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RANDOM INTEGRAL PULSE DENSITY MODULATION - CONTROL STRATEGY FOR CLASS *D* AND *DE* RESONANT INVERTERS

Summary. The work concerns the control strategy of output power of half bridge class D (DE) series resonant inverter. The control is realised inside the inverter. Proposed control strategy bases on Integral Pulse Density Modulation (IPDM) but what is new, the Integral Pulse is randomly set in modulation period. The r-IPDM ensures ZCS conditions of transistors and allows operation at relatively high switching frequency. The main idea of this paper is to emphasize advantages of r-IPDM strategy compare to standard IPDM. The r-IPDM characterised in spread output current spectrum and broadband noise spectrum. The paper contains the idea of the control strategy and results of measurements: inverter outputs voltages and current, output power control, Fourier analysis of the output current, noise spectrum. The control system bases on Hitachi H8/3048 16-bit microcontroller. It is concluded that the half bridge series resonant inverter together with the proposed r-IPDM control strategy is attractive solution for e.g. high frequency induction heating applications.

STOCHASTYCZNA MODULACJA GĘSTOŚCI IMPULSÓW ZINTEGROWANYCH - STRATEGIA STEROWANIA FALOWNIKÓW REZONANSOWYCH KLASY *D* i *DE*

Streszczenie. Artykuł dotyczy metody sterowania mocy wyjściowej szeregowych falowników rezonansowych klasy D (DE) w układzie półmostkowym, przy czym sterowanie odbywa się w obrębie falownika. Proponowana metoda sterowania bazuje na standardowej metodzie Modulacji Gęstości Impulsów Zintegrowanych (IPDM), ale, co jest nowością, Puls Zintegrowany jest losowo (random) pozycjonowany w okresie modulacji. Metodę tę oznaczono w skrócie jako r-IPDM. Tranzystory falownika pracują w warunkach ZCS pozwalając na stosowanie metody przy wysokich częstotliwościach. Głównym celem jest podkreślenie zalet metody r-IPDM w porównaniu ze standardową IPDM. Zaproponowana metoda charakteryzuje się rozmytym widmem prądu odbiornika w zakresie subharmonicznych, a hałas generowany przez falownik przyjmuje charakter szumu szerokopasmowego. W artykule opisano idee metody sterowania oraz wyniki badań laboratoryjnych: oscylogramy napięcia i prądu wyjściowego falownika, charakterystyki sterowania mocy, analizę harmoniczną prądu odbiornika oraz hałasu. Układ sterowania bazuje na 16-bitowym mikrokontrolerze Hitachi H8/3048. W podsumowaniu stwierdzono, że metoda r-IPDM jest atrakcyjnym rozwiązaniem dla półmostkowego falownika klasy D w zastosowaniu np. do wysokoczęstotliwościowego nagrzewania indukcyjnego.

1. INTRODUCTION

The need for the control of the output power realised inside the inverter still exists as, when solved, it results in its price reduction. Even if the control leads to variation of harmonic content of the output current, such solution is acceptable in certain applications. The induction heating is the application example in case there is no need to keep the frequency content within narrow limits. Searching for the solution which allows the control of the output power of the series half bridge inverter (fig. 1) was motivation for this work.

It is necessary to underline that the half bridge series resonant inverter is attractive solution as it allows to match the load and the supply *E* especially in case of small output power where the matching transformer can be eliminated.

Fig. 1 shows the half bridge topology of class D series resonant inverter. The power circuit contains the voltage divider C_{d1} and C_{d2} , and transistors *T1* and *T2*. The load of the inverter is represented by serial *RLC* branch.

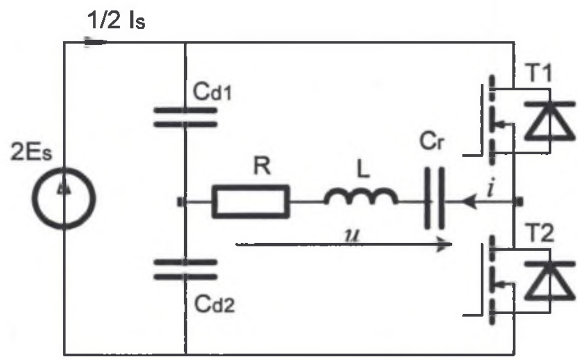

Fig. 1. Class D half bridge series resonant inverter
Rys. 1. Szeregowy falownik rezonansowy klasy D w układzie półmostkowym

