:

$$\delta = \frac{\omega_0}{\pi}\ln\frac{k}{k-1};$$

- determination of values for commutating inductivity – L_k: $L_k = \dfrac{R_{(1)}}{2\delta}$;

- determination of values of loading (parallel) capacity - $C_{пар}$:

$$C_{PAR} = \frac{tg\beta + tg\varphi_T}{\omega R_e}.$$

Determination of size of average value of current through appliances - I_{av}, of used current from feeding source - I_d, of average current through diodes - I_{dav}, of maximum value of voltage over commutating capacitor - U_{cmax}, and also of maximum value of inverted current - I_{max}, is made by relevant expressions depending on type of resonance inverter.

- maximum voltage of loading capacitor - $U_{C_{ПАР\,max}}$ is:

$$U_{CPAR\,max} = U_{T\,max};$$

Calculations made allow the choice of power appliances. Parallel and/or consecutive (serial) switching on of appliances is made if necessary.

III.2 METHODOLOGY FOR DESIGN OF SERIAL / PARALLEL ARI

As there is a big coincidence in designing of parallel RI, that paragraph shall underline only differences with above discussed case. In that case it is necessary to choose the value of inverted voltage, because normally it is not given in the task. Most often, when using consecutive – parallel resonance output circuit, loading voltage is with lower value from the inverted one.

- determination of disorder of parallel loading ring - γ:

$$\cos\gamma = \frac{U_I}{U_T}\cos\beta\ .$$

- nomination of value of loading capacity C_{PAR}: $C_{PAR} = \dfrac{tg\gamma + tg\varphi_T}{\omega R_e}\ .$

- determination of value of equivalent commutating capacitor - C_e: $C_e = \dfrac{1}{L(\omega_0^2 + \delta^2)}\ .$

- calculation of capacity of commutating capacitor - $C_к$:

$$C_K = \frac{C_e C_{(1)}}{C_{(1)} - C_e}\text{, where } C_{(1)} = \frac{1}{\omega X_{(1)}}\ .$$

- determination of maximum voltage of commutating capacitor $U_{C_{K\max}}$: $U_{C_{K\max}} = X_{C_{K\max}} I_{(1)\max} = \dfrac{1}{\omega C_k}\dfrac{U_{T\max}}{R_{(1)}}\cos\gamma\ .$

III.3 METHODOLOGY FOR DESIGN OF PARALLEL – SERIAL ARI

Choice of best value of inverted voltage is determined by the same considerations as in previous points.

- determination of disorder of serial loading circuit - φ:

$$\cos\varphi = \frac{U_T}{U_I}\cos\varphi_T\ ;$$

Serial resonance ring consisting of R_T, L_T and C_{PC} is substituted by impedance from consecutively connected active - R_T and reactive - X_{PC} components. This impedance could be transformed in equivalent consisting of parallel connected active - $1/R_{екv}$ and reactive - $1/X_e$ components.

- calculation of active loading resistance of parallel duplicating circuit of equivalent load - $R_{екv}$: $R_{екv} = \dfrac{U_I^2}{P_T}\ ;$

- nomination of first harmonics of active - $R_{(1)}$ and reactive - $X_{(1)}$ components of serial duplicating circuit of alternating circuit of inverter: $R_{(1)}=R_{екv}\cos^2\beta$, $X_{(1)}=R_{екv}\cos\beta\sin\beta$.

- determination of value of parallel capacity - C_{PAR}:

$$C_{PAR} = \frac{tg\beta + tg\varphi}{\omega R_{екv}}\ .$$

- calculation of value of serial capacity - C_{PC}:

$$C_{PC} = \frac{1}{\omega R_T(tg\varphi_T - tg\varphi)}\ .$$

- determination of maximum voltage of serial capacitor - $U_{C_{PC\max}}$:

$$U_{C_{PC\max}} = X_{C_{PC\max}} I_{T\max} = U_{C\max}(tg\varphi_T - tg\varphi)\cos\varphi\ .$$

- nomination of maximum voltage of parallel capacitor - $U_{C_{PAR\max}}$: $U_{C_{PAR\max}} = U_{I\max}\ .$

III.4 METHODOLOGY FOR DESIGN OF SERIAL – PARALLEL – PARALLEL – SERIAL ARI

Diagram of serial – parallel resonance output circuit is shown on Fig.2 Taking into consideration the abilities of serial – parallel chain to decrease respectively parallel – serial one to increase its output voltage, we choose voltage $U'_И$. It is also necessary to choose the value of inverted voltage. Further down only differences in design of parallel RI should be underlined.

- nomination of disorder of serial loading circuit - φ:

$$\cos\varphi = \frac{U_T}{U'_I}\cos\varphi_T\ .$$

- determination of disorder of parallel loading circuit - γ:

$$\cos\gamma = \frac{U_I}{U'_I}\cos\beta\ .$$

Similarly to the said for design of parallel – serial RI, serial loading resonance ring consisted from R_T, L_T и $C_{ПС}$ is substituted by impedance of consecutively connected active - R_T and reactive - $X_{ПС}$ components. This impedance could be transformed in equivalent consisting of parallel connected active - $1/R'_{екv}$ and reactive - $1/X_{ePAR}$ components.

- calculation of active loading resistance of parallel duplicating circuit of equivalent load - $R'_{екв}$:

$$R'_{EKV} = \frac{\left(U'_I\right)^2}{P_T}\ .$$

- determination of first harmonics of active - $R_{(1)}$ and reactive - $X_{(1)}$ components of serial duplicating circuit of parallel – serial loading ring: $R_{(1)}=R'_{екv}\cos^2\gamma$, $X_{(1)}=R'_{екv}\cos\gamma\sin\gamma$.

