The frequency converter with autonomous inverter output power flow research for various working modes

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Abstract. Energy characteristics of electric drives with frequency converters are generally determined with unit working mode and effectiveness of autonomous inverter (AI) operating, which set the voltage level for the actuating machines windings. Also, the structure of output power flow, consumed by actuating engine has been determined in dependence with AI mode. These facts explain the actuality of researches in the field of semiconductor converter working mode, it output power and control methods. The two methods of autonomous inverter operating have been investigated: pulse-width modulation and phase modulation. The paper shows that during pulse-modulation mode voltage distortion factor decreases, but the current distortion factor increases. Output phase current and voltage hodographs show that resultant vectors of this coordinates during PWM mode moves with higher smoothness, but in phase modulation mode it moves in steps. Power distortion for PWM mode is higher, active power share in the total power structure decrease. It leads to higher energy consumption during AI operating with an equal load. For the power consumption decreasing and higher energy efficiency, it recommended using energy saving control algorithms, providing smooth resultant output voltage hodograph shifting and higher voltage distortion factor value.

1. Introduction

Power supply and control of electrical machines and providing set working modes of actuating mechanism in modern electrical drives (ED) accomplished with semiconductor frequency converter (FC). Electric drives with FC can have a various structure with various algorithmic providing of a control system.

Frequency converter structure and control system algorithms determine the energy efficiency of the electrical drive, level of electromagnetic compatibility and safety.

FC has a variable structure. Mostly, for frequency converter use the two-section model, which include a rectifier and autonomous inverter.

In electric drives with 500-650 kW engines, generally, a two-leveled autonomous inverter is used. Block diagram of an electrical drive with frequency converter is shown in Figure1.

The two-leveled FC principle of operation bases on twice repeated electrical energy conversion. Semiconductor rectifier converts alternative voltage with industrial frequency from the power supply system (PSS) to direct voltage. After that, the direct voltage with autonomous inverter converts to alternative with set amplitude and frequency value, required for providing working modes of actuating motor and actuating mechanism (AM).

Energy characteristics of electric drive with frequency converter are extensively determined with working mode and effectiveness of autonomous inverter operating, which form set voltage for the
actuating machines windings. Also, the structure of output power flow which actuating engine consume is determined with AI working mode. This fact explains the actuality of researches in the field of inverting semiconductor converter working mode, output power structure and control methods [1-12]. The two methods of autonomous inverter operating are researched: pulse-width modulation and phase modulation.

![Figure 1. An electric drive with frequency converter and 2-leveled autonomous inverter block diagram.](image1)

**Figure 2.** Autonomous inverter and asynchronous engine equivalent scheme.

### 2. Working modes and control methods for autonomous inverter

#### 2.1. The inverter working modes

Autonomous inverter operates in 3 modes: pulse width modulation mode; overmodulation mode; phase modulation mode. Various modulation algorithms can be used for providing various autonomous inverter working modes. Mostly, in practice the AI operates in pulse width modulation mode. At that, from the theoretical point of view for critical energy parameters value analysis the phase modulation is more convenient. Overmodulation mode is unwanted. Consequently, the paper provides research of the autonomous inverter energy characteristics for pulse width and phase modulation modes.

The autonomous inverter equivalent scheme is shown in Figure 2. This scheme shows ideal semiconductor switches (K1, K2, K3, K4, K5, K6), actuating engine windings – active-inductive elements in output engine phases (R_{dr}, L_{dr}), electromotive force sources (EMF) (E_{dr}).

#### 2.2. Pulse width modulation mode

During autonomous inverter operating in pulse width modulation algorithms the load on the alternative current side is switching to positive or to negative contact of input capacitor, switching off or short circuited.

The pulse width modulation system for this mode is shown in Figure 3.

The control signals (UA, UB, UC) are voltages, which should be formed on the 3-phase load with autonomous inverter and then to be applied to system input. Carrier signal (Us) also applies to the system output and constitute voltage, which determines the switching periods for autonomous inverter semiconductor switches.

