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Fixed-frequency control strategies for a series resonant inverter for induction heating – comparison of properties

Abstract. *Three fixed-frequency control strategies for a series resonant inverter for induction heating: PS-PWM, ADC and ACM have been compared in the paper. The analysis has been carried out using decomposition of the inverter output voltage to harmonic components. Special attention has been paid to the determination of conditions assuring ZVS operation of the semiconductor devices and to the inverter efficiency.*

Streszczenie. *W artykule porównano właściwości trzech stałoczęstliwościowych metod sterowania rezonansowego falownika szeregowego do nagrzewania indukcyjnego: ADC, PS-PWM i ACM. Analizę przeprowadzono z wykorzystaniem rozkładu napięcia wyjściowego falownika na składowe harmoniczne. Szczególną uwagę zwrócono na określenie warunków zapewniających przełączanie zaworów przy zerowym napięciu (ZVS) oraz sprawność falownika.* ***(Stałoczęstotliwościowe metody sterowania rezonansowego falownika szeregowego do nagrzewania indukcyjnego – porównanie właściwości)***

Keywords: resonant inverters, ZVS, induction heating PS-PWM, ADC, ACM.
Słowa kluczowe: falowniki rezonansowe, ZVS, nagrzewanie indukcyjne, PS-PWM, ADC, ACM.

Introduction

Frequency changers with a series resonant voltage-fed inverter (Fig. 1a) are one of the basic supply units of the induction heating equipment. The inverter power is often controlled by varying the frequency of switching the power-electronic devices (Pulse Frequency Modulation – PFM, FM) [1, 2]. A drawback of this method (Fig. 1b) is variable operation frequency of the inverter, which causes problems i. a. with a more complex filtering of the output-voltage ripple and has an impact on the values of the inductor-charge system parameters.

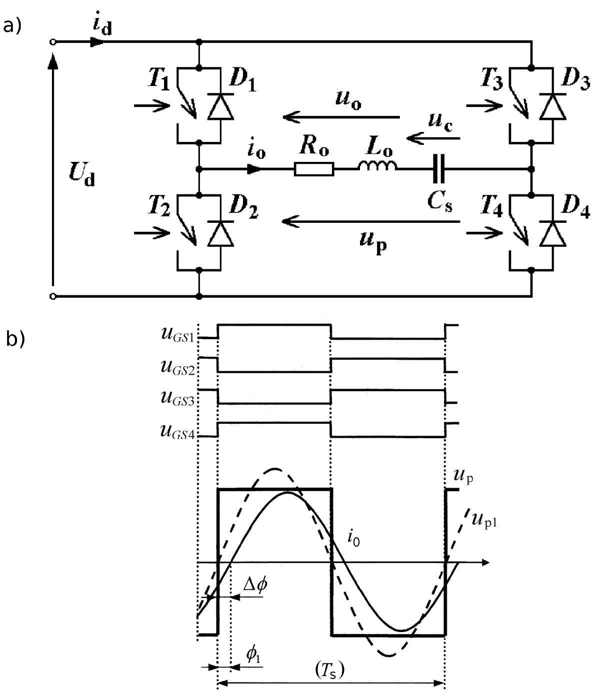

Fig.1. Class D series resonant inverter in a full-bridge configuration: a) circuit diagram b) example of time waveforms of: gate signals $u_{GS1} \div u_{GS4}$, output current i_0, voltage u_p across the resonant circuit and its first harmonic u_{p1} for FM control strategy

The problems mentioned above can be overcome by using fixed-frequency control strategies, in which the power-electronic devices are switched at a fixed frequency and the power control is achieved by varying the shape of the voltage u_p applied to the resonant circuit (inverter output voltage). The analysis of these strategies is often carried out taking into account only the first harmonic of this voltage [3]-[5]. Sometimes complicated analytical dependencies are used [6]. An alternative way of the analysis is using numerical calculations taking into account a large amount of harmonics of the inverter output voltage. The results of such research are shown in the paper.

Basic dependencies

The inverter output voltage u_p in a class D full-bridge inverter can have two or three discrete values: $+U_d$, $-U_d$ or 0 in each control period $T_s = 1/f_s$, where U_d is the supply voltage of the inverter (Figure 1a). The shape of this voltage depends upon the control strategy used. Figure 2a shows typical time waveforms of inverter currents and voltages for Asymmetrical Voltage Cancellation (AVC) strategy - a generalized control technique for resonant inverters [3]. The inverter power can be controlled by varying the angles α_+, α_- and β at a fixed switching frequency f_s.

