Simulation of Frequency Converters Operation in Industrial Power Net

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Introduction

Induction motors are widely used in various industry enterprises. Its construction is simple, motor work reliability is high, costs is not high. Main problem of using induction motors is it's speed regulation. Frequency converters are widely used for this purpose in industry enterprises. Inverters with semiconductor based power switches in this output generates voltage with different from power net frequency. Voltage and frequency is changing according to necessary induction motor speed and load. But in this time frequency converter takes from power net non sinusoidal current, with may cause voltage non sinusoid in power net and to disturb normal job of other customers. Level of voltage distortion depends from frequency inverter parameters and power net impedance. Percent of motors with frequency converters in industry is growing, and power quality problem became actually at present. Rectifier of frequency converter cause main influence to current harmonic distortion (Fig. 1), because it's current from power network is non sinusoid.

The traditional solutions for current harmonics reducing are as follows: line chokes and DC chokes (Fig. 1). Choke is inductance; voltage drop in choke for nominal current is about 3-5 %. These solutions typically reduce the THDI (total harmonic distortion of current) to a level less than 48 %. If a choke is not added, the THDI is generally between 60 and 130 % [1]. Depending on their type, external or internal chokes are most often offered as an option and have the following disadvantages: increased cost, installation time, overall size, drive losses with a DC choke.

In order to overcome these disadvantages, for example, the ALTIVAR 21 drive integrates new reduced capacitor technology [1]. This technology makes it possible to obtain a THDI less than 35 % without having to add a choke, offering the following advantages: optimized technology through the reduction of current harmonics by decreasing the value of filter capacitors [1]. Method advance is greater reduction of current harmonics compared with traditional solutions: line chokes and DC chokes.
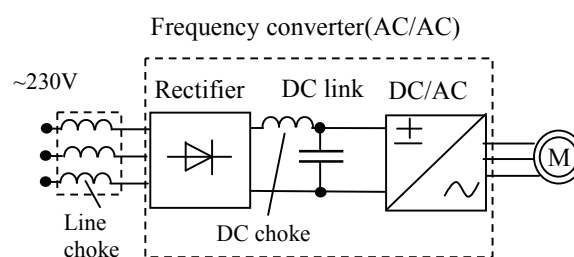

Fig. 1. Typical frequency converter structure

According to [2] value of DC link capacitor depends upon power of frequency converter and is about 80–160 μF/kW. But if this capacity there is smaller, a new problem begins. Small DC link capacitor causes large variations in the DC link voltage on inverter commutation frequency [3]. Due to these reasons, the most promising substitute of small capacitor has been the metalized polypropylene (MPPF) capacitor [3].

But in these and other research all attention is about frequency converter job and no attention to harmonic voltage level in industry enterprise network. So it is necessary to simulate industry enterprise power network model with frequency converter and after that estimate voltage distortion level, changing frequency converter load and DC link capacitor value.

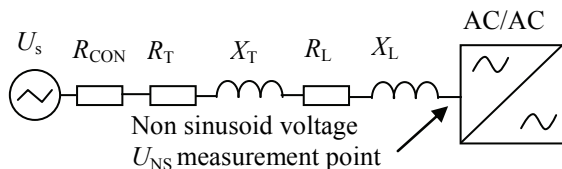## Industry enterprise power net model

In industry enterprise power network frequency converters usually are connected to 0,4 kV bus. Bus is

connected to 6 or 10 kV power distribution network over 10/0,4kV transformer. Frequency converter is connected to the busses by cable line.
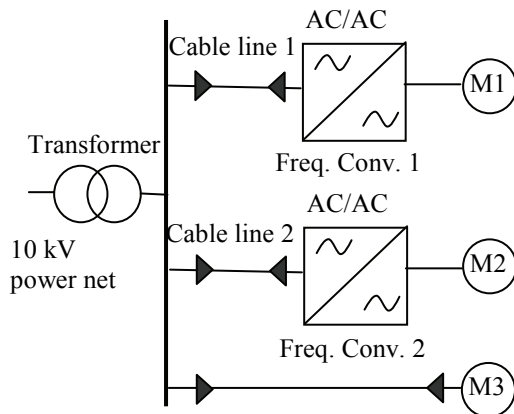
Fig. 2. Typical electric power net of industry enterprise with frequency converters

According [4], harmonic distribution in power network is calculating according diagram in Fig. 3.