2. OVERVIEW OF THE SUBJECT

There are some methods of control of output power of class D series resonant inverter. They can be divided into two classes. The first class is realised outside inverter while the second one is done by the inverter itself. The first class is termed Amplitude Modulation (AM) and is realised by, for instance, the dc/dc buck converter or controlled rectifier. The second class embraces such methods as follows: Frequency Modulation (FM), Pulse Width Modulation (PWM), Pulse Density Modulation (PDM) and mixed method, e.g. PWM & FM. The pulse density modulation (PDM) and PWM modulation has many realisations [1, 2, 3, 4, 5]. Neither of those papers reports on applied solution of PDM control strategy for half bridge resonant inverter (fig. 1). They present only the PDM control strategy for full bridge topology. Based on PDM strategy [1], authors firstly proposed the IPDM strategy for the half bridge topology [7]. Now authors propose the modification of this method - random IPDM (r-IPDM) to improve the output current spectrum and noise spectrum [10, 11]. The proposed r-IPDM control strategy ensures *ZCS* conditions for *on* and *off* of transistors and allows operation at relatively high switching frequency.

3. DESCRIPTION OF THE PROPOSED CONTROL STRATEGY

3.1. The standard IPDM control strategy

The strategy is explained using schematic diagram of the inverter output voltage and current (fig. 2). The method bases on Density Modulation of the "Integral Pulses". The length and the shape of Integral Pulse is constant in defined control strategy, e.g. *6* in *6+kp* strategy. The Integral Pulse can exist as Combined Integral Pulse (fig. 2a) or as split into High and Low Integral Pulses (fig. 2b). The control of the output power is realised by changing number of *kp* pulses in modulation period $T_M = pT/2$. The output power control range is about 10-100%. It is done in order to not disturb the natural direction of sinusoidal oscillations of serial RLC circuit and to violate ZCS conditions.

3.2. The random IPDM control strategy (r-IPDM)

The strategy is similar to IPDM but what is new, the Integral Pulses are randomly positioned in modulation period T_M. The output power depends on average density of Integral Pulses. Four random modulation algorithms were implemented [8]. They are different in shape of Integral Pulse and possible positions in modulation period T_M. The best one random modulation algorithm, with Combined Integral Pulse is presented in this paper.

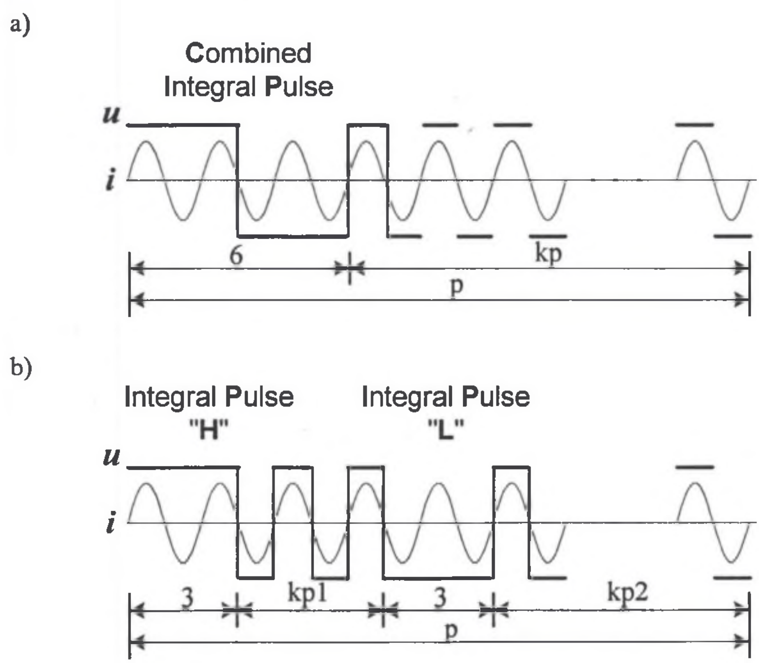

Fig. 2. Examples of standard IPDM power control strategy (*6+kp*) of Class D half bridge series resonant inverter: a) Combined Integral Pulse is applied, b) Integral Pulses is split into High and Low Integral Pulse