Assuming a constant value of supply voltage U_d in one switching period and all elements of the inverter being ideal and linear, normalized values of the inverter output voltage and the output current in a steady state for AVC control strategy can be presented as a sum of harmonics:

$$u_{pn} = \frac{u_p}{U_d} = \frac{U_{0n}}{2} + \sum_{k=1}^{\infty} U_{pkmn} \sin\left(k\omega_s t + \phi_{uk}\right) \tag{1}$$

$$i_{on} = \frac{\dfrac{i_o}{U_d}}{\sqrt{\dfrac{L_o}{C_s}}} = Q\sum_{k=1}^{\infty} \frac{U_{pkmn}}{\sqrt{1 + Q^2\left(k\dfrac{f_s}{f_0} - \dfrac{f_0}{kf_s}\right)^2}} \cdot \sin(k\omega_s t + \phi_{uk} - \phi_k) \tag{2}$$

where

$$U_{pkmn} = \frac{1}{k\pi}\sqrt{a_k^2 + b_k^2}\,;\; U_{0n} = \frac{2}{\pi}\left(\beta - \pi + \frac{\alpha_- - \alpha_+}{2}\right)$$

$$\begin{aligned} a_k &= \sin k(\beta - \alpha_+) + \sin k\beta + \sin k\alpha_- \\ b_k &= 1 - \cos k(\beta - \alpha_+) - \cos k\beta + \cos k\alpha_- \end{aligned} \tag{3}$$

$$\mathrm{tg}\phi_{uk} = \frac{a_k}{b_k};\;\; \phi_k = \mathrm{arctg}\left[Q\left(k\frac{f_s}{f_0} - \frac{f_0}{kf_s}\right)\right]$$

f_0 is the resonant frequency of the series $R_oL_oC_s$ circuit and Q – its quality factor:

(4) $$f_0 = \frac{1}{2\pi\sqrt{L_oC_s}}; \quad Q = \frac{1}{R_o}\sqrt{\frac{L_o}{C_s}}$$

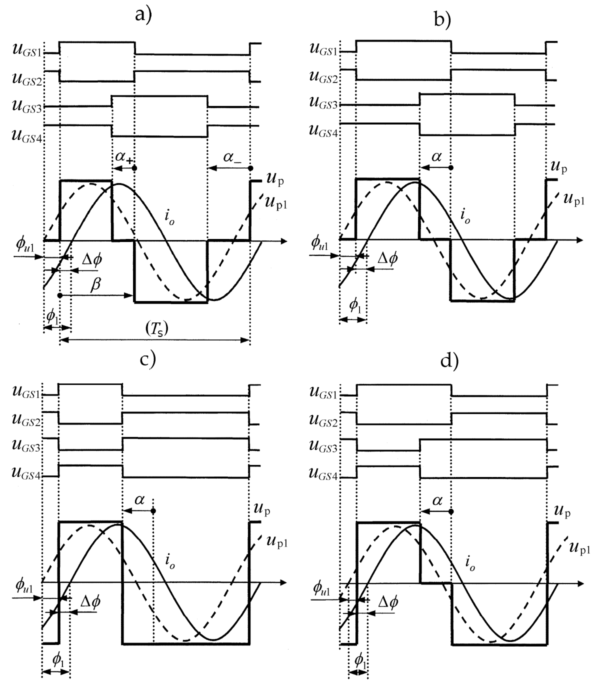

Fig.2. Typical waveforms of gate signals $u_{GS1} \div u_{GS4}$, output current i_o, output voltage u_p and its first harmonic u_{p1} for the control strategies: a) AVC, b) PS-PWM, c) ADC, d) ACM; based on [3]

The total inverter power is a sum of the powers of an infinite number of harmonics and its normalized value is given by:

(5) $$P_n = \frac{P}{\frac{U_d^2}{\sqrt{\frac{L_o}{C_s}}}} = \frac{Q}{2}\sum_{k=1}^{\infty}\frac{U_{pk\mathrm{mn}}^2}{1+Q^2\left(k\frac{f_s}{f_0}-\frac{f_0}{kf_s}\right)^2}$$

The special cases of the AVC strategy discussed in the paper are:

- pulse-width modulation by varying the phase-shift between the pulses controlling the inverter switches (Phase-Shift PWM, PS-PWM, PS, PSC – Figure 2b), in which:

(6) $$\alpha_+ = \alpha_- = \alpha; \quad \beta = \pi$$

- Asymmetrical Duty-Cycle (ADC – Figure 2c), in which:

(7) $$\alpha_+ = \alpha_- = 0; \quad \alpha = \pi - \beta$$

- voltage cancellation in only one half-period of period T_s (Asymmetrical Clamped Mode – ACM, AVC1h, optimum AVC – Figure 2d), in which:

(8) $$\alpha = \alpha_+; \ \alpha_- = 0; \ \beta = \pi$$

Minimum value of control frequency assuring zero voltage switching

The power can be controlled by varying angle α in each analyzed control strategy. It is very important to assure soft switching of the transistors in the whole range of the inverter operation. Therefore, a sufficiently high control frequency f_s has to be used in each operating point. At minimum value of that frequency the switches are turned on at zero current, and after increasing the frequency, zero voltage switching (ZVS) is achieved.

Figure 3 depicts with solid lines the computed minimum normalized switching frequency required for ZVS as a function of angle α, which is shown if Figure 2. That minimum switching frequency was determined numerically for each control strategy by searching for each value of angle α such a value of f_s/f_0, at which the switches turn on at zero current. One degree was adopted as the step of angle α and the ratio f_s/f_0 was varied with the step of 0.0005.

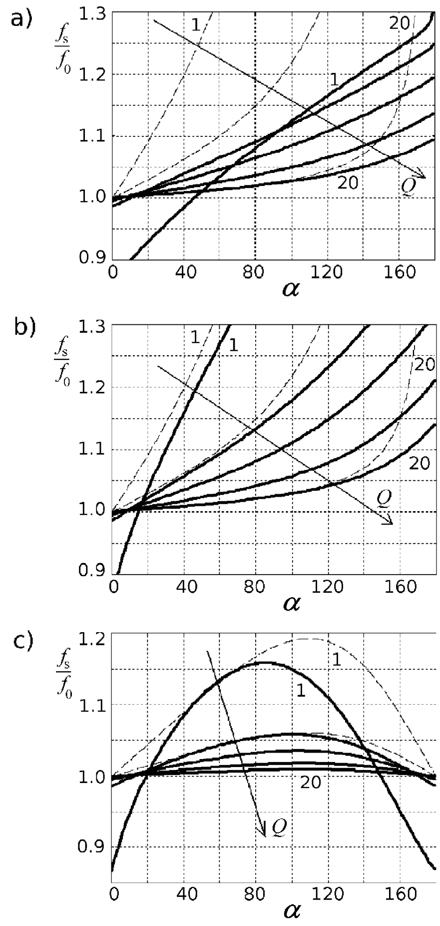

Fig.3. Minimum normalized switching frequency required for ZVS as a function of angle α (in degrees) and the Q factor: a) ADC control, b) PS-PWM control, c) ACM control. Solid lines for 1999 harmonics, Q = 1, 3, 5, 10, 20. Dashed lines – only fundamental harmonic, Q = 1, 3, 20

It results from the calculations that the minimum switching frequency increases with an increase of angle α in ADC and PS-PWM control strategies, being much higher for PS-PWM control. On the other hand, in ACM strategy the minimum switching frequency first increases and then decreases with an increase of angle α. The values of the minimum switching frequency are the smallest for ACM strategy.

The minimum switching frequency depends also on the quality factor Q of the circuit. In the prevailing range of angle α that frequency is the lower, the higher the quality factor Q.

The minimum frequencies determined using only the fundamental harmonic of the inverter output voltage u_p were shown additionally with dashed lines in Figure 3. Big differences can be seen between the results obtained using many harmonics and only the fundamental harmonic and in most cases the minimum switching frequency obtained using many harmonics is much lower. The smallest differences occur in circuits of high quality factor Q at low values of angle α.

Inverter power

Figure 4 shows the dependence between normalized inverter power P_n (5) and angle α for the discussed control strategies using solid lines. To each value of angle α corresponds a minimum switching frequency shown in Figure 3. Maximum value of power is obtained at a zero or small value of angle α, at which the normalized minimum switching frequency f_s/f_0 is near 1. When increasing angle α the power decreases: to zero at PS-PWM and ADC control strategies and to ¼ of its maximum value at ACM control. The value of power depends also significantly upon the quality factor Q of the resonant circuit: the higher Q, the higher the power. The characteristics of power in function of angle α and quality factor Q for ADC and PS-PWM control strategies are similar but not identical.