Fig. 3. Electric scheme of power net model, used for higher voltage harmonic level calculation in industry enterprise power net

Later it is necessary to choose structure and parameters for industrial power net in Fig. 2 (Tables 1, 2).

Table 1. Values of transformer parameters

Transfomer power, kV·A	R_T, Ω	X_T, Ω	L_T, mH
100	0,036	0,065	0,207
250	0,017	0,025	0,079
400	0,005	0,017	0,054
630	0,003	0,013	0,041
1000	0,0019	0,0085	0,027

Table 2. Values of cable line parameters

| Cable cross-section, mm²	Cable load, kV·A	Current, A	R_L, Ω/km	X_L, Ω/km	L_L, mH/km
2,5	12	18	12,5	0,104	0,33
16	53	78	2,3	0,09	0,29
25	68	100	1,5	0,087	0,28
50	102	150	0,77	0,087	0,28
95	150	220	0,39	0,084	0,27
150	198	290	0,2	0,081	0,26

Length of cable line is usually small, not more than 100 meters length and its resistance and inductance is necessary to estimate together with transformer parameters, if frequency converter power is big. Typical transformer of 100–1000 kV·A has significant inductance,

comparing with its resistance, necessary to estimate this in scheme. Parameters of transformer are calculated to 0,4 kV voltage level. Resistance R_{con} is total resistance of all connections between elements of low voltage net and it's value is 0,015 – 0,03 Ω in case of short-circuit current calculation. In our situation we'll use value of R_{con} equal to 5 mΩ, because of electric arc absence. Influence of this resistance is significant, when network parameters with big power transformer and short cable lines are calculating.

Numerical integration rectifier model and its current from electric supply net

It is necessary to say that authors of this article have a deal with modeling of frequency converters input currents for some time [5, 6], but previous models have several disadvantages comparing with model, designed here.

Numerical integration rectifier (NIR) model (Fig. 4) consists of six ideal diodes, capacitor network resistance and inductance and load resistor. Different current harmonic level in supply net is modeled by changing R, L, and C values.
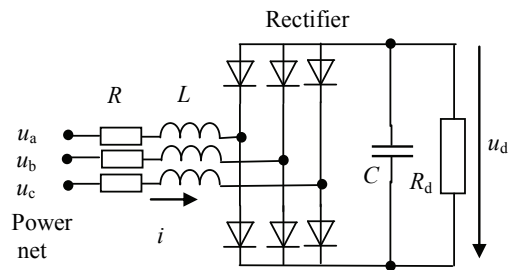
Fig. 4. Frequency converter rectifier schematic, used for input current modeling

Rectifier is simulated with software MATLAB, using specially written software. It is modified version of software, described in [5]. Operating of converter is described using series of small time intervals transients method, by calculation capacitor charging or discharging in fixed current in period of one interval. Time interval Δt is choosen equal 1μs. Main difference between this model and model in [5] is ability to estimate inductance of power net (X_T, and X_L in Fig. 3, in [5] only R was estimated), this ability rapidly change results of simulating. Main advantages of NIR model comparing with model, described in [6], are simpler algorithm and ability to calculate input currents in continuous mode of rectifier.

Resultant wiring diagrams are used in model for calculation of currents and voltages (Fig. 5). Three wiring diagrams, depending upon input voltages phases and levels are used for calculation.

Meanings of voltages in Fig. 5 are voltages of power net at moment t. U_1 – maximum source voltage from all phases in this moment, U_2 – minimum source voltage from all phases in this moment), U_3 – voltage between U_1 and U_2. These meanings are determined in each time step of calculation time. Currents i_1, i_2 and i_3 in wiring diagram are determined in same way like voltages.

