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Induction heating with a fixed control frequency guaranteeing ZVS at varying parameters of the resonant circuit

***Abstract**. An example of determining a fixed control frequency for a series inverter for induction heating is dealt with in this paper, which ensures power control with ZVS switching at varying parameters of the resonant circuit. The analysis has been carried out for three fixed-frequency switching strategies: PS, ADC and ACM. Conditions for a proper operation and resulting problems have also been presented.*

Streszczenie.** W artykule przedstawiono przykład wyznaczania stałej częstotliwości sterowania falownika szeregowego do nagrzewania indukcyjnego, która zapewni regulację mocy przy przełączaniu tranzystorów falownika przy zerowym napięciu i przy zmianach parametrów obwodu rezonansowego. Analizę przeprowadzono dla trzech stałoczęstotliwościowych metod sterowania: PS, ADC i ACM. Podano także warunki uzyskania prawidłowej pracy i występujące problemy. (**Nagrzewanie indukcyjne ze stałą częstotliwością sterowania zapewniającą przełączanie tranzystorów przy zerowym napięciu przy zmianach parametrów obwodu rezonansowego)

Keywords: resonant inverters, ZVS, induction heating, fixed-frequency control
Słowa kluczowe: falowniki rezonansowe, ZVS, nagrzewanie indukcyjne, sterowanie stałoczęstotliwościowe

Introduction

Powers of frequency changers with a series resonant voltage-fed inverter (Fig. 1a) can be controlled using fixed-frequency methods. Among the best known ones are (Fig. 1b÷d) [1 – 6]:

- pulse-width modulation by varying the phase-shift between the pulses controlling the inverter switches (PS – Fig. 1b),
- Asymmetrical Duty-Cycle (ADC – Fig. 1c),
- voltage cancellation in only one half-period of the switching period (Asymmetrical Clamped Mode – ACM – Fig. 1d),

In each control technique, the inverter operates at a fixed switching frequency f_s, and its power is controlled by varying the angle α. At zero value of this angle, voltage u_p across the resonant circuit is, in each method, a rectangular wave of duty cycle ½ - as in Pulse Frequency Modulation (PFM) method. In these conditions, the inverter power is maximum and has the same value in each method. An increase in angle α results in the inverter power decrease, which is a function of the control method and the inverter parameters. The power can be brought to zero at PS and ADC control strategies and to ¼ of its maximum value at ACM control. Control frequency f_s is also of considerable importance, as it determines the switching conditions of the power-electronic devices. A decrease in power requires an increase in frequency f_s, to maintain a zero voltage switching (ZVS) operation.

Fixed-frequency control strategies can be used successfully for power control in the case of loads with constant parameters. However, for large load or output power variations, problems can arise with guaranteeing soft-switching operation of the inverter [1]. In some cases narrow-range frequency variations can be helpful.

Fixed-frequency operation might be advantageous in the process of induction heating. Some difficulties may arise, as stated above, due to load variations with temperature. However, fixed-frequency or narrow-frequency range operation of the inverter may be possible. A crucial problem is the choice of such a switching frequency that will assure soft switching in the whole power range. This article focuses on the problems mentioned above, and the discussion is based on an example.

Minimum value of control frequency guaranteeing zero voltage switching

The analysis of the inverter operation was carried out using numerical calculations, and taking into account a large amount of harmonics of the inverter output voltage [1, 6]. Selected results from [6, 7] were utilized in this paper, and some new calculations have been done.

The following designations are used in this paper

$$(1)\quad f_0=\frac{1}{2\pi\sqrt{L_0C_S}}\,,\ \rho=\sqrt{\frac{L_0}{C_S}}\,,\ Q=\frac{\rho}{R_0}\,,\ f_{sn}=\frac{f_s}{f_0}$$

where f_0, ρ, Q and f_{sn} are the resonant frequency of the series $R_0L_0C_s$ circuit, its characteristic impedance and quality factor and normalized control frequency, respectively.

