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New methods of control of a series-resonant inverter for purpose of corona surface treatment

***Abstract**. This paper presents a new methods of controlling corona treatment. The methods are based on PDM and PFM modulation. The control characteristics are determined. The circuits were tested by means of simulation and experimentally by industrial applications. Those methods differ from the described PDM method as the operation of the inverter is not stopped but instead it operates with much higher frequency. The paper describes a mathematical model and proprieties of series resonant inverters used in application for corona treatment system for polyethylene foil. The method of identification of corona treatment parameters and power calculation is described as well. The areas of soft switching and corona discharge are presented.*

***Streszczenie.** W artykule przedstawiono nowe metody sterowania szeregowym falownikiem rezonansowym, które łączą w sobie własności metody modulacji PDM oraz FM. Metody te zostały zastosowane w przemysłowych urządzeniach do powierzchniowej obróbki tworzyw sztucznych – do tzw. aktywacji. W odróżnieniu od klasycznej metody PDM przestrajana jest jednocześnie częstotliwość, która może zmieniać się w narzuconych procesem technologicznym granicach. W artykule przedstawiono model i opis układu aktywatora folii polietylenowej oraz uzasadniono zalety zastosowanej metody powołując się na wyniki badań eksperymentalnych **(Nowe metody sterowania falownikiem rezonansowym w zastosowaniu do obróbki powierzchniowej tworzyw sztucznych)**.*

Keywords: series resonant inverter, corona treatment, ZVS, ZCS, PDM and PFM modulation
Słowa kluczowe: szeregowy falownik rezonansowy, aktywator folii, ZVS, ZCS, modulacja PDM i PFM

Introduction

In order to improve adherence, before printing or gluing, a modification of polymer surface by activation is employed. The structure of corona treatment system for polymer foil [1-3, 5-10] is presented on Figure 1a. The main elements of corona treatment system are: voltage source inverter (1), HV transformer (2) and set of discharge electrodes: (rotating) (3) and bar (static) (4). The parameters of this system are as follows: power - 0.5…10kVA, frequency - 5…50kHz, voltage on the electrodes - 4…20kV. Discharge electrodes along with two dielectric layers (silicone and air)

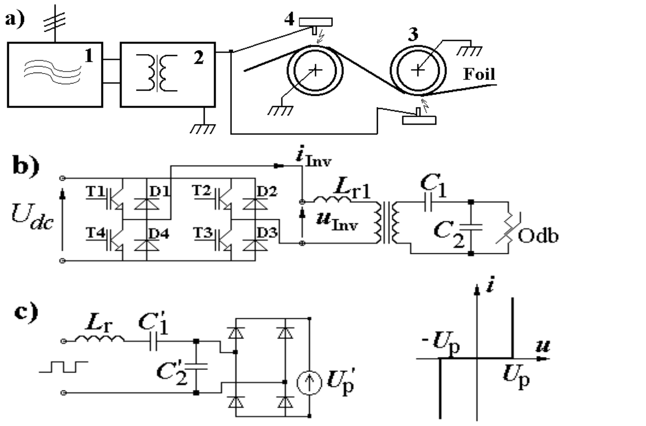

Fig.1. Series resonant inverter in corona discharge treatment system: a) system configuration, b), c) equivalent circuit and characteristics of corona discharge

form a set of capacitors C_1 (silicone) and C_2 (air). A third and the thinnest layer of the dielectric is a foil. A capacity related to this foil and connected in series with C_1 is greater then C_1 and can be omitted further on. Capacity of electrodes and leakage inductance of transformer constitute resonant circuit which can be used to assist switching processes in the inverter.

Figures 1b and 1c depict equivalent circuit and current-voltage characteristic of corona discharge in the air.
In reality when electrodes are long a significant amount of ignition centers is formed. Various ignition centers have different ignition voltage and voltage of discharge suppression. Intentionally a simplified model (Fig. 1c) with one ignition voltage and voltage of discharge suppression (threshold voltage U_p) is used [9]. The value of voltage that initiates the corona discharge is a function of electrodes' shape and product of pressure and distance between those electrodes [4].

When the main inductance of transformer is omitted, the inductance of the resonant circuit amounts $L_r=L_{r1}+L_{\sigma1}+L_{\sigma2}'$ where: $L_{\sigma1}$, $L_{\sigma2}'$ – leakage inductances of a transformer (seen form primary side). Additional inductor L_{r1} enables adjustment of free oscillation frequency and impedance of the resonant circuit to assumed working frequency range and assumed output power.