Current in wiring diagrams is calculated according Ohm's law. For example, equations for one of wiring diagram in Fig. 5 (Fig. 5, a) look as follows:

$$\begin{cases} U_1 - i_1R - L\dfrac{\mathrm{d}i_1}{\mathrm{d}t} - u_d - L(\dfrac{\mathrm{d}i_1}{\mathrm{d}t} + \dfrac{\mathrm{d}i_3}{\mathrm{d}t}) - (i_1 + i_3)R = U_2; \\ U_3 - i_3R - L\dfrac{\mathrm{d}i_3}{\mathrm{d}t} - u_d - L(\dfrac{\mathrm{d}i_1}{\mathrm{d}t} + \dfrac{\mathrm{d}i_3}{\mathrm{d}t}) - (i_1 + i_3)R = U_2 \; ; (1) \\ i_2 = i_1 + i_3 \,. \end{cases}$$

It is possible to calculate currents derivatives from (1) expression:

$$\begin{cases} U_1 - i_1R - u_d - (i_1 + i_3)R - U_2 = CN1; \\ U_3 - i_3R - u_d - (i_1 + i_3)R - U_2 = CN3; \\ \dfrac{\mathrm{d}i_3}{\mathrm{d}t} = \dfrac{2 \cdot CN3 - CN1}{3L}; \\ \dfrac{\mathrm{d}i_1}{\mathrm{d}t} = \dfrac{2 \cdot CN3}{L} - 2\dfrac{\mathrm{d}i_3}{\mathrm{d}t}. \end{cases} \qquad (2)$$
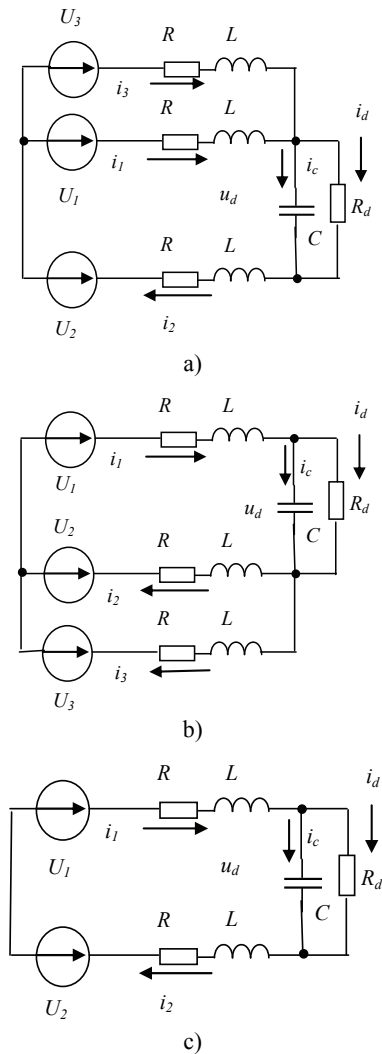

a)

b)

c)

Fig. 5. Three possible variants of wiring diagram, used for frequency converter currents and voltages calculation