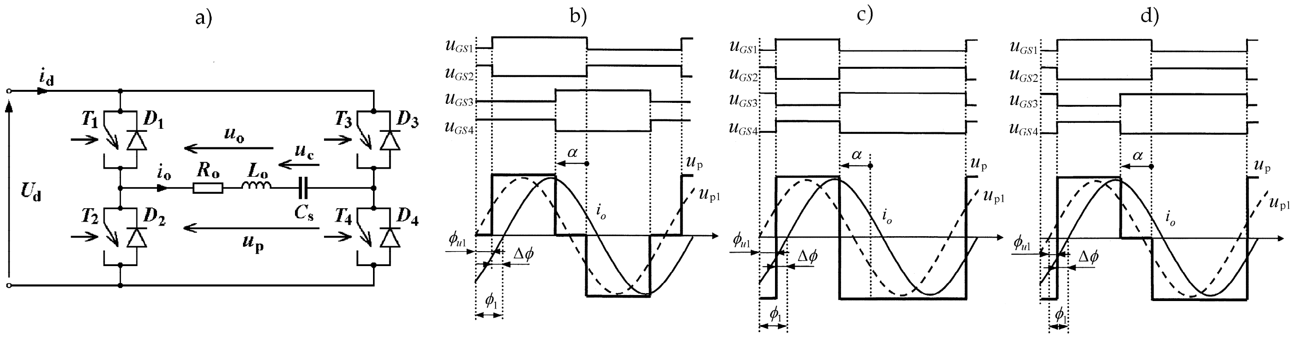

Fig. 1. Class D series resonant inverter in a full-bridge configuration: a) circuit diagram, and examples of time waveforms of gate signals u_{GS1}÷u_{GS4}, output current i_0, voltage u_p and its first harmonic u_{p1} in control strategies: b) PS, c) ADC, d) ACM; based on [1], [6]

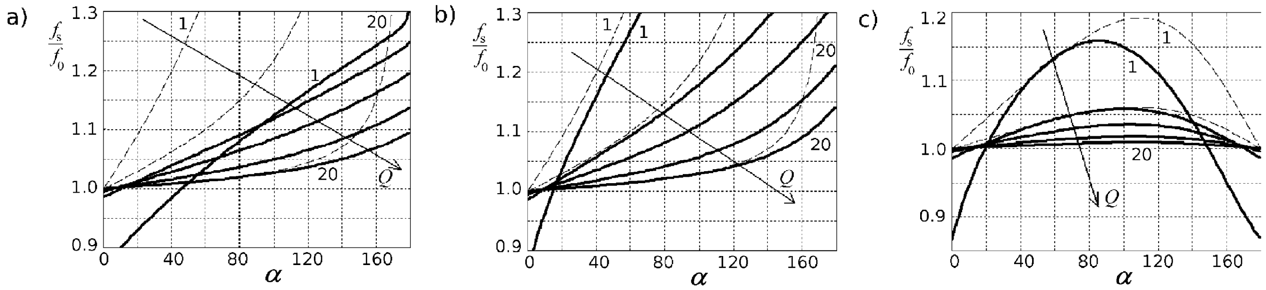

Fig. 2. Minimum normalized switching frequency required for ZVS as a function of angle α (in degrees) and Q factor: a) ADC control, b) PS control, c) ACM control. Solid lines for 1999 harmonics, Q = 1, 3, 5, 10, 20. Dashed lines – only fundamental harmonic, Q = 1, 3, 20 [6]

A sufficiently high control frequency f_s has to be used in each operating point, to guarantee soft switching of the transistors. Minimum values of normalized switching frequency f_s/f_0 required for ZVS, determined numerically for each control strategy, are shown in Fig. 2, as a function of angle α [6]. The minimum switching frequency increases with an increase of angle α in ADC and PS control strategies. However, 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 in ACM strategy.

In fixed frequency control strategies, power is controlled by varying angle α. Maximum value of power is obtained at a zero value of angle α. When increasing angle α, the power decreases: to zero at PS 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. Dependences between power, angle α and Q are presented in [1, 6, 7].

A very important issue in the design of an inverter operating at a fixed control frequency in the whole range of an assumed power, is a proper selection of this frequency guaranteeing ZVS. The value of the quality factor Q of the circuit should also be taken into account. This frequency, at which the power can be varied in the range of $(0.25\div1)P_{\max}$ maintaining ZVS, is referred to as $f_{\text{sn-fxd}}$.

Figure 3 presents the relationship between $f_{\text{sn-fxd}}$ and quality factor Q for three discussed control methods. Its values are the highest in PS and the smallest in ACM strategy, and it decreases with increasing Q in each control method.