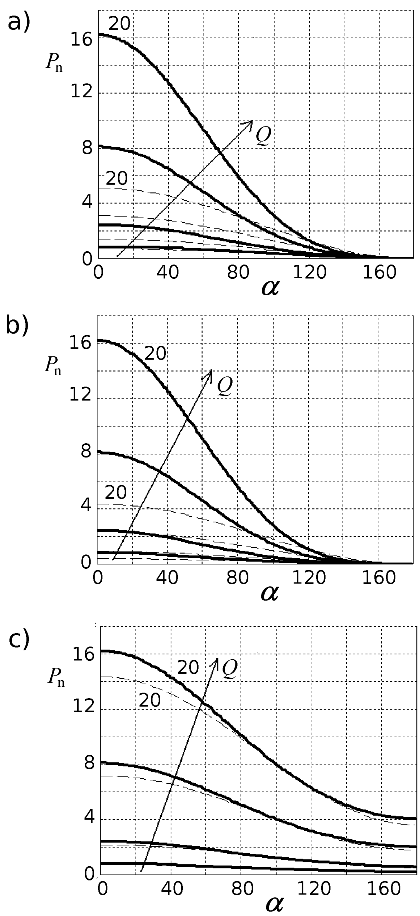

Fig.4. Normalized inverter power P_n (5) as a function of angle α (in degrees) and the Q factor: a) ADC control, b) PS-PWM control, c) ACM control. Solid lines – minimum control frequency (shown with solid lines in Figure 3) in each operating point, dashed lines – fixed control frequency (Table 1). Q = 1, 3, 10, 20

Determination of control frequency of the inverter

A very important issue at the inverter design is a proper selection of its fixed control frequency guaranteeing ZVS in the whole range of the assumed power, taking into account the value of the quality factor Q of the circuit. Based on the data in Figures 3 and 4 minimum normalized control frequencies were determined numerically at which the power can be varied in the range of (0.25÷1)P_{max} maintaining ZVS. A fixed value of Q was assumed. The results are shown in Table 1.

Table 1. Normalized control frequencies required for ZVS operation in power range of (0.25÷1)P_{max} and ratios of maximum powers

Q	f_s/f_0			$P_{max}/P_{max\text{-}f0}$		
	ADC	PS-PWM	ACM	ADC	PS-PWM	ACM
1	1,1785	1,5880	1,1580	0,8313	0,4801	0,8484
3	**1,1505**	**1,2345**	**1,0580**	**0,5722**	**0,3773**	**0,8862**
5	1,1090	1,1500	1,0355	0,4801	0,3359	0,8874
10	1,0655	1,0805	1,0180	0,3825	0,2937	0,8860
20	1,0375	1,0420	1.0090	0,3155	0,2695	0,8859

The frequency determined depends strongly upon the control strategy used and the quality factor Q. It is the highest at PS-PWM and the lowest – at ACM. It decreases with an increase of the Q factor.

Additionally, normalized inverter power obtained using a fixed control frequency given in Table 1 is shown in Figure 4 with dashed lines. In the range from 0,25P_{max} to P_{max} the inverter power is lower than the power obtained using the minimum switching frequency. This reason is that in almost the whole range of the power the control frequency is higher than the minimum switching frequency.

The requirement for inverter operation with the control frequency f_s higher than resonant frequency f_0 (4) causes that the maximum power P_{max} which can be achieved using fixed frequency strategies is lower than the maximum power $P_{max\text{-}f0}$ which could be achieved at $f_s = f_0$. The ratios of these powers are shown in Table 1. Their smallest values are obtained using PS-PWM strategy and the highest - using ACM strategy. In ADC and PS-PWM control strategies these ratios decrease rapidly with the quality factor Q increase, whilst in ACM control strategy their dependence upon the quality factor is small. Obtaining equal maximum powers in an inverter with set parameters using various control strategies requires also using another supply voltage in each control strategy (Table 2).

Simulation of inverter operation using IsSpice

A simulation of the inverter operation was carried out using IsSpice. The parameters assumed were: IGBT modules CM30TF-12H, R_o = 3.131 Ω, L_o = 30 μH, C_s = 340 nF and P_{max} = 10 kW. It results from the above: Q = 3.0 and f_0 = 49.83 kHz. Supply voltage U_d and control frequency f_s were selected based on the calculation results in Table 1. When selecting U_d the value of 204 V was assumed as a reference, at which P_{max} equal to 10 kHz is obtained for FM control at $f_s = f_0$ (Table 2).

