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The Impact of Output Voltage Modulation Strategies on Power Losses in Inverter

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Introduction

At the moment the development of power electronics equipments is focused on high component density approach [1, 2]. This allows decreasing the dimensions and weight and improving the cost-effectiveness. The frequency converter for control of AC induction motors is one of the most promising power electronics equipment that has the constantly increasing market [3]. Inverter, which converts the DC voltage into variable frequency variable amplitude three phases AC voltage, is the main and most expensive part of the frequency converter. The three-leg voltage source inverter, which contains six switches, usually is used in frequency converters [4]. The IGBT transistors shunted by the free-wheeling diodes are commonly used as switches. They commute the windings of motor, therefore, conduct relatively high current in circuits with relatively high voltage. Since transistor is not ideal switch, there is some voltage drop across the open transistor, i.e. it produces so-called conducting losses. During the transient caused by switching of transistor both, transistor current and voltage drop across the transistor become high and the switching losses are generated. The transistor chip temperature must not exceed limiting value for reliable operation of inverter transistors, therefore, the power losses analysis and determination of means for their reduction is essential in the design of frequency converters.

The power losses in inverter are determined not only by the parameters of transistors used as switches but by the output voltage modulation method as well. Nowadays the methods based on the Space Vector Modulation (SVM) [5] are used commonly. The technique and results of investigation of power losses in inverter for case when proposed Space Vector Pulse Frequency Modulation (SVPFM) method with averaged pulse lengths was employed are presented in this work. The obtained results were compared with the results gained for commonly used conventional SVPFM method [5]. It is shown that suggested SVPFM method allows us to decrease the power losses in inverter as compared to conventional SVPFM method. The investigation was performed according the High-tech Development Program project dedicated to development of frequency converters for control of AC induction motor fan drives of advanced energy-saving industrial ventilation systems.

The inverter output voltage formation method

Let us remind the main principles of Space Vector Modulation (SVM) method [5, 6]. The switches in each leg of inverter (Fig. 1a) must work in opposite phase in this method, i.e. if the top switch of the leg is in state "On", the bottom switch must be in state "Off" and vice versa.

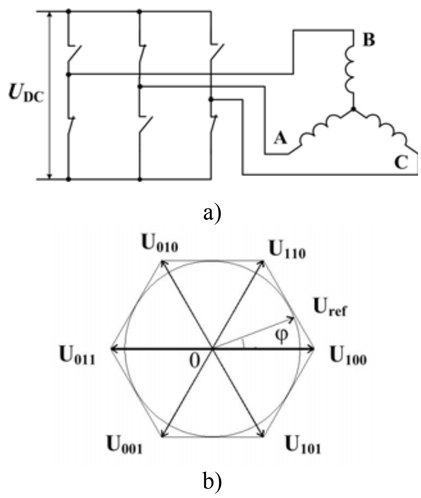


Fig. 1. Inverter with the connected motor (a) and hexagonal diagram, which presents the SVM principle (b)

The inverter has 8 states in such a situation. States (0,0,0) (all three bottom switches are in state "On") and (1,1,1) (all upper switches are in state "On") are zero states. The remaining 6 states are base states and correspond with the apexes of hexagon in Fig. 1b. Vector

$\mathbf{U_{ref}}$ presents the voltage generated by inverter: its length corresponds with amplitude of the first harmonic A_1, angle φ - with angle relative to initial point of period. Depending on the φ value, $\mathbf{U_{ref}}$ can be inside of one of the six sectors and is formed by two closest base vectors ($\mathbf{U_{100}}$ and $\mathbf{U_{110}}$ in Fig.1b) and zero vectors. The time periods $T_1(\theta)$ and $T_2(\theta)$, at which are active base vectors $\mathbf{U_{100}}$ and $\mathbf{U_{110}}$, respectively, determine the value of φ. They are calculated using following expressions: $T_1(\theta) = T_c$ m $sin(\pi/3 - \theta)$, $T_2(\theta) = T_c\ m\ sin(\theta)$, where $T_c = 1/f_c$ is period of carrier signal, which determines the discreetness of φ change, θ is angle between the first base vector and $\mathbf{U_{ref}}$ (θ matches with φ in Fig. 1b) and m is modulation index. The zero vectors work within time period $T_0(\theta) = T_c - T_1(\theta) - T_2(\theta)$. The usage of different zero vectors gives different algorithms of inverter switches commutation. The frequency of the first harmonic of generated voltage, which determines the rotation speed of motor supplied by inverter, is called phase frequency (f_p), the frequency of carrier signal – carrier frequency (f_c). The m modulates the length of vector $\mathbf{U_{ref}}$ (modulates the amplitude of the first harmonic of the generated voltage A_1). The m value is changed from value, which is close to zero (at low phase frequency f_p), to value m=1 at nominal phase frequency $f_p = f_{nom}$ (usually f_{nom} =50 Hz). The linear control of A_1, at which ratio $A_1/\ f_p$ is constant, allows keeping constant motor torque. In such a situation $m = f_p\ /\ f_{nom}$. The linear control law of A_1 is used in case when motor load torque is independent of rotation speed. In case when motor is applied for fan and pump drives the load torque decreases when rotation speed decreases, therefore, the law of control with decreased A_1, at which $m<f_p\ /\ f_{nom}$, can be used.