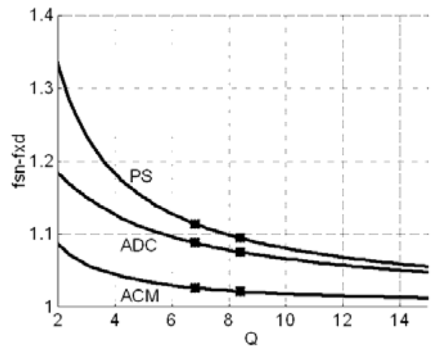

Fig. 3. Minimum normalized control frequency $f_{\text{sn\_fxd}}$ as a function of quality factor Q in PS, ADC and ACM control strategies [7]. Marked points correspond to quality factors Q in Table 1

Determination of fixed control frequencies

The objective of his paper is to analyze possibilities and conditions for a fixed-frequency induction heating process, guaranteeing zero voltage switching within a preset temperature range. Moreover, it is assumed that some inverter parameters will be adjusted accordingly, to obtain required values of power.

The analysis is based on the example of heating of aluminum cylinders from initial temperature of 20°C (cold state) to final temperature of 500°C (hot state) with a frequency of ca 1000 Hz. The values of the inductor-charge system parameters determined in [8] were accepted for calculations. A fixed supply voltage of 540 V, inverter nominal power of 20 kW (minimum power equals ¼·20 kW = 5 kW) and the use of an output transformer (heating coil on the secondary side) with an appropriate turns ratio were assumed. The capacitance C_S was selected so as to obtain resonant frequency f_0 adequately lower than the required control frequency f_S. The values of the assumed quantities and those of power factor Q and resonant frequency f_0 calculated for both limit temperatures are shown in Table 1. Owing to charge resistivity increase with temperature rise, Q and f_0 are lower in the hot state (500°C).

Table.1. Parameters of the inverter resonant circuit in limit temperatures [7]

ϑ °C	R_0 mΩ	L_0 μH	turn ratio	C_S μF	Q	f_0 Hz
20	30.21	44.29	1:10	6.8	8.45	915.5
500	38.15	45.68			6.79	900.6

Calculation results are presented in Table 2, separately for each control strategy. Column 3 contains values of normalized frequencies $f_{\text{sn-fxd}}$ marked in Fig. 3, and corresponding control frequencies $f_{\text{s-fxd}}$ are shown in column 4. Column 5 shows proposed control frequencies – one frequency was chosen for each method, slightly exceeding the higher value of column 4. Maximum power available in each operating point, at α = 0 (Fig. 1), is presented in column 7.

Table.2. Calculations results for inverter parameters in Table 1 [7].

1	2	3	4	5	6	7
control strategy	ϑ °C	$f_{\text{sn-fxd}}$	$f_{\text{s-fxd}}$ Hz	f_s Hz	f_{sn}	$P_{\max}$ kW
PS	20	1.094	1001.6	**1004**	1.097	23.396
	500	1.114	1003.3		1.115	20.122
ADC	20	1.075	984.2	**985**	1.076	31.832
	500	1.088	979.9		1.094	25.864
ACM	20	1.021	934.7	**935**	1.021	70.710
	500	1.026	924.0		1.038	50.659

There are remarkable differences between control frequencies and maximum powers in the discussed control methods. In addition, when we consider a particular method, we can see differences between maximum powers in initial and final temperature. They are the result of the temperature dependence of the inverter parameters, and are inevitable in a fixed-frequency operation at a constant supply voltage (Fig. 4).

Powers at operation with α = 0 as a function of control frequency f_s for circuit parameters in Table 1 are shown in Fig. 4. Operating points corresponding to those in Table 2 are marked. This figure explains the reasons for various values of P_{max} in Table 2.

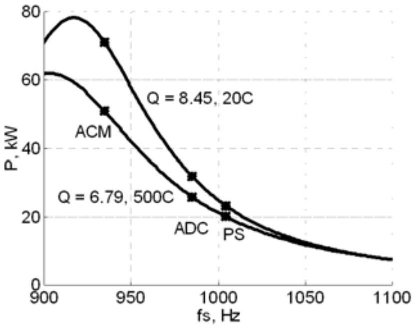

Fig. 4. Powers at operation with α = 0 as a function of control frequency f_s; All control strategies. Circuit parameters as in Table 1. Marked points correspond to f_s and P_{max} in Table 2.

Fixed frequency control – PS strategy

The inverter parameters in Table 1 can be considered as correct for fixed frequency operation using PS control strategy. At f_s = 1004 Hz, maximum power is nearly equal to nominal power (20 kW) at 500°C, and about 17% higher at 20°C. Table 3 presents inverter powers in selected operating points. At 20°C, nominal power is obtained at α = 44 degrees. Maximum value of angle α is 121 degrees – ZVS limit. Further increase in α would result in losing ZVS, therefore it is not admissible. In this operating point, inverter power is 24.3% of its maximum power and 28.4% of nominal power (5.684). This is more than the expected minimum power 5 kW. The power can be decreased by a slight increase in control frequency; rising f_s do 1007 Hz makes it possible to increase α to 124 degrees and obtain power of 4.935 kW.