Theoretical background

Figure 2 depicts a wave of voltage $u_C(t)$ on the set of capacitors in a function of charge $q(t)$. One can distinguish two operation states (Fig. 1c, 2): state 1, without corona discharge (rectifier is off); state 2, with corona discharge (rectifier is on). In state 1, rate at which voltage $u_C(t)$ rises, describes equivalent capacity C_z of series connected capacitors C_1 and C_2 (equation 1). Whereas in state 2 , rate at which voltage $u_C(t)$ rises, describes capacity of capacitor C_1 (equation 2). The operating frequency of the inverter f_{syn}, at which the voltage and output current waves are synchronized, is situated in the following range $f_{r\max} > f_{syn} > f_{r\min}$ (Formula 3 and 4).

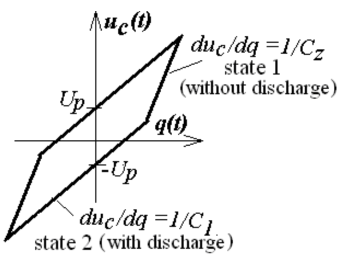

Fig. 2 Voltage $u_C(t)$ on electrodes in function of a charge $q(t)$

(1) $$\frac{du_C}{dq} = \frac{1}{C_z} = \frac{C_1 + C_2}{C_1 \cdot C_2}$$, (2) $$\frac{du_C}{dq} = \frac{1}{C_1}$$

(3) $$f_{r\max} = \frac{1}{2\pi\sqrt{L_r C_z}}$$, (4) $$f_{r\min} = \frac{1}{2\pi\sqrt{L_r C_1}}$$

For the supply voltages and frequencies at which the value of voltage amplitude on the capacitor C_2 doesn't reach the value of U_p a rectifier is off (Fig. 1c). The current does not flow through the non linear load. The current flowing through this circuit as well as the voltage at the capacitors has almost a sinusoidal shape. In this case a classic circuit analysis for the fundamental harmonics can be conducted. The quotient of amplitudes at the capacitor C_2 (for fundamental harmonics) and at the inverter's output is described by the dependence (5), where: $U_{C2\,1m}$, U_{Inv_1m} – the amplitude of the capacitor's C_2 voltage and the inverter's output voltage (for fundamental harmonics), $\omega_s = 2\pi f_s$ – the angular frequency of inverter's voltage, f_s - the switching frequency.

The value of the fundamental harmonics' amplitude of the input voltage of the bridge inverter is described by the dependence (6). Whereas the limiting value of the amplitude of the voltage U_{C2m} at the capacitor C_2, that causes the load current to flow is described by the dependence (7).

(5) $$\frac{U_{C2\_1m}}{U_{Inv\_1m}} = \left| \frac{1}{\omega_s^{\,2} \cdot L \cdot C_z - 1} \cdot \frac{C_z}{C_2} \right|$$

(6) $U_{Inv\_1m} = \dfrac{4}{\pi} U_{dc}$, (7) $U_{C2m} = U_p \approx U_{C2\_1m}$

From the equations (5), (6) and (7) it is possible to determine the boundary frequencies at which corona discharge starts occurring.

(8) $$f_{sgr1} = \frac{1}{2\pi} \sqrt{\frac{1}{L \cdot C_2} \left(\frac{C_2}{C_z} - \frac{4 \cdot U_{dc}}{\pi \cdot U_p} \right)}$$

(9) $$f_{sgr2} = \frac{1}{2\pi} \sqrt{\frac{1}{L \cdot C_2} \left(\frac{C_2}{C_z} + \frac{4 \cdot U_{dc}}{\pi \cdot U_p} \right)}$$

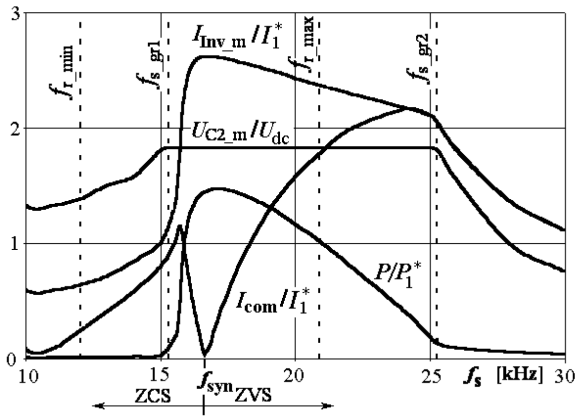

Fig. 3. Output power, inverter output maximal current, transistor current during commutation and voltage on capacitor C_2 in function of switching frequency (chamber 1, U_{dc}=300V)

Dependences above were confirmed by the simulations and experiments. The current of the corona discharge flows if the following condition is meet $f_{sgr1} < f_s < f_{sgr2}$. According to (8) and (9) the values of boundary frequencies depend on the value of the inverter's input voltage. For U_{dc} approaching to zero the boundary frequencies tend to approach to f_{rmax} (formula 3, 8 and 9).