This algorithm (Fig. 6) works very stable in wide interval possible meanings of L, R and C, so it is easy to simulate various situations in power net.
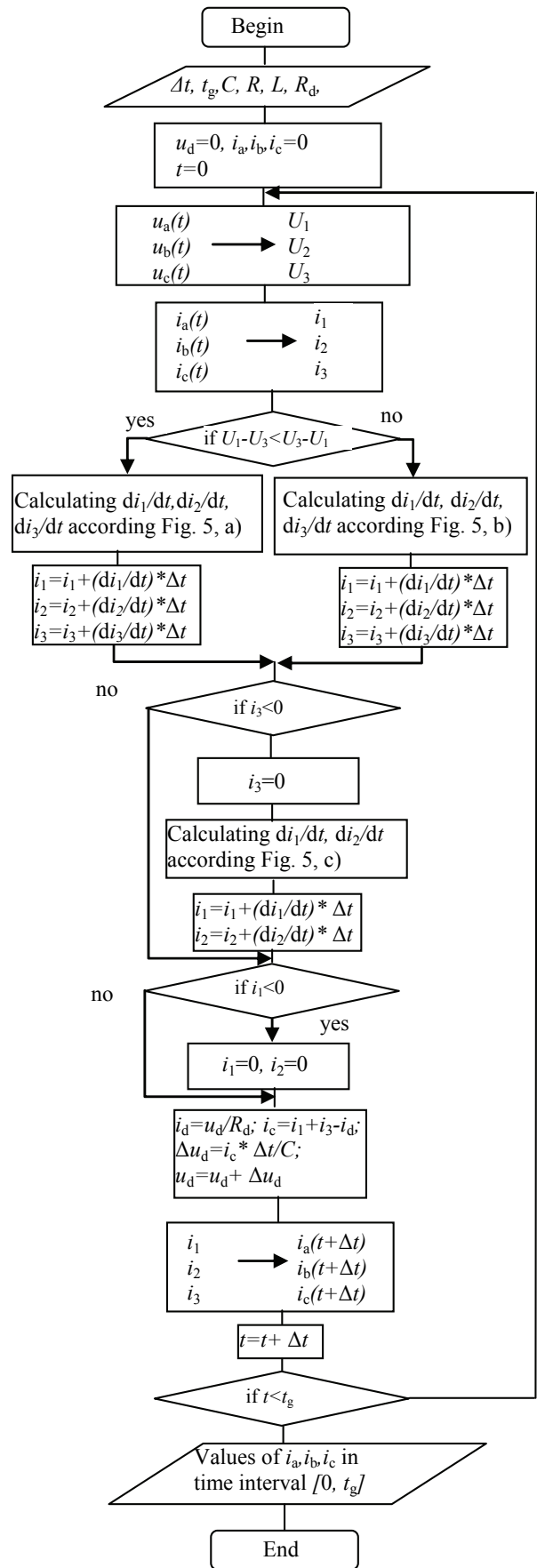

Fig. 6. Algorithm of numeric integration rectifier model

MatLab/Simulink model for frequency convertor input currents

For verification of modeling results obtained by using of the designed NIR model, MatLab/Simulink model has been elaborated. It's Simulink part (Fig. 8) was formed in correspondence to frequency converter rectifier schematic (Fig. 4) and consists of standard blocks, simulating working of basic frequency converter and power net circuits components, such as uncontrolled diode rectifier, DC-link capacitor C, resistor R_d (represents active load of motor), three phase power supply source ideal voltages U_a, U_b and U_c, inductance L and resistance R. Main results of simulation are curves of input converter currents and power supply voltages.

The basic particularity of MatLab/Simulink model is the method of R_d resistance revision during simulation process.

To use the designed model it is required to know the value of resistance R_d, which can be calculated by following expression

$$R_d = \frac{U_d^2}{P_d}, \qquad (3)$$

here U_d – mean value of DC-link voltage; P_d – active power consumed by induction motor and voltage inverter.

If accepted that P_d is a constant parameter, then, using R_d obtained from (3), we'll get curve of DC-link voltage u_d with mean value U_d is not equal to the used in (3) because of influence not only of R_d but also C, L and R. The following calculation of R_d will give us another result in comparison with done first. So, to obtain correct results of simulation, it is necessary to do a series of modeling – iteration process with U_d and R_d recalculations on its every step. The number of iterations depends on given calculation accuracy δ. Thereby, in result of final calculation of model we'll receive the most correct curves of currents and voltages greatly corresponding to motor load mode, power supply system and converter parameters.