Maximum and minimum power can be obtained at a fixed frequency at a decreased supply voltage. At U_d = 500 V and α = 0, power is equal to 20.058 kW, and at α = 120 degrees, it equals 5.023 kW, which is practically equal to minimum power.

At 500°C, nominal power is obtained practically at α = 0 degrees. Maximum value of angle α is 119 degrees, and the corresponding power is just slightly higher that minimum power.

For comparison purposes, frequencies required to obtain maximum and minimum powers in PFM strategy (inverter of the same parameters) were computed. They are 1014 Hz, 1149 Hz for cold state, and 1004 Hz, 1155 Hz for hot state. The required frequency increase is ca 12-13%.

Fixed frequency control – ACM strategy

Powers achieved in ACM control strategy are much higher than nominal power of 20 kW (Table 2).

One way to obtain the desired values of powers is by increasing the circuit impedance. The calculations and their results are presented in [7]. Turn ratio of 1:15, C_s = 2.68 μF and control switching frequency f_s of 1000 kHz were chosen. At 500°C, maximum power is obtained at α = 0 – as in PS strategy, and it is possible to obtain minimum power without increasing the frequency. At 20°C, maximum power is about 42% higher than nominal power, which is considerably more than in PS strategy (Table 2). Nominal power is obtained at α = 77 degrees. Moreover, similarly as in PS control, it is not possible to achieve minimum power at the fixed frequency; an increase to f_s = 1022 Hz is required.

Table. 3. Inverter powers in PS control strategy, and frequencies required to obtain minimum and maximum power in PFM strategy. Circuit parameters as in Table 1 and U_d = 540 V; based on [7]

ϑ °C	control strategy	f_s Hz	α degrees	P kW	Notes
20	PS	1004	0	23.396	
			44	**20.102**	
			73	15.111	
			98	10.073	
			121	**5.684**	ZVS limit
		1007	124	**4.935**	ZVS limit
	PS **500 V**	1004	0	20.058	
			120	5.023	ZVS limit
	PFM	1014	-	20.128	
		1149	-	4.978	
500	PS	1004	**0**	**20.122**	
			60	15.080	
			90	10.061	
			119	**5.196**	ZVS limit
	PFM	1004	-	20.122	
		1155	-	5.006	

Frequencies required to obtain maximum and minimum powers in PFM strategy (inverter of the same parameters) are presented in [7]. They are 1021 Hz and 1116 Hz for cold state, and 1000 Hz and 1110 Hz for hot state. The required frequency increase is lower than in PS method.

Another way to obtain the desired values of powers is by decreasing the input voltage without changing the circuit parameters (Table 1). Switching frequency is f_s = 935 Hz (Table 2). The calculation results are shown in Table 4, and they demonstrate that by adjusting supply voltage for each temperature, it is possible to operate within the required power range at a fixed frequency.

Table. 4. Inverter powers in ACM control strategy with adjusted supply voltage. Circuit parameters as in Table 1.

ϑ °C	U_d V	f_s Hz	α degrees	P kW	Notes
20	287.2	935	0	20.002	
			180	5.000	¼ P_{max}
500	339.3	935	0	20.000	
			180	5.000	¼ P_{max}

Fixed frequency control – ADC strategy

Maximum powers in ADC strategy are higher than those in PS method, but not as high as those in ACM method (Table 2). The possibilities are:

a) operation with unchanged circuit parameters (Table 1):
   - at frequency f_s in Table 2; decreasing power will require increasing f_s, as in PS method (Table 3),
   - at an increased frequency, e.g. that determined for PS method in Table 2; this will result in a slight efficiency decrease,

b) adjusting of circuit parameters (turn ratio and C_s) to match the maximum power, as was presented for ACM method in previous Section and in [7],

c) adjusting supply voltage, in a way presented for ACM method in previous Section.

Simulation of inverter operation in selected operating points

Simulations of the inverter operation were carried out using IsSpice, to verify the calculation results. Figure 5a shows the output voltage and currents in the hot state for PS control at maximum power (Table 3). Waveforms of corresponding voltage and currents for the cold state at ACM operation at minimum power and a decreased supply voltage (Table 4) are presented in Fig. 5b. The obtained results are in good accordance with those of analytical calculations, and slightly lower powers are a consequence of using models of real transistors in the simulations. The transistors are switched at zero current. An exception are T_3 and T_4 in Fig. 5b: T_3 conducts all load current, and T_4 is off all the time. This is a feature of ACM strategy at angle α = 180 degrees.