Rys. 2. Przykład sterowania falownika rezonansowego klasy DE standardową metodą IPDM (*6+kp*): a) sterowanie impulsem zintegrowanym, b) puls zintegrowany podzielony na Puls Górny (H) i Puls Dolny (L)

3.3. Control circuit

The control is realised in the system presented in fig. 3. It bases on Phase Locking Loop (*PLL*: PD, LPF, VCO) with the reference signal, which is the instant the current of RLC branch crosses zero. The modulation procedure is realised by the Hitachi H8/3048 16-bit microcontroller [9, 12, 13].

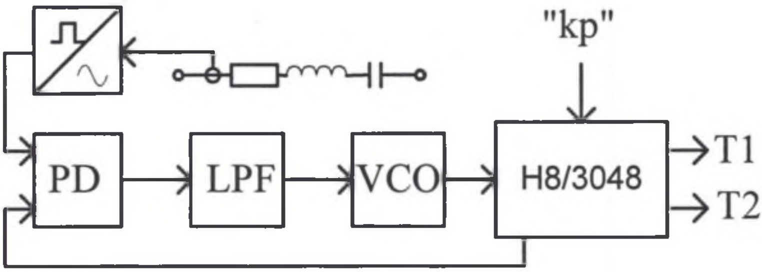

Fig. 3. IPDM and r-IPDM control circuit of class D inverter: PD - phase detector, LPF - lowpass filter, VCO - voltage controlled oscillator, H8/3048-16bit controller, T1, T2 - transistors control signal

Rys. 3. Układ sterowania falownika klasy D: PD - komparator fazy, LPF - filtr dolnoprzepustowy, VCO - przetwornik napięcie/częstotliwość, H8/3048 - mikrokontroler 16-bitowy; T1, T2 - sygnały sterowania tranzystorów

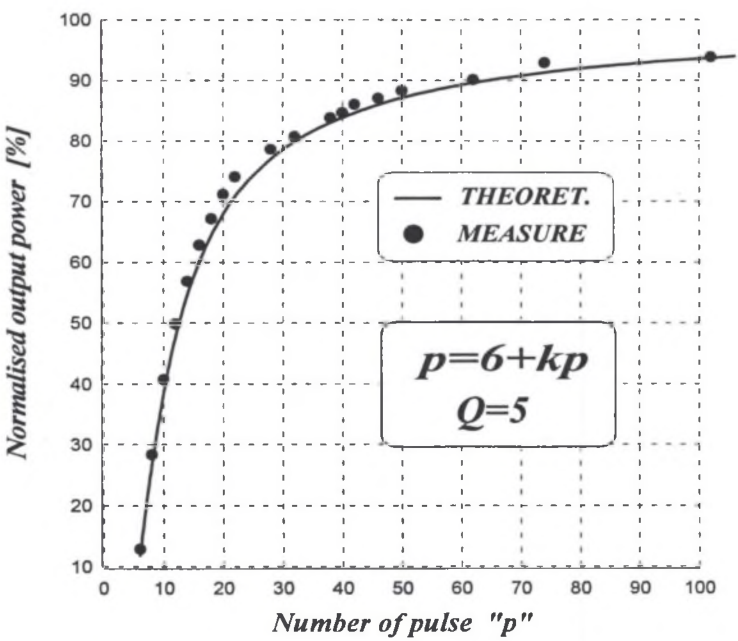

Fig. 4. Normalised output power characteristics of standard IPDM *6+kp* control strategy - the comparison of measurements and analytical results for Q=5

Rys. 4. Charakterystyki sterowania mocy wyjściowej dla standardowej metody *6+kp* - porównanie wyników pomiarowych i teoretycznych dla odbiornika o dobroci Q=5