One of the peculiarities of the developed SVPFM method with averaged pulse lengths, as compared to the conventional SVPFM method, which is based on the traditional ideas of SVM, is fact that base vector activity periods are calculated on basis of trigonometric function integrals [7]

$$\begin{cases} T_1(\theta,\ \Delta\theta) = (T_c\ m\ /\Delta\theta) \int\limits_{\theta}^{\theta+\Delta\theta} \sin(\pi/3 - x)dx\ , \\ T_2(\theta,\ \Delta\theta) = (T_c\ m\ /\Delta\theta) \int\limits_{\theta}^{\theta+\Delta\theta} \sin(x)dx\ . \end{cases} \qquad (1)$$

The base vectors activity periods in this method are fit not to initial angle θ, as it is in conventional SVPFM, but to interval $[\theta,\ \theta+\Delta\theta]$. The investigation shows that using of pulses with averagedd lengths allows improving the initial part of voltage spectrum (Fig 2).

The ratio $f_c\ /\ f_p = M$ is constant in SVPFM methods, because of this , $\Delta\theta = 2\ \pi\ /\ M$ is constant as well and the values of integrals can be calculated in advance. This fact allows us simplify the formation of control signals for inverter switches.

In parallel with the averaged pulse length in the proposed SVPFM method the switch commutation algorithm, which allows us to minimize the number of switching of inverter switches (Fig. 3) and avoid commutations at maximal phase current, is employed. This allows reduction the switching losses in inverter.

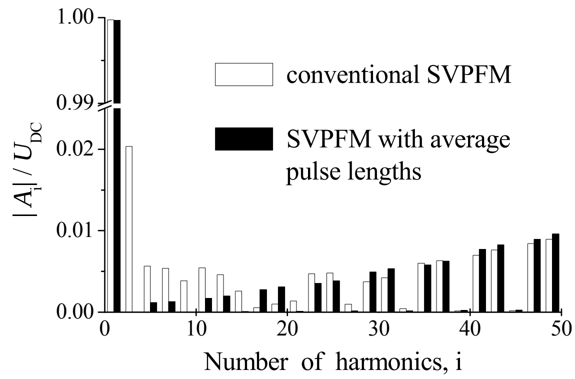


Fig. 2. The spectrum of the voltage generated by SVPFM with averaged pulse lengths and conventional SVPFM methods at $f_p = f_{nom}$ and M=96

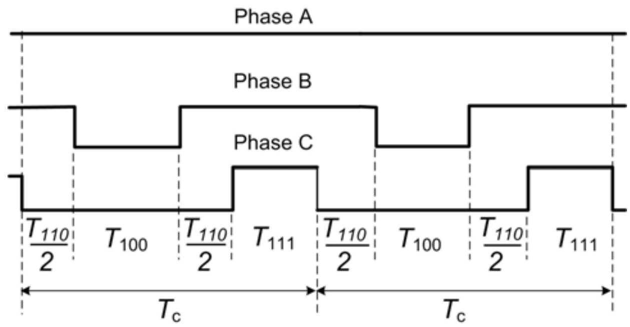


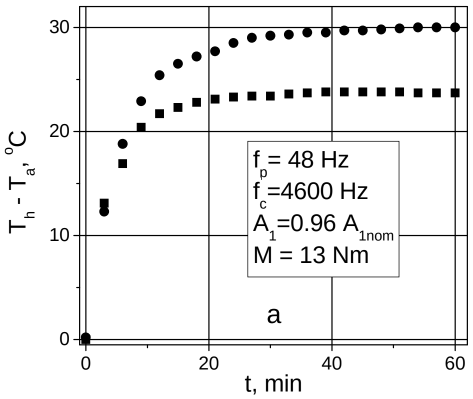
Fig. 3. The switch commutation algorithm with the minimized number of switching for the first sector (high level in the diagram corresponds to the state 1 of the appropriate leg, low – to the state 0)

