ERROR ELIMINATION FOR CURRENT CONTROL LOOP FOR MULTI-FUNCTIONAL SINGLE-PHASE GRID-CONNECTED INVERTER

Purpose. Elimination of the error of the inverter current control loop by improving its structure and justifying the parameters, which will ensure compliance with the current quality standard at the common coupling to the distribution grid of the load and the multi-functional grid inverter at the output of the renewable source of electrical energy. Methodology. Synthesis of structure of current control loop based on analysis of processes in electrical circuits and computer simulation. Results. Relationships for determining the input voltage of the inverter, reactor inductance and modulation frequency in accordance with the grid voltage, the maximum values of the inverter current and the amplitude of its ripple when combining the function of the active power filter. Dependencies of the amplitude of the pulsations of the output current of the inverter and the errors in the fundamental harmonic in accordance with the voltage at the input of the inverter, the modulation frequency and inductance of the output reactor are obtained. Originality. The structure of the inverter current control loop has been improved with a combination of proportional, integrating and differentiating links, and their parameters have been determined to ensure compensation of the disturbing action on input of the reference and compensation of the error of current from the disturbing action of the grid voltage regardless of its value. Practical value. The obtained solutions are the basis for the design of converters of electric power systems with renewable energy sources. The multi-functional grid inverter at the output of the renewable source of electrical energy.

Key words: multi-functional single-phase grid-connected inverter, nonlinear load, PWM, current control loop, current error compensation, THD, simulation.

Introduction. The use of a renewable energy source (RES) implies the presence of a fairly complex and expensive conversion unit with an output grid-connected autonomous voltage inverter (AVI). Under natural conditions, the use of equipment for a photovoltaic solar cell does not exceed 20% [1]. For local objects (small enterprise, cottage, mini-hotel, etc.) with power supply from the RES and the distribution grid (DG) of the alternating current, increasing the efficiency of the use of the conversion unit is achieved by the use of a multi-functional grid-connected AVI with a combined function of the power active filter (PAF) [1-9] thanks to its round-the-clock use to maintain the maximum (close to 1) power factor at the point of connection to the DG.

Typical solutions in the current control circuit (CCC) of the multi-functional AVIs are the use of a proportional-integral (PI) regulator [1, 3, 4], the
proportional-resonant regulator [1], the relay current regulator [1, 2], the regulator on the basis of the fuzzy-logic [5]. Solutions using PWM are more widespread [1, 3, 5-9]. The development of the CCC with the use of PWM is quite diverse. So, in [1, 5] the deviation ΔIC of the current IC of the AVI relative to the given value i* C (ΔIC = i* C − IC) is fed to the proportional-integral (PI) current regulator. Since its efficiency is insufficient, variants are given in [1], where to the output voltage of the current regulator they add the voltage proportional to the current regulator they add the voltage proportional to i* C, IC and u1.

The data above is not sufficient for perception and evaluation. For example, oscillograms of currents and indicators of circuits are given, but it is not indicated for which value (nominal, maximum, minimum). Structures are mostly declared, techniques for calculating parameters are absent. For a nonlinear load, the current IC is non-sinusoidal, compensating for the distortion of the load current form iL. For this, the DG current i1 = IC − IL contains the first harmonic, and higher (modulation) harmonics are suppressed by the filter. The operation error i* C leads to the appearance in the current i1 of higher harmonics of low order and the deterioration of the harmonic composition of the current, especially for its relatively small values, as evidenced by the oscillograms given in [3, 4]. This complicates the issue of ensuring the correspondence of the current harmonic composition to standards [10].

Consequently, the question of the implementation of the CCC of multi-functional grid-connected AVI has not been studied sufficiently and requires additional research.

The goal of the work is to eliminate the error of the inverter current control circuit by improving its structure and justification of the parameters that contributes to compliance with the current quality standard at the point of connection to the distribution grid of the load and the multifunctional grid-connected inverter at the output of the renewable energy source.

Main research materials. Consider the bridge circuit of the grid-connected AVI (Fig. 1) with the output LC-filter (Cf) with insignificant RFC at the point of connection to the AC grid with the voltage u1 = U1m sin t and load. The input AVI circuit contains a solar cell (SC) with a voltage converter (VC) that supports a given voltage value U at the AVI input.

