Effect of different methods of pulse width modulation on power losses in an induction motor

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Abstract. We consider the calculation of modulation power losses in a system "induction motor–inverter" for various pulse width modulation (PWM) methods of the supply voltage. Presented values of modulation power losses are the result of modeling a system "DC link - two-level three-phase voltage inverter - induction motor - load". In this study the power losses in a system "induction motor - inverter" are computed, as well as losses caused by higher harmonics of PWM supply voltage, followed by definition of active power consumed by the DC link for a specified value mechanical power on the induction motor shaft. Mechanical power was determined by the rotation speed and the torque on the motor shaft in various quasi-sinusoidal supply voltage PWM modes. These calculations reveal the best coefficient of performance (COP) in a system of a variable frequency drive (VFD) with independent voltage inverter controlled by induction motor PWM.

1. Introduction.
Energy conservation is one of the priorities of the state policy aimed at ensuring the state's energy needs given the shortage of energy resources and restrictions on new generating capacities developing. The volumes of energy resources consumption in the organizations should be reduced by 15%. By the energy strategy of Russia up to 2030 energy conservation reserves estimated at 40%, to be achieved through integrated solutions of various kinds. Achieving set by the Russian government energy efficiency and further reduction in power consumption requires innovative approaches to the implementation of energy saving systems. Measures to improve the quality and energy saving through the use of power electronics are the priorities in the electrical engineering and related to such a scientific and technical direction as the VFD with a sinusoidal motor current [1]. In this regard, an urgent task in the power engineering is a simulation of an induction motor using a modified PWM methods.

2. An Experimental section.
In terms of PWM supply voltage higher harmonics generate additional losses in an induction motor [2]. To reduce them using classical PWM, the frequency of the pulse modulation signal is increased. However, this increases losses in the inverter. In the classical algorithm of the sinusoidal PWM the reference voltage of the triangular form is given by the following equation (1) [1, 3]

\[ U_{ref} = A_{ref} \arcsin[\sin(k_{ref} \omega t)] \]  

(1)

where \( A_{ref} \), \( k_{ref} \) are for the controllable amplitude and the corresponding degree of control over the reference voltage frequency.
Let’s consider the modified PWM methods [4, 5, 6, 7] that reduce loss in an induction motor and the switching loss.

For the modified PWM methods [5, 7] with a predetermined reference periodic signal of different freeform (triangle, sawtooth, trapezoidal, sinusoidal) we form the following analytical expression (2).

\[
U_{\text{ref}} = \begin{cases} 
U_{\text{cont}} < a, A_{\text{ref}} \arcsin[k_{\text{ref}} \omega_s t] \\
U_{\text{cont}} > a, A_{\text{ref}} \arcsin[k_{\text{ref}} \omega_s t] 
\end{cases}
\]

(2)

where \(U_{\text{cont}}\) is for the control signal value (modulated sinusoidal signal); \(a\) is for the modulation function value at the transition point between the sectors;

Figure 1 is a graphical description of the modified PWM algorithms [5, 7], where the horizontal axis shows the time \(t\) in microseconds and the vertical axis represents the signal value.

![Figure 1. Modified PWM](image)

Also, to improve the quality of the inverter output voltage let’s consider the case with a smooth change of the PWM pulse signal frequency [4, 6]. Determination of the discrete signal timing is performed using an auxiliary sinusoidal signal with smaller amplitude relative to the control signal (figure 2). In this case, the pulse duration (duty cycle) and frequency of pulse control signal for a half cycle of the fundamental harmonic frequency of the modulated sinusoidal signal are varied depending on the amplitudes ratio of the control and auxiliary signals in accordance with the following formulas (3, 4, 5).

\[
DC = \frac{t_{\text{int}}}{T_i} \times 100\% = f(T_1, T_2, \ldots, T_i)
\]

(3)

\[
t_{\text{int}} A_{\text{cont}} = \int_{t_i}^{t} A_{\text{aux}} \sin(\omega t) dt,
\]

(4)

\[
T_i = \frac{1}{\omega} \arcsin \left[ \frac{A_{\text{aux}}}{A_{\text{cont}}} \sin(\omega t_{i-1}) \right].
\]

(5)

where \(A_{\text{aux}}\) is the amplitude of the auxiliary signal; \(A_{\text{cont}}\) is for the control signal amplitude.
Thus, for each discrete signal pulse of the inverter switches control we determine its own unique duty cycle value and a new frequency, which is different from the previous and subsequent pulses of the PWM generated signal sequence.

Figure 2. Determining the frequency of the control signal pulse algorithm

The period of every single pulse according to the algorithm will be reduced during a quarter period at dependence calculated in Excel and shown in Figure 3.

Figure 3. Control signal pulse period reduction

The VFD system is implemented in *NI Multisim* simulation program and integrated into *LabVIEW* visual programming environment. To join the modeling capabilities of Multisim and the processing, visualization and data storage in LabVIEW, *NI Control Design and Simulation Module* is used. We used for modeling the one-step explicit Runge-Kutta method of second and third order with the Bogatsky-Shampen coefficients set for solving the second-order equations (Runge-Kutta 23).
3. Results section.

Obtained from the simulation of power consumption values for different values of mechanical load on the motor shaft are shown in table 1. The simulation was performed at a constant value of useful power of induction motor at rated supply voltage and in PWM conditions.

**Table 1. Analysis of the classical and modified PWM methods**

| Shaft load | Power consumption (W) of the DC link with classical PWM | Power consumption (W) from the DC link with two-frequency PWM of sawtooth reference signal and 60 degrees intervals | Power Consumption (W) from the DC link with a smooth pulse width change of the PWM |
|------------|-------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|
|            | 1 kHz | 2 kHz | 3 kHz | 4 kHz | Shaft load | 2/4 kHz |
| 40 kW      | 48 851 | 49 497 | 49 576 | 51 114 | 40 kW     | 49 100  |
| 30 kW      | 39 689 | 40 217 | 41 162 | 44 018 | 30 kW     | 39 881  |
| 25 kW      | 35 916 | 36 563 | 35 509 | 39 775 | 25 kW     | 35 177  |

Sine wave generator

**Figure 4.** Block diagram of dual frequency PWM forming (LabVIEW)
4. A Discussion section.
We can evaluate the modulation losses in different PWM methods by the formula (6) [2, 8].

\[
P_{\text{mod,los.}} = P_{ct} - P_{\text{mod}}
\]  

(6)

where \(P_{\text{mod,los.}}\) is modulation losses, \(P_{ct}\) is power consumption of the DC link with classical PWM, \(P_{\text{mod}}\) is power consumption of the DC link with a modified PWM. A numerical determination of the modulation losses by computer simulation leads to the conclusion that the modulation losses in the researched variants of the modified PWM are less in comparison with the classic algorithm by 3.9-11.5% due to two-step change of the reference signal frequency and by 6.7-13.9% when using a sinusoidal signal to generate an inverter control pulses. Thereby, modified PWM methods can increase the COP of a system “converter-induction motor” by 3.8-14% and 10-20% respectively for the modulation methods described above under different load levels. System COP for the classical PWM is 78% and for the modified algorithms it’s 81% and 86% respectively at nominal motor COP 90.2%. Thus, the proposed PWM methods have some advantages in comparison with methods such as discontinuous PWM [9], modulation Modified SVPWM algorithms [10], overmodulation methods for PWM [11], and other methods described in [12, 13, 14].

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