Improving the energy efficiency of frequency converters in networks of limited power

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Abstract. The article discusses a method for improving the energy efficiency of a two-unit frequency converter with an active voltage rectifier using an input LCL filter. Studies are conducted on the basis of an asynchronous motor. The article presents the simulation results in the Matlab Simulink package. Improving the energy efficiency of elements of the energy system is especially important in networks of limited power.

1. Introduction

Engineering of the electric drives, especially in limited capacity networks, have many problems, for example, increasing energy efficiency of the electric drive [1–5]. While solving such problems, researcher may encounter resulting difficulties: synchronizing frequency converter and a power supply, etc. [6–12]. Problem is that there should be no obvious resonance between the power supply and the frequency converter when installing the filters. To solve this problem, there are different ways to implement the topology of frequency converter circuits. This article will consider only one way - the frequency converter of the input LCL filter [13].

The following is the algorithm for calculating buffer reactors and capacitors for a two-stage transistor frequency converter; for calculating thyristor converters, the calculation may look slightly different and be adjusted.

Initial data:

- $P_{d.n}$ - power AVR (active voltage rectifier) nominal (W);
- $P_{d.max}$ - AVR maximum power (W);
- $U_{p.n}$ - nominal mains voltage (V);
- $U_{p.min}$ - minimum network voltage (V);
- $U_{p.max}$ - voltage of the wireless communication network (V);
- $F_m$ - mains voltage frequency (Hz);
- $F_{pwm}$ - PWM frequency (pulse width modulation) (Hz);
- $U_{d.n}$ - nominal DC link voltage (V);
- $I_{d.n}$ - peak value of constant load (A);
\( K_h \) - harmonic phase current harmonics in nominal mode (PU);

\( \mu_0 = 4 \cdot \pi \cdot 10^{-7} \) - magnetic constant (GN / m);

The proposed method for calculating the parameters of buffer reactors is recursive and involves several stages.

2. **Determination of the required inductance of buffer reactors**

The inductance value of the reactors is calculated on the basis of the specified harmonic coefficient of the network currents. For this, the rated phase current is calculated:

\[
I_{p,n} = \frac{P_{d,n}}{3 \cdot U_{p,n}}; \tag{1}
\]

maximum phase current:

\[
I_{p,max} = \frac{P_{d,max}}{3 \cdot U_{p,min}}; \tag{2}
\]

peak phase current:

\[
I_{p,n} = \frac{I_{d,dc} \cdot U_{d,n}}{3 \cdot U_{p,min}}. \tag{3}
\]

To calculate the required inductance of network reactors, it is necessary to obtain the spectral composition of the voltages applied to the reactors. Since the harmonic composition of a given voltage depends on a variety of parameters (type of PWM, modulation depth, etc.) varying in different modes, conducting an analytical analysis is time consuming and impractical. It seems more effective to use the method of mathematical modeling. In the first approximation, the required value of reactor inductance can be obtained as:

\[
L = \frac{U_{d,n}}{6 \cdot \pi \cdot F_{\text{PWM}} \cdot \Delta I_p}, \tag{4}
\]

where, neglecting higher harmonics:

\[
\Delta I_p = K_h \cdot I_{p,n} \cdot \sqrt{2} \tag{5}
\]

the amplitude of the PWM harmonic current.

Then this value of inductance is refined according to the simulation results.

The constructive stage of the calculation of buffer chokes will be omitted due to its massiveness.

3. **Calculation of parameters and selection of a smoothing capacitor**

The calculation of parameters and the selection of a smoothing capacitor is made on the basis of the following data:

- \( K_U \) - the amplitude of the pulsations of the rectified voltage (pu);
- \( I_{p,n} \) - nominal phase mains current (A);
- \( I_{p,max} \) - maximum phase mains current (A);
- \( F_m \) - mains voltage frequency (Hz);
- \( F_{\text{PWM}} \) - PWM frequency (Hz);
- \( U_{d,n} \) - DC link voltage nominal (V);

The calculation of the capacitance value for a given ripple level of the rectified voltage is based on the following assumption. Since the PWM frequency is much higher than the frequency of the first
harmonic of the network currents and the currents consumed from the network are close to sinusoidal, we assume the network currents to be constant at the PWM interval [14].