- nomination of value of parallel capacity - C_{PAR}:

$$C_{PAR} = \frac{tg\gamma + tg\varphi}{\omega R'_{EKV}}.$$

- nomination of value of serial capacity - C_{PC}:

$$C_{PC} = \frac{1}{\omega R_T (tg\varphi_T - tg\varphi)}.$$

- calculation of value of equivalent commutating capacity - C_e: $C_e = \dfrac{1}{L(\omega_0^2 + \delta^2)}$.

- nomination of capacity of commutating capacitor - $C_к$:

$$C_K = \frac{C_e C_{(1)}}{C_{(1)} - C_e}\text{, where } C_{(1)} = \frac{1}{\omega X_{(1)}}.$$

- determination of maximum voltage of serial capacitor - $U_{C_{PC\max}}$:

$$U_{C_{PC\max}} = X_{C_{PC\max}} I_{T\max} = U'_{C\max}(tg\varphi_T - tg\varphi)\cos\varphi.$$

- calculation of maximum voltage of parallel capacitor - $U_{C_{PAR\max}}$: $U_{C_{PAR\max}} = U'_{I\max}$.

- determination of maximum voltage of commutating capacitor $U_{C_{K\max}}$: $U_{C_{K\max}} = X_{C_{K\max}} I_{(1)\max} = \dfrac{1}{\omega C_K}\dfrac{U'_{I\max}}{R_{(1)}}\cos\gamma$.

By using suitable numerical coefficients results from analysis of bridged circuit, could be spread also for other circuit types of serial RLC inverters.

IV. OBTAINED RESULTS

For confirmation of achieved results at design of parallel electric inverters, following computer simulations were made on jumping and fixed regimes with the help of simulator PSPICE.

Initial data for design of parallel RI working in regime of uninterrupted current is:

- output active loading power P=100 кW;
- $\cos\varphi_T$=0.15;
- effective value of loading voltage U_T=750V;
- output frequency f=2400Hz.

In Table 1 comparison is made between results calculated with the help of Design Methodology for parallel electric inverter and these obtained from the simulator.

Table 1

results	R_T,Ω	L_T,μH	$C_{\text{пар}}$,μF	L_k,mH	I_d,A
calculated	0.12656	55.319	88.406	2.18	200
simulated	0.12656	55.319	88.406	2.18	195.7
results	U_T,V	U_{Dm},V	t_q,μs	f,Hz	
calculated	750	1060.6	48.874	2400	
simulated	751.7	1064.1	49	2400	

Data listed in Table 1 shows that for all values determined at Design, mistake is less than 2 %.

Initial design data for serial – parallel RI, working in regime of discontinued current is:

- output active loading power P=160кW;
- $\cos\varphi_T$=0.1;
- effective value of loading voltage U_T=650V;
- output frequency f=2400Hz.

In Table 2 comparison is made between results calculated with the help of computer organizes methodology for design of serial – parallel electric inverter and these obtained from simulator

Table 2

results	R_T,Ω	L_T,μH	$C_{\text{пар}}$,μF	$C_к$,μF	L_k,mH
calculated	0.0264	17.423	265.146	114.87	1.3669
simulated	0.0264	17.423	265.146	114.87	1.3669
results	I_d,A	U_T,V	U_{Dm},V	t_q,μs	f,Hz
calculated	320	650	1060.66	48.874	2400
simulated	324.15	652	1056.6	48.4	2400

Data listed in Table 2 shows that for all values determined at design, mistake is less than 2 %.

Initial design data for parallel resonance inverter is:

- output active loading power P=100кW;
- $\cos\varphi_T$=0.15;
- effective value of loading voltage U_T=750V;
- output frequency f=4000Hz.

In the examined case there is an inclusion of commutating inductivity wholly in the direct current chain of the inverter.

In Table 3 there is a comparison between results calculated with the help of design methodology for parallel resonance inverter and these obtained from the simulator.

Table 3

results	R_T,Ω	L_T, μH	$C_{\text{пар}}$,μF	L_k,μH	I_d,A
calculated	0.12656	33.191	56.877	69.578	215.256
simulated	0.12656	33.191	56.877	69.578	217.8
results	$I_{\max}$,A	U_T,V	U_{Dm},V	t_q,μs	f,Hz
calculated	396.82	750	1060.6	45.31	4000
simulated	377.117	749.70	1056.2	45.4	4000

Data listed in Table 3 shows that for all values determined at design, mistake is less than 2 %.

Initial data for design of parallel-serial resonance inverter is:

- output active loading power P=400кW;
- $\cos\varphi_T$=0.08;
- effective value of loading voltage U_T=1500V;
- output frequency f=4000Hz.

In the examined case there is an inclusion of commutating inductivity in the alternating and also direct current chain of inverter, at coefficient value ρ=0.92.

In Table 4 there is a comparison between results calculated with the help of design methodology for serial-parallel resonance inverter and these obtained from simulator.

Table 4

results	R_T,Ω	L_T,μH	$C_{\text{пар}}$,μF	$C_{\text{пс}}$,μF	L_k, μH	I_d,A
calculated	0.036	17.847	215.77	175.70	17.394	860
simulated	0.036	17.847	215.77	175.70	17.394	846

results	I_{max},A	U_T,V	U_{Dm},V	t_q,μs	f,Hz
calculated	1587.0	1500	1030.6	117.29	4000
simulated	1568.5	1500.4	1030.2	117	4000

V. CONCLUSIONS

When comparing the characteristics of resonance inverters with serial and parallel compensated load, it is obvious that by increasing hesitance coefficient of input current, output voltage and circuit time for recuperation of key semiconductor appliances goes up and changes are almost the same in the two types of compensation. At the same time increase of frequency coefficient does not lead to increase in size of inspected values at parallel compensation of load and to decrease at consecutive compensation.

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