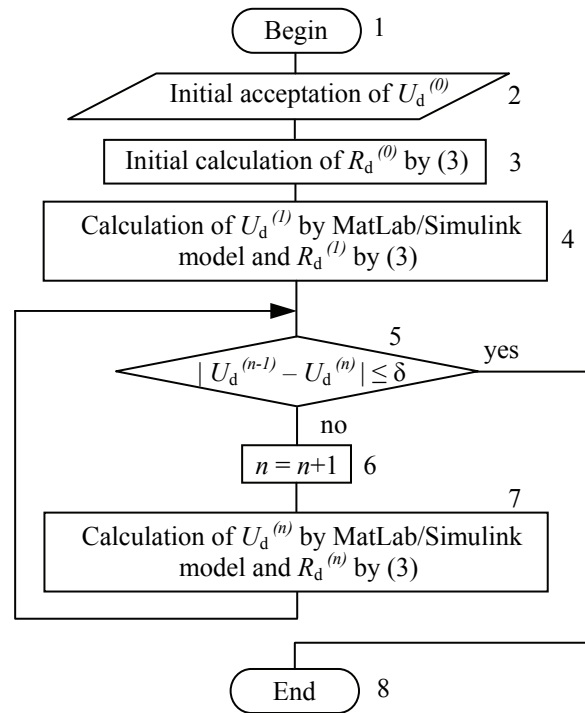Considered process can be described by the following algorithm (Fig. 9).

Fig. 8. Algorithm, illustrating iteration process of simulation

Initial mean value of DC-link voltage $U_d^{(0)}$ may be accepted near 535 V, which corresponds to amplitude of power supply line-to-line voltage with RMS of 380 V.

To realize algorithm shown on Fig. 8, in addition to Simulink part (Fig. 7) of MatLab/Simulink model two MatLab-functions were written. First function intended for calculation of initial approximation $R_d^{(0)}$ (block 3 on Fig. 9), and second – for further calculations of $R_d^{(n)}$ and mean value $U_d^{(n)}$ of DC-link voltage u_d curve, which transferred to MatLab workspace from Simulink part of model (blocks 4-7 on Fig. 8). Simulink part of model working inside the 4 and 7 blocks of algorithm, presented on Fig. 8.
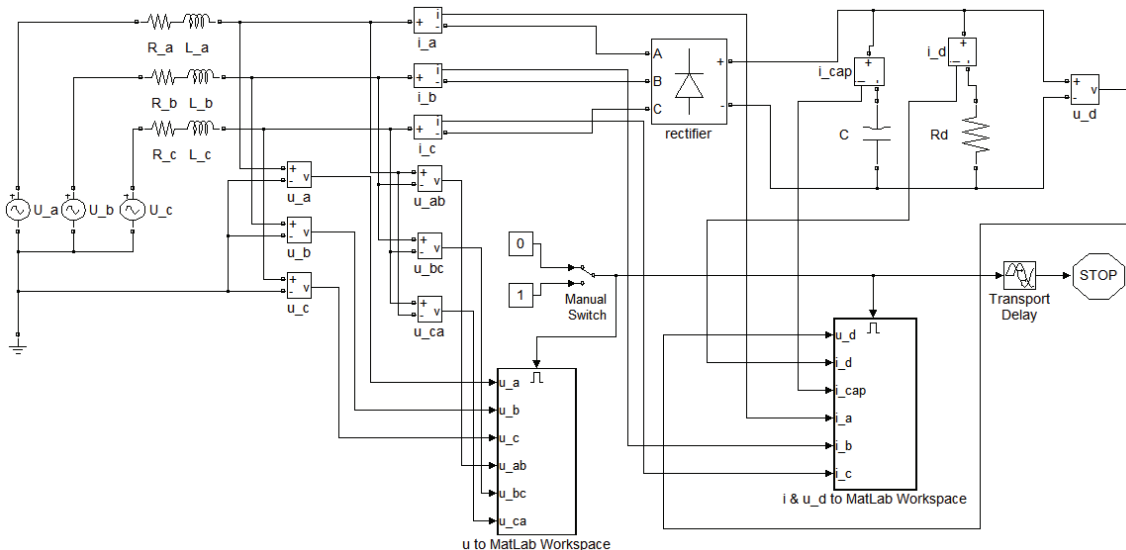

**Fig. 7.** Simulink part of MatLab/Simulink model for calculation of frequency convertor input currents

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Voltage harmonic level in power supply net calculated using NIR and MatLab/Simulink models

Using rectifier and network model in Fig. 3, 6 and 7 dependency of total voltage harmonic distortion level on rectifier load was calculated. Calculations were done using typical 630 kV·A 10/0,4 kV transformer parameters (Table 1). Such kind transformer is very often used in industry electric power supply nets. Connection of converter to power transformer was done by 100 m length cable of 95 mm^2 cross section (Table 2). Transformer was loaded by frequency converters with 20, 50, 100 and 200 µF/kW capacitor; its load was changed during simulation.