Usually, carrier and control signals amplitude is regulated as follows:


\[
U_{\text{control}}^A = [0; 1], \quad U_{\text{control}}^B = [0; 1], \quad U_{\text{control}}^C = [0; 1] \quad \text{(1)}
\]

\[
U_{\text{carr}}^A = [0; 1] \quad \text{(2)}
\]

\[
S_1 = \begin{cases} 
1, & \text{if } U_{\text{control}}^A > U_{\text{carr}}^A \\
0, & \text{if } U_{\text{control}}^A < U_{\text{carr}}^A 
\end{cases}, \quad S_2 = -S_1
\]

\[
S_3 = \begin{cases} 
1, & \text{if } U_{\text{control}}^B > U_{\text{carr}}^B \\
0, & \text{if } U_{\text{control}}^B < U_{\text{carr}}^B 
\end{cases}, \quad S_4 = -S_3
\]

\[
S_5 = \begin{cases} 
1, & \text{if } U_{\text{control}}^C > U_{\text{carr}}^C \\
0, & \text{if } U_{\text{control}}^C < U_{\text{carr}}^C 
\end{cases}, \quad S_6 = -S_5
\]

The output voltage of AI has a high frequency impulse sequence form. When control impulse has a sinusoidal form, as it shown in Figure 4, then AI forms voltages, symmetrical relatively control signal peaks, and average values on the carrier frequency period changes with sinusoidal form too.

Output AI phase voltage forms as follows:

\[
U_{\text{phase}}^A = \frac{2S_1 - S_2 - S_3}{3}, \quad U_{\text{phase}}^B = \frac{-S_1 + 2S_2 - S_3 - S_5}{3}, \quad U_{\text{phase}}^C = \frac{-S_1 - S_2 + S_3}{3} \quad \text{(4)}
\]

2.3. Phase modulation mode

After considerable control signal increasing relative to carrier signal amplitude

\[
U_{\text{control}}^A >> U_S, \quad U_{\text{control}}^B >> U_S, \quad U_{\text{control}}^C >> U_S \quad \text{(5)}
\]

Operating and amplitude value of AI output phase voltage, working in phase modulation mode:
Operating and amplitude value of phase voltage first harmonic on the AI output, working in phase modulation mode calculates as:

\[ U_{A(l)}^{\text{phase}} = U_{B(l)}^{\text{phase}} = U_{C(l)}^{\text{phase}} = \frac{2}{\pi} \sqrt{2} U_{dc} \]

\[ U_{A(l)}^{\text{max}} = U_{B(l)}^{\text{max}} = U_{C(l)}^{\text{max}} = \frac{2}{\pi} U_{dc} \]  \hspace{1cm} (6)

Output voltage distortion factor for 2-levelled autonomous inverter evaluated as follows:

\[ K_{U} = \frac{U_{A(l)}^{\text{phase}}}{U_{A(l)}^{\text{max}}} = \frac{\frac{2}{\pi} \sqrt{2} U_{dc}}{\frac{2}{\pi} U_{dc}} = \frac{3}{\pi} = 0.955 \]  \hspace{1cm} (7)

Output current distortion factor for autonomous inverter within the accuracy of the thousands is assumed to be 1:

\[ K_{I} = 1 \]  \hspace{1cm} (9)

The displacement factor of actuating engine can be calculated as:

\[ \chi_{dr} = \cos \phi_{dr}^{(1)} = \frac{p_{dr}^{(1)}}{s_{dr}^{(1)}} \]  \hspace{1cm} (10)

The power factor of actuating machine, which is switched to AI as a load evaluates:

\[ \lambda = K_{U} K_{I} \chi_{dr}^{(1)} = \frac{3}{\pi} \frac{P_{dr}^{(1)}}{S_{dr}^{(1)}} \]  \hspace{1cm} (11)
3. Output autonomous inverter voltages and currents

Figure 5 show oscillograms of output phase currents and voltages for phase A switching mode. Figure 6 show the oscillograms of the output power for phase switching and pulse-width modulation, respectively.

Figure 7 (a) and Figure 7 (b) shows the hodographs of the output currents of the AI, output phase and line voltages for phase switching mode and pulse width modulation, respectively.

Table I shows the oscillograms analysis.

Conclusion

The resultant oscillograms show that during pulse-modulation mode operating the voltage distortion factor decreases, but the current distortion factor increases.

Output phase current and voltage hodographs show that resultant vectors of this coordinates during PWM mode moves with higher smoothness, but in phase modulation mode it moves in steps.