The operation of the AVI in parallel with the DG in the mode of the current source provides for the fulfillment of the condition U = aU1m (a = 1) [6, 9]. The rate of change of the AVI output current dIC/dt in this case must exceed the maximum value for the current setting d i* C/dt. In the case of the formation of a sinusoidal current, the maximum value (d i* C/dt)max = 2πfCmax (ω = 2πf) is the angular frequency, f = 50 Hz, Cmax is the amplitude for the maximum value iLm (the AVI current). The value of dIC/dt is determined by the voltage at the AVI output reactor

\[ u_L = u_C - u_1 = L \frac{d i_C}{dt} \],

where uC is the AVI voltage.

The least value of uL takes place at u1 = U1m and

\[ U_L = U - U_1 = L \frac{d i_C}{dt} \max. \]

From here \( a > 1 + \frac{L \frac{d i_C}{dt}}{U_1m} \).

According to Fig. 2, constantly acting disturbing influence, which causes the «static» error of current processing, is the voltage u1, even at i* C = 0.

The typical nonlinear load of local objects is uncontrolled rectifiers (usually with an output capacitive

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The inductance L of the AVI reactor according to the coefficient of b of the voltage U1 (by the 1st harmonic) for the maximum AVI current ICmax b = U1 / U1 = ωL/Cmax / U1 (where U1 is the current value of the DG voltage), we determine as

\[ L = \frac{bU_1m}{\omega L/Cmax}. \]

Accordingly, \( a > 1 + 2b \).

The simplified structure of the CCC in accordance with (1) is shown in Fig. 2. The dotted line shows the compensation circuits. TP is the small uncompensated time constant of the AVI, which is determined by the frequency of PWM. The coefficients k, j, the compensating links of the DC and K are discussed further.

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consider the implementation of PWM for the case when two reference voltages \( u_{TR} \) and \((-u_{TR})\) of a triangular shape with a modulation frequency \( f_M \) which are symmetric with respect to 0 are used (Fig. 3). Switching of the keys of the first arm (K1, K2) is carried out provided that the given voltage \( u' \geq u_{TR} \), and of the second one (K3, K4) \(-u' \leq -u_{TR}\).

In the absence of regulators in the PWM block, the voltage, which is proportional to \( \Delta i_c \), is compared with \( u_{TR} \). In the case of the formation of positive half-wave of \( i_c \), two voltage values \( U \) and 0 (for negative half-wave, respectively, \(-U \) and 0) are used and the voltage \( u_L \) takes the value:

- if \( u_c = U \), then the value \( u_L = U - u_1 = L \frac{di_c}{dt} \) and the current \( i_c \) increases (the initial deviation \( \Delta i_c \) relative to the average value of the \( \Delta i_{CAV} \) (error of current processing) is positive \( (i_c > i_c) \) and decreases to zero and then becomes negative \( (i_c < i_c) \) (Fig. 3);

- if \( u_c = 0 \), then the value \( u_L = 0 - u_1 = L \frac{di_c}{dt} \) and the current decreases \( (\Delta i_c \) increases to zero, and then becomes positive). Since \( f_M \) is large enough, it can be assumed that on the modulation interval \( T \) the voltage \( u_1 \) and current \( i_c \) are unchanged. Consequently, the current fluctuates relative to the given value and changes according to the linear law, the rate of its change depends on the values \( u_1 \) and \( u_c \).

We assume that the current \( i_c \) and, accordingly, \( di_c/dt \) vary according to the harmonic law. The amplitude of current pulsations \( \Delta i_{Cm} \) is determined by the coefficient of filling the pulses of the AVI voltage \( \gamma = I_{CAV} / T \) (\( I_{CAV} \) is the key activation time, \( T \) is the modulation period) and does not depend on the current value. Therefore, we assume that the given value of the AVI current is zero. So, we have:

- at \( u_t \rightarrow 0 \), the value \( \gamma \rightarrow 0 \), accordingly, \( \Delta i_{Cm} \rightarrow 0 \) (Fig. 3,a). For this, the mean value of the current deviation during the modulation period is \( \Delta i_{CAV}(t) = 0 \). The rates of growth and decrease of current are different, which in the case of \( \gamma > 0 \) leads to an increase \( |\Delta i_{CAV}(t)| > 0 \). That is, the mean value \( |\Delta i_{CAV}(t)| \) gradually increases;

- the value \( \gamma = 0.5 \), when \( \Delta i_{Cm} \) is the maximum (Fig. 3,b), meets the condition

\[
\Delta i_{Cm} = aU_{im} / 16 I_{M} \quad \text{or} \quad \Delta I_{Cm} = \frac{aU_{im}}{16 I_{M}}. \tag{3}
\]

\[
\text{at } u_t = U_{im}, \text{ the value of } \gamma \text{ is maximal (Fig. 3,c), it can be found under the condition that } \frac{T}{u_C dt} = 0, \text{ or } \gamma = 1/a, \text{ and }
\]

\[
\Delta i_{Cm} = \frac{\gamma(a-1)U_{im}}{4 I_{M}}. \tag{4}
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We take into account the relation of the rate of change of $i_c$ and the reference voltage $\frac{di_c}{dt} > \frac{di_c}{dt}$. The value $\frac{d\tau_{TR}}{dt} = 4 \mu_{TR} f_m$. The maximum value $\frac{di_c}{dt}$ takes place, when $u_I = 0 - U_{1m} = -U_{1m}$ and equal to $\frac{d\tau_{TR}}{dt} = \frac{U_{1m}}{L}$. So, $\frac{di_c}{dt} = 4 \mu_{TR} f_m \geq \frac{U_{1m}}{L}$ (Fig. 10 - modulation - amplitude of $\tau_{TR}$), from here $f_m \geq \frac{U_{1m}}{4 \mu_{TR} L}$. (5)

Based on the condition $\int u_{L} dt = 0$, we can determine dependencies $\gamma(t)$ and $\Delta I_{Cm}(t)$. So, for $U_{C} > 0$ we have $U_{1m}(a - \sin \alpha t) + U_{1m}(0 - \sin \alpha t)(1 - \gamma) = 0$. From here $\gamma = -\frac{\sin \alpha t}{a}$. Current deviation amplitude $\Delta I_{Cm} = \frac{\gamma(1 - \gamma) a U_{1m}}{2 a f_M}$. Taking into account the value of $\gamma$ we obtain $\Delta I_{Cm}(t) = \frac{U_{1m}}{2 a f_M} \{a \sin \alpha t - 0.5 + 0.5 \cos 2 \alpha t\}$. For $U_{C} < 0$ we have the same situation. So, $\Delta I_{Cm}(t) = \frac{U_{1m}}{2 a f_M} \{a \sin \alpha t - 0.5 + 0.5 \cos 2 \alpha t\}$, $\Delta I_{Cm}(t) = \frac{U_{1m}}{a f_M} \sin \alpha t$.

The boundary is the mode where the current error amplitude $I_m$ approaches $u_{TRm}$ and $\Delta I_{Cm} = 0$ at $a = 1$. In general, it is necessary to fulfill the condition $I_m + \Delta I_{Cm} \leq u_{TR}$. (6)

Otherwise there is an additional (superfluous) switching of the keys of the inverter.

The amplitude $u_{TRm}$ can be determined according to (5), then the amplitude of the fundamental harmonic of the current error, accordingly to (4) and (6) $I_m \leq \frac{U_{1m}}{a f_M}$, or $I_m = \frac{u_{TRm}}{a}$. (7)

Values $\Delta I_{Cm}$ at $\gamma = 0.5$ and $\gamma_{\text{max}}$ are, respectively, $\Delta I_{Cm \text{max}} = \frac{a u_{TRm}}{4 f_M}$, $\Delta I_{Cm} = \frac{(a - 1)}{4 a u_{TRm}}$.