Figure 3 depicts values of power, current and voltage in the circuit in relation to base values: U_{dc}, $I^*_1 = U_{dc}/\sqrt{L/C_1}$, $P^*_1 = U_{dc}^2/\sqrt{L/C_1}$. Distinctive frequencies, calculated from dependencies (3), (4), (8) and (9), were marked. Illustration 3 represents the results of a computer simulation of a real object: (discharge chamber no 1): P_N=4kW, length of the electrodes 3,3m, cylinder electrode φ=100 mm, silicon d =2 mm. The simulation model assumed a negligible current of transformer's magnetization.

While analyzing Figure 3 and dependence (9) one can conclude that when the inverter operates with a frequency $f_s > f_{sgr2}$ then the power flow to the nonlinear load is cut. As a result the activation process is stopped.

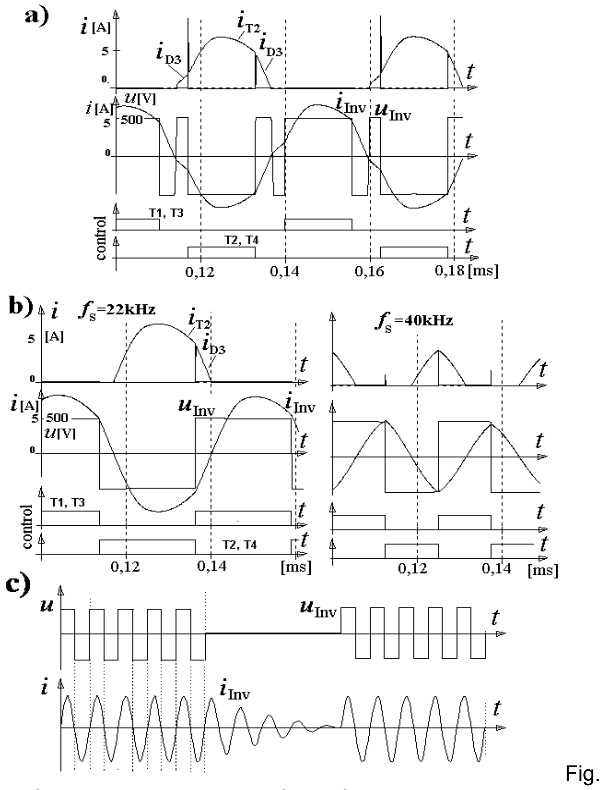

Fig. 4. Current and voltage waveforms for modulation: a) PWM, b) PFM, c) PDM; i_T, i_D – transistor and diode current; i_{Inv}, u_{Inv} – inverter output current and voltage

This property will be used for the power adjustment of the activation process with a help of new PDM-PFM methods with periodic change of frequency.

Control method of corona treatment process

Control of the corona treatment process' power can be run in the following ways [8]: by pulse width modulation (PWM), by pulse frequency modulation (PFM), by amplitude modulation (PAM), by pulse density modulation (PDM), by the combination of the above mentioned methods.

Usage of the popular control method by PWM (Fig. 4a) results in losses during hard switching with a high switching frequency.

The control method by PAM requires a controlled voltage source for the inverter. For this reason the main circuit and control circuit are more complex. This voltage source can be a thyristor rectifier or diode rectifier with a chopper [6, 8,10].

The control method by PFM (Fig. 4b) should take place when the switching frequency is higher than f_{syn}. Then conditions for a soft switching (ZVS) are created and the transformer will be not saturated. The main circuit is relatively simple because the DC voltage is not controlled. The control circuit is also relatively simple. During the work with frequency near to f_{syn} the inverter's output power is maximal and is described by equation (10).