Results of calculation, obtained by using of both models were very similar each to other, which confirms their adequacy.
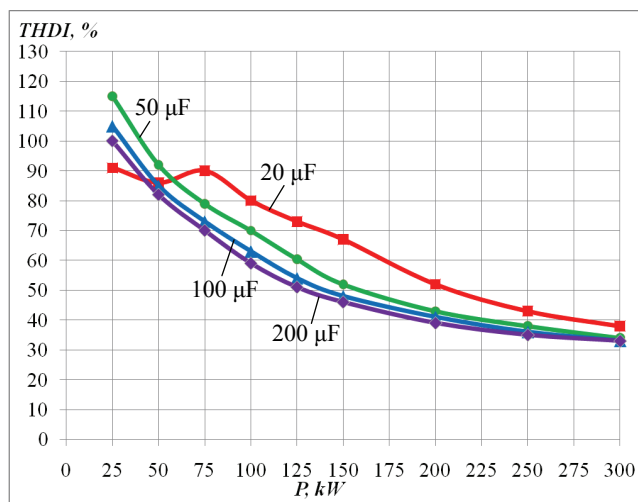
Fig. 9. Total current harmonic distortion (THDI) in power net with 630 kV·A 10/0,4 kV transformer, loaded by frequency converters with power P_{inv}
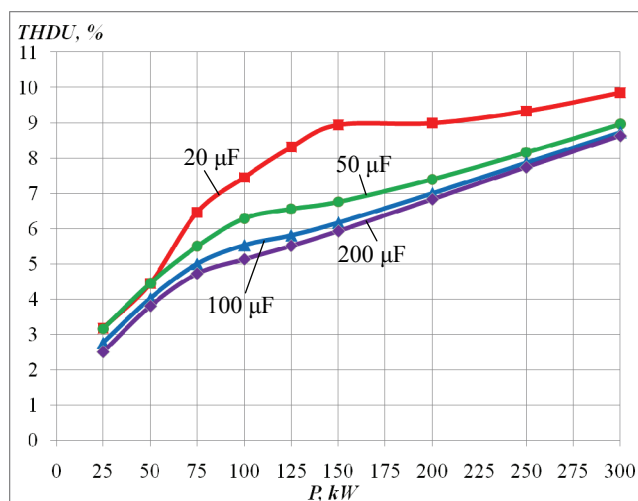

Fig. 10. Total voltage harmonic distortion (THDU) in power net with 630 kV·A 10/0,4 kV transformer, loaded by frequency converters with power P_{inv}

Dependencies in Fig. 9 shows that with rise of transformer load, consisting of frequency converters, THDI of input current is decreasing. Reason is influence of

transformer inductance to rectifier job; it is become significant when load of transformer is relatively big. When load of transformer reaches 48% (300 kW), THDI is about 34% and it's further decreasing becomes difficult. For this reason, using of line-chokes in case of great power frequency converters is unnecessary, because transformer inductance itself works like line-chokes.

Levels of THDI and THDU depends on capacitor value and is rising when it's value is decreasing. It is necessary to note that in [5] publication was done the opposite conclusion, but it is true only without estimation of network inductance.