Let’s turn to relative value $\Delta I_{Cm \text{max}}$ (to the amplitude $I_{Cm \text{max}}$) $c = \frac{\Delta I_{Cm \text{max}}}{I_{Cm \text{max}}}$, then accordingly to (2), (3) $f_M \geq \frac{a a \omega \gamma}{16 b c}$. (8)

So, for example, at $b = 0.15$, $c = 0.05$, $a = 1.3$ values $I_m = 0.77 u_{TRm}$, $\Delta I_{Cm \text{max}} = 0.25 u_{TRm}$, $\Delta I_{Cm} = 0.23 u_{TRm}$. If $I_{Cm \text{max}} = 25 A$ ($I_{Cm \text{max}} = 35.35 A$), the modulation frequency by (8) $f_M = 3400$ Hz, then $\Delta I_{Cm \text{max}} = 1.77 A$. Here $I_m = \frac{a a \omega \gamma}{16 b c}$ and $\Delta I_{Cm \text{max}} = 4.19 A$.

To reconcile the scale of the quantities in the direct channel of deviation, coefficients are introduces (Fig. 2): $k = \frac{a}{4 a f_M}$ (without taking into account transmission coefficients of sensors and $u_{TRm} = 1$) and $j = u_{TRm} / u_{TRm}$.

Without taking into account the modulation components, the «smooth» component of the reactor voltage according to (1)

$$u_1 = u_1 - u_1 = \frac{L d^2 i_1}{dt^2} = j u_K - u_t$$

Here $u_K = L \frac{di_1}{dt} + \frac{u_t}{j}$. Error $\Delta C_{AV} = 0$ provided that $i_1 = \frac{u_1}{j}$, respectively, $\frac{di_1}{dt} = \frac{di_1}{dt}$. From here $u_K = L \frac{di_1}{dt} + \frac{u_t}{j}$.

In the case $i_1 = 0$, the value $u_K = u_t$. The voltage $u_t$ is measurable and the static error can be compensated by the introduction of the corresponding connection (link $K$ in Fig. 2).

The exclusion of the current error caused by the perturbation by the control signal is possible using the differential link of dynamic compensation (DC) according to (9) in the AVI current assignment channel.

In real conditions, $U_1$ varies in certain limits. With the change of $U_1$ at constant $f_M$, (8) $b = b / U_1 \cdot U_1 = U_1 / U_1 N$., where $U_{1N}$ is the nominal voltage), $a' = a / U_1 \cdot \gamma$, $c' = \frac{a' b c}{b a}$, which requires readjustment of the CCC. Another version of the compensation of static error is the introduction of the integrative link (Fig. 4) with the coefficient $g = f_a / k$, which calculates the actual value of $\Delta C_{AV}(t)$ and adds it to the signal of deviation of current.

The proposed structure of the CCC of the AVI (Fig. 4) contains final devices, a proportional link with coefficient $k$, an integrative link, multipliers, a block of comparators BC, a generator of reference voltage GRV, a block of phase auto-adjustment of frequency PLL, a link of dynamic compensation DC. According to the signal of the setting of the amplitude of the current of the grid $I_1$ from the output of the external voltage regulator OR (it supports the voltage at the AVI input at a given level $U = U^*$) a sinusoidal signal of the grid current setting $i_1$ is formed, which, when generating energy of the SC to the grid is shifted relative to voltage $u_1$ by 180°, and in the case of power consumption from the grid coincides by the phase. The AVI current setting is determined taking into account $i_1$ and the capacitive current component of the filter with the amplitude $I_{01} = \omega_C U_{1N}$. PLL according to the DG voltage $u_1 = U_1 \sin \omega_t$ and the given value of the angular frequency $\omega_0$ forms signals $\sin \omega_t$, $\cos \omega_t$. 

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Simulation in Matlab and its results. It made with combination of nonlinear load (uncontrolled rectifiers with output capacitance filter and RL-load) and RL-load \((I_{\text{lin}(1)} = 19.6 \, \text{A}, \, \varphi_{(1)} = 27^\circ)\). The DG contains the resistances \(R = 0.02 \, \Omega, \, X_L = 0.02 \, \Omega\). Reactor with \(L = 0.0042 \, \text{H}\) and \(R = 0.1 \, \Omega, \, R_p = 0.3 \, \Omega, \, C_f = 60 \mu\text{F}\). AVI parameters: \(I_{\text{cin}} = 25 \, \text{A}, \, f_M = 6800 \, \text{Hz}, \, U = 405 \, \text{V} \) \((a = 1.3)\).