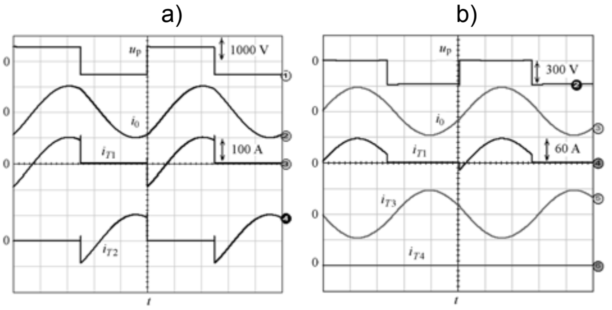
a) b)

Fig. 5. Time waveforms of inverter output voltage and transistor currents; a) PS strategy, 500°C, f_s = 1004 Hz, U_d = 540 V, P = 19.9 kW [7], b) ACM strategy, 20°C, f_s = 935 Hz, U_d = 287.2 V, P = 4.83 kW. Circuit parameters as in Table 1.

Control system requirements

One of the main tasks of the control circuit is guaranteeing soft switching throughout the heating process. The best way is to calculate the required fixed frequency in advance. However, this may be impossible. What is more, unpredictable disturbances can affect the circuit parameters. Therefore, the control system should have a possibility of detecting ZVS limit and increasing the control frequency, if necessary.

A possible way of operation is that the inverter starts with an expected value of frequency, and the control system increases it, if necessary, to maintain ZVS switching. The maximum frequency can be saved and used in the consecutive heating cycles, if concerned.

If ZVS limit is reached at decreasing power, as described above, further power decrease can be obtained either by increasing frequency or decreasing supply voltage. This depends upon the assumed control algorithm.

Conclusions

In this paper, an example of a fixed-frequency induction heating, guaranteeing zero voltage switching within a preset temperature range, is discussed. Conditions for a proper operation and resulting problems are presented.

To guarantee ZVS, a sufficiently high inverter control frequency is required, which fulfills the condition $f_s/f_0 \geq f_{sn\text{-}ZVS}$ in each operating point. It depends upon the control strategy, quality factor Q of the resonant circuit and the angle α. The values of $f_{sn\text{-}ZVS}$ are presented in Fig. 2.

A fixed-frequency ZVS operation in an assumed power range at varying charge temperature requires a proper selection of this frequency, which should be equal to or higher than the highest frequency occurring in all the operating points. Therefore, the condition $f_s/f_0 \geq f_{sn\text{-}fxd}$ should be fulfilled. The values of $f_{sn\text{-}fxd}$, at which the power can be varied in the range of $(0.25\div1)P_{max}$, maintaining ZVS, are presented in this paper.

The determined frequency $f_{s\text{-}fxd}$ is highest in PS and lowest in ACM strategy. In view of the inverter efficiency, it is most advantageous to select a frequency possibly near the resonant frequency, which occurs in ACM method.

On the assumption of a constant supply voltage of the inverter, its maximum power (at α = 0) varies with the charge temperature. It is advisable to chose the inverter parameters (supply voltage, turn ratio of the output transformer and capacitance C_S) so that the smallest maximum value equals nominal value. These parameters depend on the selected control strategy.

The highest power variations with temperature occur in ACM method.

In operating points, in which maximum power is higher than nominal power, the latter can be achieved by a proper increase in angle α. However, it may be impossible to obtain minimum power: as a result of losing ZVS at further increase in angle α (ZVS limit reached) in PS and ADC methods, or due to this feature of ACM method that its minimum power equals ¼ of maximum power. In such cases, a decrease in power can be obtained at a fixed supply voltage by a slight increase in control frequency f_s (narrow-range frequency control). The required frequency variations are much lower than those in PFM control.

An alternative is varying supply voltage so as to achieve nominal power at angle α = 0 in each operating point. However, the costs of such a system are higher.

The choice of the fixed control frequency and other inverter parameters (turn ratio of the output transformer, C_S) should be done individually, based on the knowledge of the values of the inductor-charge system parameters in each operating point. In addition, the control system should have a possibility of detecting ZVS limit and increasing the control frequency, if necessary.

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