The change in voltage on a capacitor during the PWM interval is defined as:

$$\Delta U_{d_{\text{pwm}}} = \frac{I_{\text{c,a}} T_{p}}{C_{d}},$$

(6)

where $I_{\text{c,a}}$ is the average capacitor current for the PWM interval;

$T_{p}$ – pulse repetition period, in the mode of symmetric PWM, $T_{p} = 0.5 T_{\text{pwm}}$.

The average value of the output current AVR on the PWM interval in the nominal mode can be determined as follows:

$$I_{a,a} = I_{p,n} M \frac{3}{2\sqrt{2}} \cos(\varphi_{l}) \text{ or } I_{a,a} = \frac{P_{d}}{U_{d}}.$$

Since the load of the designed AVR is an autonomous voltage inverter, also operating in the PWM mode, we assume that at certain PWM intervals there may be cases when the load current is zero. Then the maximum possible average value of the capacitor current with a modified symmetric sinusoidal or vector PWM is:

$$I_{\text{c,a,max}} = I_{a,a,max} = \frac{I_{p,n}}{\sqrt{2}} \sqrt{3}$$

(7)

From equations (6) and (7) we determine the required value of the capacitance of the capacitor on the basis of a given value of ripple:

$$C_{d} = \frac{I_{p,n} T_{\text{pwm}} \sqrt{3}}{\Delta U_{d_{\text{pwm}}}} \sqrt{2}$$

(8)

To select the type of capacitor of the DC link and the calculation of the reliability indices, the determination of temperature conditions is required. Capacitor heat loss power:

$$P_{C} = P_{R} + P_{D}$$

(9)

includes two components. Power loss on active resistance of capacitor conductors:

$$P_{R} = I_{C}^{2} R_{C}$$

(10)

and dielectric loss power:

$$P_{D} = U_{AC}^{2} \pi F_{AC} C \tan \delta$$

(11)

where

$I_{C}$ – effective current value of the capacitor;

$R_{C}$ – active resistance of the capacitor circuit;

$U_{AC}$ – effective value of the variable component of the voltage of the capacitor;

$F_{AC} = F_{\text{pwm}}$ – the frequency of the variable component of the capacitor voltage;

$tg\delta$ – dielectric loss tangent.
The effective value of the variable component of the output current ABH is calculated by the following formula:

\[
I_c = I_{\phi u} \left[ M \left( \frac{\sqrt{3}}{2\pi} + \left( \frac{2\sqrt{3}}{\pi} - \frac{9}{8} M \right) \cos^2 (\phi_1) \right) \right]^{1/2}
\]  

The effective value of the variable component of the capacitor voltage is approximately defined as:

\[
U_{AC} \approx \frac{\Delta U_{d \text{ RMS}}}{2\sqrt{2}}
\]

The internal capacitor temperature is calculated as:

\[
T_C = T_o + P_t R_{CT} \quad (K)
\]

where \( T_o \) - ambient temperature (K);
\( R_{CT} \) – thermal resistance capacitor-environment (K / W).

4. Research results and conclusions

The above method takes into account the variable component of the capacitor current generated only by the AVR, the load current is assumed to be constant. To obtain the optimal solution for the frequency converter as a whole, it is necessary to analyze the total charging current of the capacitor created by both the rectifier and the inverter [15].

By calculating the inductance of the buffer chokes and the capacitance of the capacitor, we obtain the values for the calculated LCL filter.

Next, we will build models in the Matlab Simulink package for converters with L and LCL filters, and compare the obtained energy efficiency indicators.

As a result of the simulation, the results obtained in Table 1 were obtained. It is clear from these results that the nonlinear distortion coefficients for current and voltage, when using the LCL filter, are lower than in the case of using the L filter.

| Converters             | Efficiency | cos\( \phi \) | THD(I),% | THD(U),% |
|-----------------------|------------|---------------|----------|----------|
| Converter with L-filters | 0,96       | ≈1           | 7        | 5        |
| Converter with LCL-filters | 0,98       | 1            | 5        | 3        |

Figures 1 and 2 show waveforms of currents and voltages for the cases of using the L-filter and LCL-filter, respectively.

**Figure 1** Current waveform for the case of using L-filter.
From the above, we can draw the following conclusions: firstly, the installation of the LCL filter reduces the likelihood of resonance between the power supply and the frequency converter; secondly, it reduces harmonic distortion, and thus contributes to the energy efficiency of the electric drive. Therefore, we can conclude that the installation of an additional input filter can be an option to increase the energy efficiency of electric drive systems.

5. References

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