Three variants of CCC are considered: variant 1 – with DC and compensatory connection by \(u_1\); variant 2 – with DC and the integrating link; variant 3 – using PI-regulator with adjustment on the symmetric optimum \(k = k \cdot j\).

Variant 3 at nonlinear load is operational only with DC and compensating link by \(u_1\) and has the worst performance at small DG current values.

For example, in the case of \(I_{\text{lin}} = 3 \, \text{A}\), the value \(I_{\text{lin}(1)} = 2.973 \, \text{A}, \, \text{THD}_{i_1} = 4.79 \%\). Under the same conditions for variant 1 \(I_{\text{lin}(1)} = 2.943 \, \text{A}, \, \text{THD}_{i_1} = 3.41 \%\), for variant 2 \(I_{\text{lin}(1)} = 2.966 \, \text{A}, \, \text{THD}_{i_1} = 2.68 \%\). In addition, variant 2 has the best DG current spectrum (Fig. 5) and provides \(\text{THD}_{i_1} \leq 5 \%\) in the range of values of \(I_{\text{lin}}\) up to 0.05 \(I_{\text{lin(max)}}\) (\(I_{\text{lin(max)}}\) in this case is 35.35 A). In the case of change of \(u_1\), variant 2 does not need to be readjusted, so by \(U^* = 0.85 \) at \(I_{\text{lin}} = 3 \, \text{A}, \, I_{\text{lin}(1)} = 2.97 \, \text{A}, \, \text{THD}_{i_1} = 2.5 \%\). In variant 1, under the same conditions, \(I_{\text{lin}(1)} = 3.3 \, \text{A}, \, \text{THD}_{i_1} = 2.83 \%\), which implies a change in the coefficient in the link \(K\) (Fig. 2).

Oscillograms of \(u_1, \, u_C, \, i_1, \, \Delta I_{\text{cin}(t)}\) at the linear load with the DC are shown in Fig. 6. Oscillograms of \(u_1, \, u_C, \, i_1, \, i_C, \, i_L\) for \(I_{\text{lin}} = 3 \, \text{A}\) at the combined linear and nonlinear load (rectifiers with capacitive filter and RL-load) for variant 2 are shown in Fig. 7 (\(I_{\text{lin}} = 3 \, \text{A}, \, I_{\text{lin}(1)} = 2.97 \, \text{A}, \, \text{THD}_{i_1} = 2.97 \%\)).

For comparison in [3] with use in the CCC of the PI-regulator at \(f_M = 20 \, \text{kHz}, \, I_{\text{lin}} = 10 \, \text{A} \) \((I_{\text{cin}} = 20 \, \text{A}, \, \text{current amplitude of the nonlinear load} \, I_{\text{lin}} = 9 \, \text{A})\), the value of \(\text{THD}_{i_1} = 4.8 \%\).
Conclusions.

Based on the received dependencies of the amplitude of the pulsations of the AVI output current and the fundamental harmonic error according to the voltage at the AVI input, the PWM frequency and the inductance of the output reactor, the parameters of the links to compensate for disturbing influences are justified. It is shown that the compensation of the perturbation of the DG voltage using in the channel of the current deviation of the integral link does not require readjustment in the event of a change in the voltage of the grid. The proposed structure of the CCC of the multifunctional AVI with a combination of proportional, integrative and differential links with their respective parameters allows for a limited value of PWM frequency of 6800 Hz to expand the range of current values $i_1$ at the point of connection to the grid in the direction of lower values up to 0.05 from the maximum current value at the value of THD$i_1 \leq 5 \%$ In this case, the value of the inverter voltage and the PWM frequency are determined according to the DG voltage, the reactor inductance, the maximum values of the AVI current and the amplitude of its pulsations. The results are obtained for relative values: amplitude of current pulsations $c = 0.0025$, the voltage drop on the reactor at the maximum current (for the 1st harmonic) $b = 0.15$ and $a = 1.3$. A further direction of work is the development of a model for researching the AVI operation, taking into account the discreteness of the operation of the digital control system, to clarify the requirements for its elements and to assess real indicators.

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