Investigation of inverter power losses

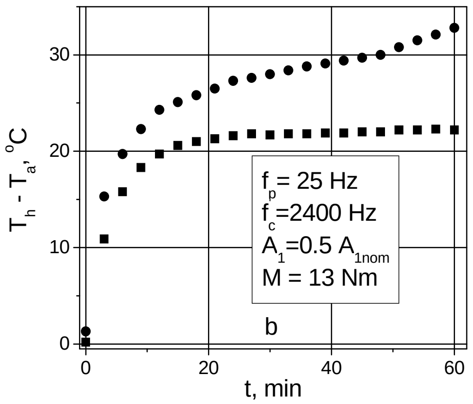
The power losses in inverter, which is used in frequency converter, were investigated experimentally. The inverter was based on six separate IGBT transistors, which were mounted on the heat sink. The direct measurement of inverter power losses is complicated and not accurate, therefore, they were evaluated indirectly by measurement of heat sink temperature. The inverter supplied the 4 kW AC induction motor loaded mechanically. The temperature of inverter heat sink was investigated for cases when output voltage was formed using SVPFM method with averaged pulse lengths and conventional SVPFM method. The results were obtained at f_p = 48 Hz , f_c = 4.6 kHz, and f_p = 25 Hz, f_c = 2.4 kHz . The investigation was performed at nominal 13 Nm and decreased 6.5 Nm motor load torque (M). The temperature measurement was provided using Dallas Semiconductor digital thermometers DS18B20 with the maximal measurement error ±0.2 ^{0}C.

The obtained results are given in Figs. 4, 5 and 7. They present the transients of heat sink temperature (T_h) in respect to ambient temperature (T_a) at various f_p, f_c, A_i and M. It is seen that employment of SVPFM method with averaged pulse lengths allows us to reduce the heat sink temperature (reduce the power losses in inverter), as compared to the case when conventional SVPFM is used. This happens because the switches of the appropriate inverter leg are not commuted in the proposed SVPFM method during the time periods, which correspond to the maximal phase current provided by this leg (Fig. 6). Therefore, the switching losses in inverter decrease.

Additional reduction of power losses in inverter using SWPFM method with the average pulse length is caused by the low harmonic content in the initial part of voltage spectrum (Fig.2).



a)



b)

Fig. 4. The transients of inverter heat sink temperature in respect to ambient temperature for case when voltage is formed using SVPFM method with averaged pulse lengths (square dots) and conventional SVPFM method (round dots) at nominal motor load torque for various phase and carrier frequencies and linear control of A_1

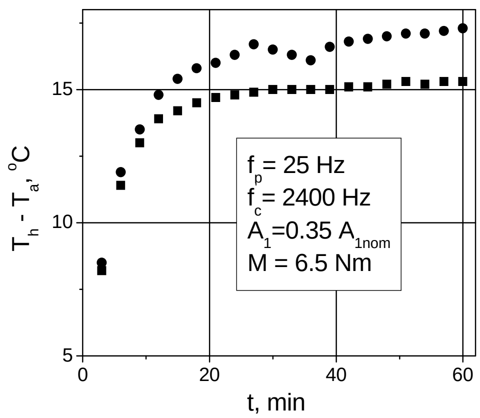


Fig. 5. The transients of inverter heat sink temperature in respect to ambient temperature for case when voltage is formed using SVPFM method with averaged pulse lengths (square dots) and conventional SVPFM method (round dots) at decreased motor load torque with control of inverter voltage by law with decreased A_1

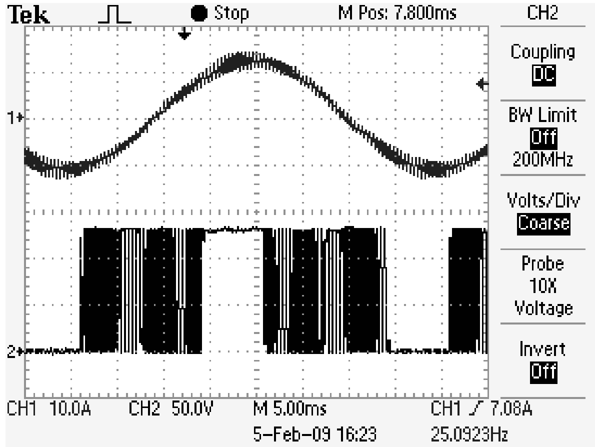


Fig. 6. The AC induction motor phase current (upper curve) and phase voltage (bottom curve) formed using SVPFM method with averaged pulse lengths at f_p=25Hz, f_c=2400Hz, A_1= 0.5 A_{1nom}, M=13Nm. (The voltage has been measured using 1/4 voltage divider)

The results of investigation of impact of carrier frequency on inverter power losses are presented in Fig. 7. It is seen that in case when carrier frequency rises from 2400 Hz to 6000 Hz (by 250%), the inverter heat sink temperature increases by 5^{o}C or by 17% only. This fact shows that mainly conducting losses cause the power losses in inverter. Therefore, the additional power losses reduction could be achieved by employment of transistors with low voltage drop across the open transistor.