However, low value of DC-link capacitor causes other problems. In Fig. 11 we can see that in mentioned case high-frequency oscillations in rectifier input currents occurs, and that phenomenon is the reason of unalike nature of 20 µF capacity case line in Fig. 9.
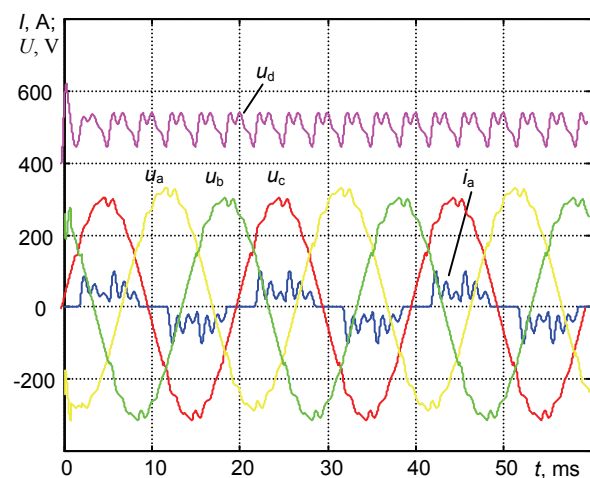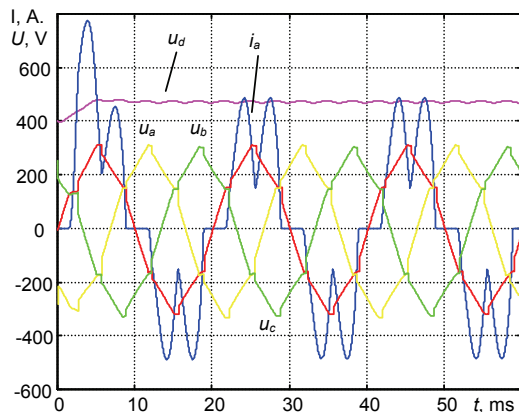

Fig. 11. Input current i_a, capacitor voltage u_d and input voltages u_a, u_b and u_c of 25 kW power rectifier with C=10 µF/kW, THDI= 60,2%, THDU= 1,40%
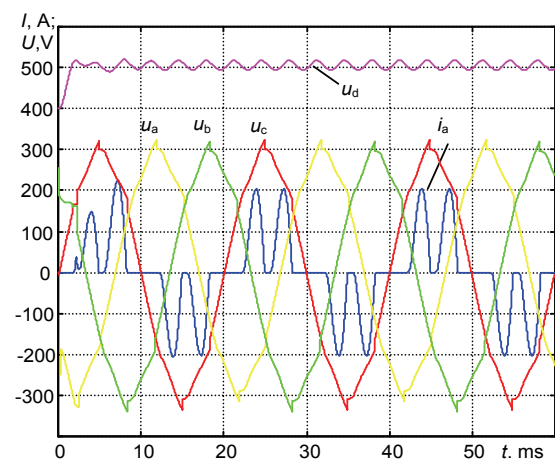
**Fig. 12.** Input current i_a, capacitor voltage u_d and input voltages u_a, u_b and u_c of 50 kW power rectifier with C=100 µF/kW, THDI= 85%, THDU= 3,9%

Fig. 12 shows a typical converter input current form when influence of power net inductance is not significant. In Fig. 13 there's other sample of rectifier work – power net inductance has the greater value. The curves of rectifier input currents, presented in Fig. 13, are very similar to

experimental curves of Mitsubishi frequency converter (Fig. 14).

Fig. 13. Input current i_a, capacitor voltage u_d and input voltages u_a, u_b and u_c of 200 kW power rectifier with C=100 µF/kW, THDI= 42%, THDU= 6,8%
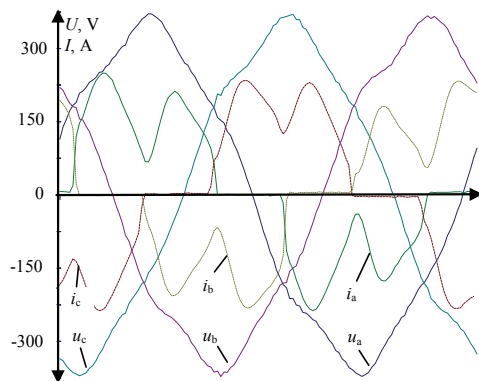
Fig. 14. Input currents and voltages, measured of 160 kW power Mitsubishi frequency converter (with 70 % of nominal load), connected to 630 kV·A transformer

According to result, presented in Fig. 10, it is possible to say, that transformer of 630 kV·A may be loaded of frequency converter with 250 kW power to not to exceed the allowed by [7] value of voltage THD, which is equal to 8%.