Table 2 presents also the estimated inverter efficiency at full power of 10 kW and at power of 2.5 kW. Only the losses in the power-electronic devices were taken into account. The efficiency was determined as the ratio of the power dissipated in the equivalent resistance of the inductor – charge system and the inverter input power. The most advantageous control strategy is ACM, in which the highest efficiency is achieved and its dependence upon the inverter power is the smallest. PS-PWM control is a little bit less advantageous than ADC control.

The efficiency obtained using FM control was also calculated. At P_{max} it is the highest of all the strategies analyzed, due to the lowest control frequency. However, the

FM strategy requires big control frequency variations and is characterized by the highest efficiency drop at decreasing power.

Table 2. Required inverter supply voltage U_d, control frequency f_s required for ZVS operation in power range of $(0.25\div1)P_{max}$ and the inverter efficiency η calculated taking into account only the losses in the power-electronic devices for various control strategies. IsSpice simulation results

Control strategy	U_d, V	f_s, kHz	η, %	
			P_{max} = 10 kW	P = 2.5 kW
ADC	264	57.47	93.7	90.9
PS-PWM	323	61.54	91.6	90.8
ACM	214	52.63	95.5	95.7
FM	204	49.83 (at 10 kW) 67.11 (at 2.5 kW)	96.7	89.7

Time waveforms of voltage u_p and transistor currents in an inverter controlled using ADC strategy at powers of 10 kW and 2.5 kW are show In Figure 5. It can be clearly seen that in the latter case the inverter operates at minimum switching frequency - the currents of transistors T_1 and T_4 increase from a zero value. On the other hand, at 10 kW the control frequency is much higher than the minimum switching frequency for his operating point.

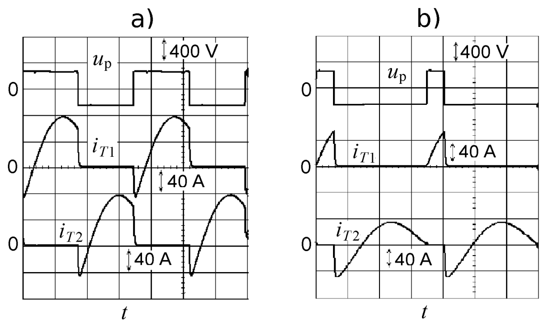

Fig.5. Examples of time waveforms of inverter output voltage and transistor currents using ADC control at U_d = 264 V, f_s = 57.47 kHz (Table 2) and output power equal to: a) 10 kW, b) 2.5 kW. IsSpice simulation results

Conclusions

The results of the analysis of the properties of a series resonant inverter controlled using three control strategies: ADC, PS-PWM and ACM have been presented in the paper. Using these strategies it is possible to control the inverter power by varying angle α.

For each control strategy:

- the minimum value of the control frequency, depending upon angle α and quality factor Q, has been determined, at which zero voltage switching of all the inverter power-electronic switches is ensured,
- the inverter power has been determined at its control with minimum switching frequency,
- the fixed control frequency has been determined, which makes it possible to vary the inverter power from a maximum value to ¼ of this value while maintaining ZVS in each operating point and the inverter power was calculated for this frequency in function of angle α,
- the inverter efficiency has been evaluated for the inverter operation at maximum power and at ¼ of this value using IsSpice simulation program.

It results from the comparison of the presented control strategies that the most advantageous strategy is ACM. It requires the smallest minimum switching frequency and guarantees the highest efficiency. Therefore, it is also called "optimum AVC" control. PS-PWM is the least advantageous of the presented fixed frequency control strategies. The highest efficiency drop when decreasing the power occurs in FM strategy.

The drawback of the ACM strategy is that the minimum power equals ¼ of maximum power, while PS-PWM and ADC make it possible to decrease the power to zero.

In case of using the presented control strategies in inverters for induction heating:

- a fixed control frequency is advantageous, as the impact of frequency variations upon the circuit parameters is eliminated,
- the circuit parameters during the whole heating process and the expected range of power variations should be taken into account to properly select the fixed control frequency, so that ZVS is guaranteed throughout the heating process.

The way of determining the inverter properties by using numerical calculations based on the inverter output voltage distribution on higher harmonics, which is presented in this paper, gives much more exact results than those obtained using only the first harmonic and does not require using sophisticated analytical calculations.

The results presented can be useful for designing inverters, which make it possible to vary the output power at a fixed control frequency.

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