The PDM control method (Fig. 4c) consists in sending the maximal power to the load with variable duty cycle *D* [1, 2, 3, 7, 8]. The inverter's output power by PDM modulation is proportional to *D*. The maximal inverter's output power during the synchronization of the inverter's voltage and current waves (and *D* = 1) is described by equation (10).

$$(10)\quad P_{Inv\_\max}(f_{syn}) = \frac{1}{T_s/2}\int_0^{T_s/2} U_{dc} I_{Inv\_m} \sin(\omega_s t)\,dt \approx 0.9 U_{dc} I_{Inv}$$

The power flow is interrupted by turning off all transistors or turning on two bottom (or upper) transistors. The main circuit is relatively simple because of non-controlled DC voltage, whereas the control circuit is complicated. This control circuit should guarantee, that the transformer will not be saturated regardless of the duty cycle. Especially an even number of half waves of the inverter's output voltage should be guaranteed. During an interruption of the power flow the control circuit should guarantee, that the switching frequency (noted before the interrupt) is stored.

The PDM method is especially profitable for low treatment power because it ensures that the discharges are even and stable. Other methods did not secure the stability of discharges and were not suitable for systems operating in wide range of power (Tab.1). However the PDM method has a drawback: it often produces an electric spark or an arc discharge because of high maximal power. In this case combination of the above mentioned methods are desirable. The combinations of PFM, PAM, PDM methods guarantee soft switching in the inverter.

The inverter's output power (11) can be controlled by the PDM and PFM modulations as follows:

$$(11)\quad P_{Inv} = D \cdot P_{Inv\_\max}(f_s)$$

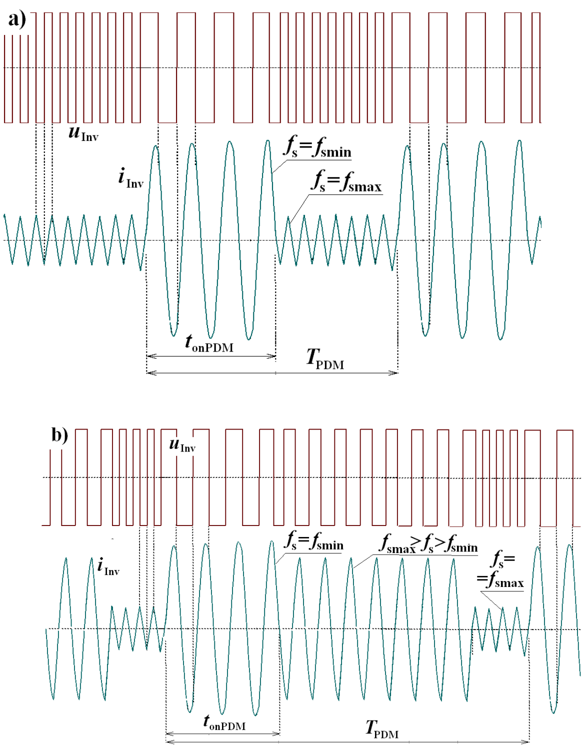

Fig.5. New PDM-PFM control methods of a series-resonant inverter for purpose of corona surface treatment: a) with controlled duty cycle, b) with not controlled duty cycle (example)

Combination of PDM and PFM methods were earlier described in publications [2, 3]. Author of those papers developed a method of control which is a combination of PDM and PFM. This method differs from the ones described in publications [2, 3], as the operation of the

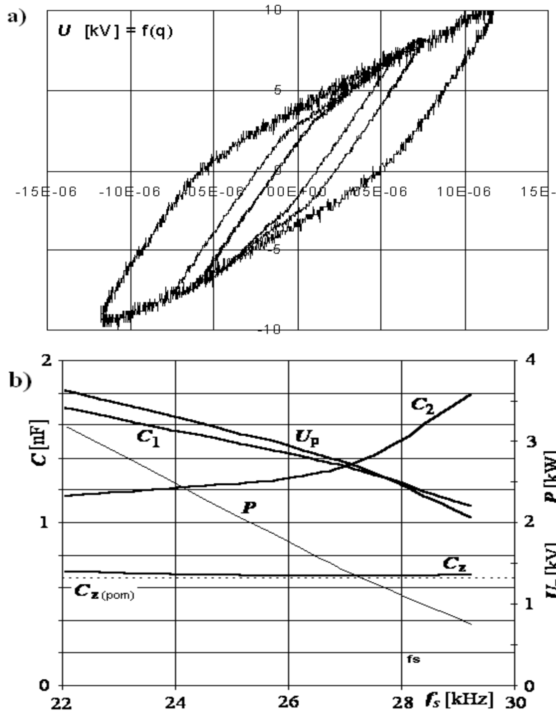

Fig. 6. Characteristics of the corona treatment system during controlling switching frequency of inverter (chamber 2): a) voltage of electrodes in function of a charge (*P*= 25, 50, 106% x 3kW) ; b) power, U_p voltage and capacity of electrodes in function of switching frequency f_s

inverter is not stopped but instead it operates with much higher frequency.