Power distortion for PWM mode is higher, active power share in the full power structure decrease. It leads to higher energy consumption during AI operating with an equal load.

For the power consumption decreasing and higher energy efficiency, it needs to use energy saving control algorithms, providing smooth resultant output voltage hodograph shifting and higher voltage distortion factor value.

Table 1. Autonomous inverter energy characteristics analysis.

| Characteristic                  | Value                     |
|--------------------------------|---------------------------|
|                                | Phase switching mode      | Pulse-width modulation   |
| Phase voltage, pu              | 0.4714                    | 0.4286                   |
| Phase voltage first harmonic, pu | 0.4502                    | 0.3535                   |
| Voltage distortion factor, pu  | 0.9549                    | 0.8247                   |
| Phase current, pu              | 2.9900                    | 2.3350                   |
| Phase current first harmonic, pu | 2.9634                    | 2.3270                   |
| Current distortion factor, pu  | 0.9912                    | 0.9968                   |
| Power distortion factor, pu    | 0.9465                    | 0.8221                   |
| Displacement factor, pu        | 0.9450                    | 0.9540                   |
| Efficiency factor, pu          | 0.9029                    | 0.7843                   |
| Full power, pu                 | 1.4090                    | 1.0000                   |
| Active power, pu               | 1.2730                    | 0.7848                   |
| Reactive power, pu             | 0.4001                    | 0.2466                   |
| Distortion power, pu           | 0.4549                    | 0.5697                   |

Figure 5. Autonomous inverter output voltage for phase modulation mode.
Figure 6. Output AI total power for various operating modes.

Figure 7. Output current travel time curves, phase and line voltage of the inverter in autonomous phase modulation mode.

References

[1] Chandorkar M, C, Divan D. M and Adapa R 1993 Control of parallel connected inverters in standalone AC supply systems IEEE Transactions on Industry Applications 29(1) 136–43

[2] Prasanna K I 2013 Development of Fuzzy Control Scheme with UPFCs for damping of oscillation in multi machine integrated power systems IJERA 1(2) 230–4

[3] Patel R, Bhatti T S, Kothari D P 2002 MATLAB/Simulink based Transient Stability Analysis of Multi-Machine Power System, International Journal of Electric Engineering Education 39(4) 320–33

[4] Frolov V Ya and Ivanov D V 2018 A two-dimensional axisymmetric model of an AC arc Proceedings of the 2018 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering ElConRus 430–2

[5] Semykina I and Tarnetskaya A 2018 Magnet synchronous machine of mine belt conveyor gearless drum-motor E3S Web of Conferences 41 03014

[6] Frolov V Y, Bystrov A V and Neelov A A 2017 Imitating model of a microprocessor trip unit of a circuit breaker Proceedings of the 2017 IEEE Russia Section Young Researchers in
Electrical and Electronic Engineering Conference, ElConRus 7910686 838–40

[7] Pankov I A and Frolov V Ya 2017 Increase of electric power quality in autonomous electric power systems Journal of Mining Institute 227 563–8

[8] Zhukovskiy Y L, Starshaia V V, Batueva D E and Buldysko A D 2019 Analysis of technological changes in integrated intelligent power supply systems Innovation-Based Development of the Mineral Resources Sector: Challenges and Prospects 11th Conference of the Russian-German Raw Materials 249–58

[9] Zhukovskiy Y L, Koteleva N I, Kovalchuk M S 2019 Development of course feedback questionnaires of continuing professional education in the mining industry. Innovation-Based Development of the Mineral Resources Sector: Challenges and Prospects - 11th conference of the Russian-German Raw Materials 589–97

[10] Kolesnichenko S V and Afanas’eva O V 2018 Theoretical aspects of the technical level estimation of electrical engineering complexes Zapiski Gornogo Instituta / Journal of Mining Institute 230 167

[11] Zhukovskiy Y and Koteleva N 2018 Development of augmented reality system for servicing electromechanical equipment Journal of Physics: Conference Series 1015(4)

[12] Alekseev V V, Vershinin V I and Vasi'ev B Yu 2016 Definition of parameters of vectors of magnetic flux in electric drives with the vector control Zapiski Gornogo Instituta / Journal of Mining Institute 196 222–5