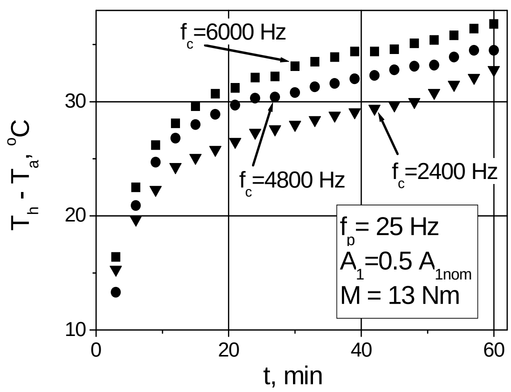


Fig. 7. The transients of inverter heat sink temperature in respect to ambient temperature at nominal motor load torque for various carrier frequencies and linear control of A_1

Conclusions

The introduction of averaged pulse lengths in SVPFM method allows improving the initial part of voltage spectrum. The use of the special switch commutation algorithm enables to minimize the number of switching of inverter switches and avoid commutations at maximal phase current. These solutions, which are employed in proposed SVPFM method with averaged pulse lengths, allows decreasing the power losses in inverter as compared to the case when conventional SVPFM method is used.

Most of all the conducting losses cause the power losses in inverter. Therefore, the additional power losses reduction can be achieved by employment of transistors with low voltage drop across the open transistor.

Acknowledgements

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The technique and results of investigation of power losses in inverter obtained for case when proposed Space Vector Pulse Frequency Modulation (SVPFM) method with averaged pulse lengths is employed for forming of three-phase inverter output voltage are presented in the work. The obtained results were compared with the results gained for conventional SVPFM method. It is shown that employment of the suggested modification of the SVPFM method allows decreasing the power losses in inverter, which is used in frequency converter for AC induction motor control, as compared to the case when conventional SVPFM method is employed. It is stated that reduction of power losses is caused by introduction of the switch commutation algorithm, which enables to minimize the number of switching of inverter switches and avoid commutations at maximal current. Additional reduction of the power losses is achieved by use of averaged pulse lengths, which allow improving the initial part of voltage spectrum. Ill. 7, bibl. 7 (in English; summaries in English, Russian and Lithuanian).

А. Башкис, В. Блейзгис, В. Гобис. Влияние стратегий модуляции выходного напряжения на потери мощности в инверторе // Электроника и электротехника. – Каунас: Технология, 2009. – № 6(94). – С. 47–50.

Представлены методика и результаты исследования потерь мощности в инверторе для случая, когда для формирования трёхфазного выходного напряжения используется предложенный метод пространственно-векторной модуляции частоты импульсов (ПВМЧИ) с усреднёнными длинами импульсов. Результаты исследования сравнены с результатами, полученными, применяя обычный ПВМЧИ метод. Показано, что применение предложенной модификации ПВМЧИ метода, по сравнению с обычным ПВМЧИ методом, позволяет уменьшить потери мощности в инверторе, используемом в преобразователе частоты, применяемом для управления асинхронных трёхфазных электродвигателей. Констатируется, что уменьшение потерей мощности достигается за счёт того, что применение импульсов с усреднёнными длинами позволяет уменьшить низкочастотные составляющие спектра напряжения, а также транзисторы ключей инвертора в предложенном методе некоммутируются в интервале времени, когда ток имеет максимальные значения. Ил. 7, библ. 7 (на английском языке; рефераты на английском, русском и литовском яз.).

A. Baskys, V. Bleizgys, V. Gobis. Išėjimo įtampos moduliavimo strategijos įtaka inverterio galios nuostoliams // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 6(94). – P. 47–50.

Pateikta inverterio galios nuostolių tyrimo metodika ir rezultatai, gauti, kai jo trifazei išėjimo įtampai formuoti taikomas pasiūlytas vidutinės trukmės impulsų vektorinės erdvinės moduliacijos metodas. Tyrimų rezultatai lyginami su rezultatais, gautais įprastiniu EVIDM metodu. Parodyta, kad pasiūlytas metodas leidžia sumažinti galios nuostolius inverteryje, naudojamame dažnio keitiklyje asinchroniniams trifaziams elektros varikliams valdyti. Konstatuojama, kad galios nuostoliai sumažėja todėl, kad pasiūlytu metodu suformuota įtampa turi mažesnes žemojo dažnio spektro dedamąsias ir yra naudojamas raktų junginėjimo algoritmas, kuris leidžia išvengti raktų junginėjimosi laiko intervale, kuriame šiais raktais tiekiama srovė yra didžiausia. Il. 7, bibl. 7 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).

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