Conclusions

Parameters of electric power net cause the great influence on input current curves of frequency converter, especially if the converter power is significant.

Using of line-chokes, offered by manufacturers as an option to frequency converters for current THD decreasing, in case of great converter power is unnecessary, because transformer inductance itself works like line-choke.

To avoid total harmonic voltage distortions more than 8%, it is necessary to limit power of frequency converters, connected to power net transformer.

References

1. **Variable speed drives ALTIVAR 21 for 3 phase asynchronous motors from 0,75 to 75 kW.** – Catalogue, 2006. – 74 p. Online: www.schneider–electric.com.
2. **Dojkic S. Ž., Stockman K., Milanovic J.V., Desmet J. J. M., Belmans R.** Sensivity of AC adjustable speed drives to voltage sags and short interruptions // IEEE transactions on power delivery, 2005. – Vol. 20. – No. 1. – P. 220–223.
3. **Sarén H.** Analysis of the voltage source inverter with small DC–link capacitor (thesis for the degree of Doctor of Science). – Lappeenranta University of Technology, 2005. – 143 p.
4. **Arrillaga J., Watson N. R.** Power system harmonics. – Chichester: John Wiley & Sons, Ltd., 2003. – 399 p. http://dx.doi.org/10.1002/0470871229.
5. **Svinkunas G., Sabunaite D.** Higher harmonic of frequency converters in industrial power net. The 6th International Conference on Electrical and Control Technologies (ECT'2011). – Kaunas: Technologija, 2011. – P. 280–283.
6. **Firago B. I., Medvedev K. M., Pawlaczyk L.** Określenie prądów sieciowych układu falownik z MSI – silnik indukcyjny w przypadku niesymetrii napięć zasilających // Elektrotechnika – Prądy niesinusoidalne EPN 2006: materiały VIII Konferencji. – Szkoły, Łagów, Uniwersytet Zielonogórski, Zielona Góra, 2006. – P. 1–4.
7. **Voltage characteristics of electricity supplied by public distribution systems, Lithuanian standard EN 50160.** – Vilnius: Lithuanian standard department, 2001. – 17 p.

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Frequency converters, used for induction motors regulation, cause higher voltage harmonic in power net. Level of harmonic depends upon inverter and power net parameters; sometimes power net parameters make more influence for electric energy quality than frequency converter parameters. In this research some models of frequency converters were analyzed, comparing simulation results each with other and with real converter voltages and currents measurement results. Analysis of voltage harmonics in power nets with frequency inverters was done in this article, analyzing influence of power net parameters to power quality. Ill. 14, bibl. 7, tabl. 2 (in English; abstracts in English and Lithuanian).

G. Svinkūnas, K. Medvedev. Dažnio keitiklių darbo modeliavimas pramoniniame elektros tinkle // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 1(117). – P. 65–70.

Dažnio keitikliai, naudojami asinchroniniams varikliams valdyti, sukelia aukštesniąsias harmonikas įmonės elektros tinkle. Harmonikų lygis priklauso nuo dažnio keitiklio ir elektros tinklo parametrų, o kartais elektros tinklo parametrai turi didesnę įtaką įtampos kokybei negu dažnio keitiklio elektriniai parametrai. Išnagrinėti keli dažnio keitiklių modeliai, modeliavimas atliekamas lyginant tarpusavyje šių keitiklių veiką, taip pat naudojamasi eksperimentiniais dažnio keitiklio darbo parametrų matavimo rezultatais. Elektros tinklo įtampos aukštesniųjų harmonikų lygis ištirtas priklausomai nuo dažnio keitiklių ir juos maitinančio transformatoriaus galių santykio. Il. 14, bibl. 7, lent. 2 (anglų kalba; santraukos anglų ir lietuvių k.).