New PDM-PFM control methods of corona treatment

<u>First method</u> relies on transfer of the maximal power with a controlled duty cycle but limited like in [2,3].

<u>Second method</u> relies on transfer of the maximal power with uncontrolled duty cycle limited like in [2,3].

After an ignition of the corona discharge and operating with maximal (limited) power, the power decreases so it's average value is equal to a reference value. Despite the power decreasing, the discharges are even and stable on full- length of the electrodes because of a strong ionization of the air, which is a result of the operation with maximal power. In this case, a condition of discharge evenness is a relatively high PDM frequency.

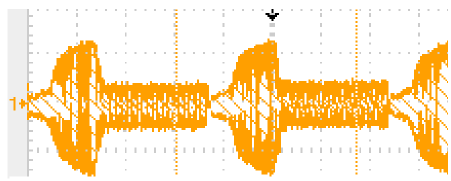

Fig.7. Output current waveform of a PDM and PFM controlled inverter (new control strategy); *i* [10A/u], *t* [2,5ms/u]

The main circuit (for the new PDM-PFM methods) is relatively simple because of non-controlled DC voltage. The control circuit is simple too. The control circuit is simpler than the circuits described in [1, 2, 3, 8, 9]. It does not require circuits for counting half waves of inverter's output voltage and for remembering the frequency for the moment

Table 1. Chosen attributes of different control methods for series resonant inverter in application for corona treatment system.

feature	PWM	AM	PFM	PDM	PDM-PFM according to [2, 3]	Now PDM-PFM	
						method 1	method 2
treatment with "low" power	bad	bad	bad	good	good	good	good
treatment with "high" power	good	good	good	good	good	good	good
prevention of spark / arc	$D < D_{ogr}$	$U_{dc} < U_{ogr}$	$f_s > f_{ogr}$	lack of possibilities	$(f_s > f_{ogr})$		
soft switching (ZVS)	no	yes	yes	yes	yes	yes	yes
main circuit	simple	complex	simple	simple	simple	simple	simple
control circuit	simple	complex (control of rectifier or chopper and inverter)	simple	complex (additional circuits responsible for counting half waves of the output voltage and storing the frequency)		simple	simple

when the power was cut. A combination of PDM and PFM methods where the operations of the inverter are not stopped but instead the inverter works with much higher frequency, is unique (Fig. 7). The rate of changes of the frequency is limited from the top and from the bottom according to the power characteristics depicted on figures 3 and 6b. Increasing the switching frequency above the f_{sgr2} (9) results in complete lack of discharges (Fig. 3).

The selected properties of different resonant inverter's control methods used for the treatment of polymer materials are presented in Table 1. Variables' names with an „ogr" subscript indicate values of limits enforced by the control circuit.

Experimental results

Figure 6 presents characteristics of a prototype system (chamber 2, P_N=3kW; 2 rotating electrodes 170cm, Φ100, silicone Luraflex 2mm; 2 bar toothed electrodes: 160cm x 3,6cm) during the controlling of the switching frequency f_s of the inverter. Values C_1, C_2 and U_p that are depicted on the Figure 6b were determined from waveforms on Figure 6a. The DC voltage was constant (about, 510V).

Figure 7 presents output current waveforms of a PDM and PFM controlled inverter (new control strategy).

On this figure periodic growth and a reduction of the inverter's output current corresponding to power pulsations of the activation process are clearly visible. It corresponds to the changes of working point location on characteristic P=f(f_s) (fig. 3, fig. 6b).

The shapes of characteristics in Figure 6a prove that the assumed model of the discharge chamber (fig. 1c) and discharge are correct.

The value of the ignition voltage U_p depends on the degree of the air ionization. The shorter the time for the deionization (i.e. the higher is the switching frequency), the ignition voltage is lower. Similarly the higher the frequency, the bigger the ionization and higher capacitance of the air capacitor C_2 (Figure 6b).

Conclusions

The author of this paper elaborated a new methods of control which is a combination of PDM and PFM. Those methods enable a possibility of power regulation of the corona treatment and secure the conditions for the soft switching process (ZVS). The method was evaluated through simulations and experiments. A few prototypes has been built and tested.

The developed methods of control have excellent properties in terms of quality of the technological process and the simplicity of the main circuit and the control circuit.

Simulations and mathematical models are well suited for practical use. Analytical determination of the boundary frequencies, parameters of the discharge chamber and the power of the process basing on the trajectory of u=f(q) are important factors while designing an inverter device.

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