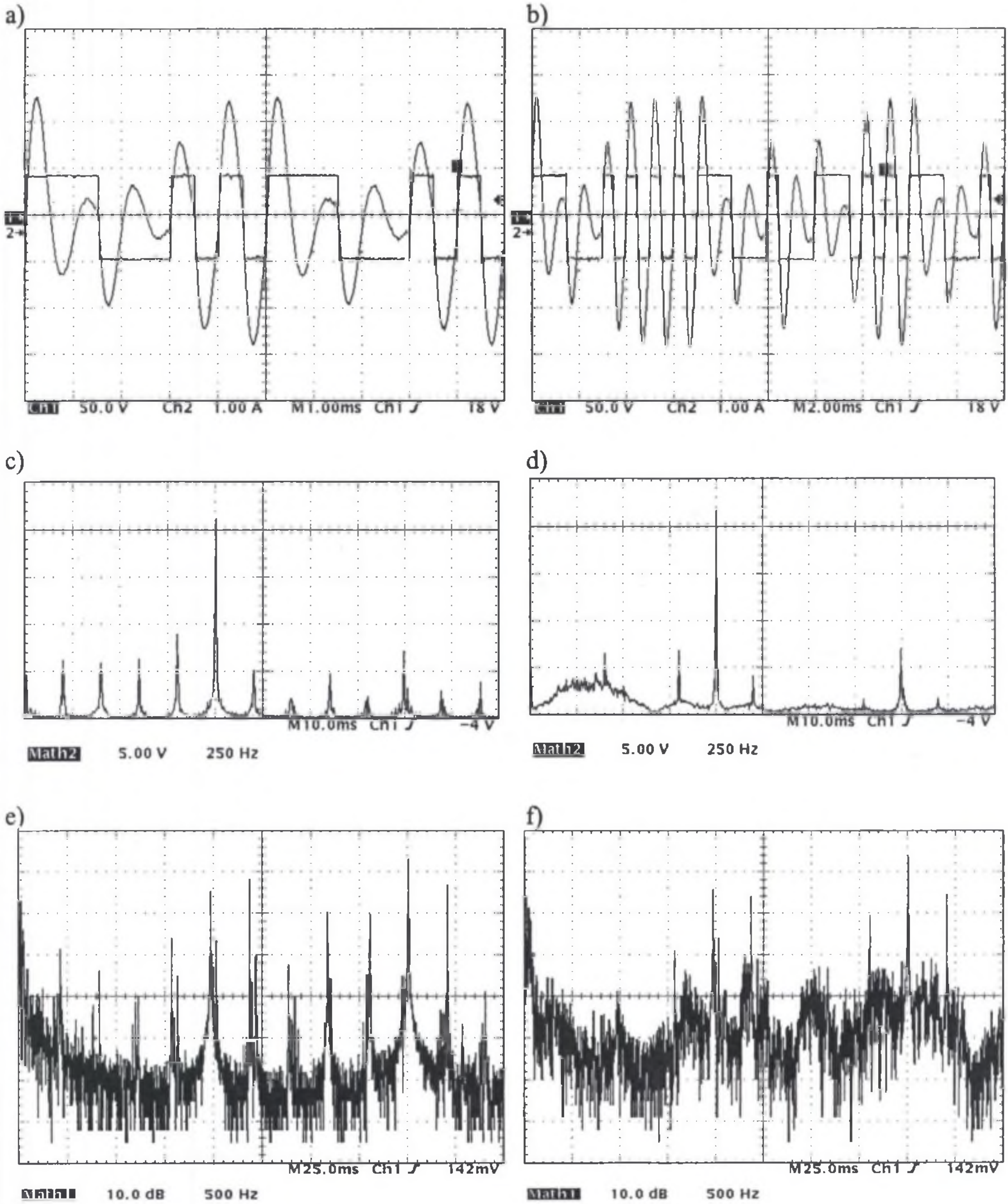

Fig. 5. Comparison of the standard IPDM (Left Side) and Random r-IPDM (Right Side). Strategy (*6+4*) - Combined Integral Pulse; *Q*=5, resonant frequency of *RLC* load *fo*=1 kHz; a, b) output voltage and current of the inverter; c, d) spectrum of output current, scale - 1 A/div; e, f) spectrum of the noise

Rys. 5. Porównanie standardowej metody IPDM (lewa kolumna) i stochastycznej metody r-IPDM (prawa kolumna). Strategia (*6+4*) - Puls Zintegrowany Zespolony; *Q*=5, częstotliwość rezonansowa obwodu *RLC* *fo*=1 kHz; a, b) napięcie i prąd wyjściowy falownika; c, d) widmo harmonicznych prądu odbiornika, skala 1 A/dz; e, f) widmo hałasu

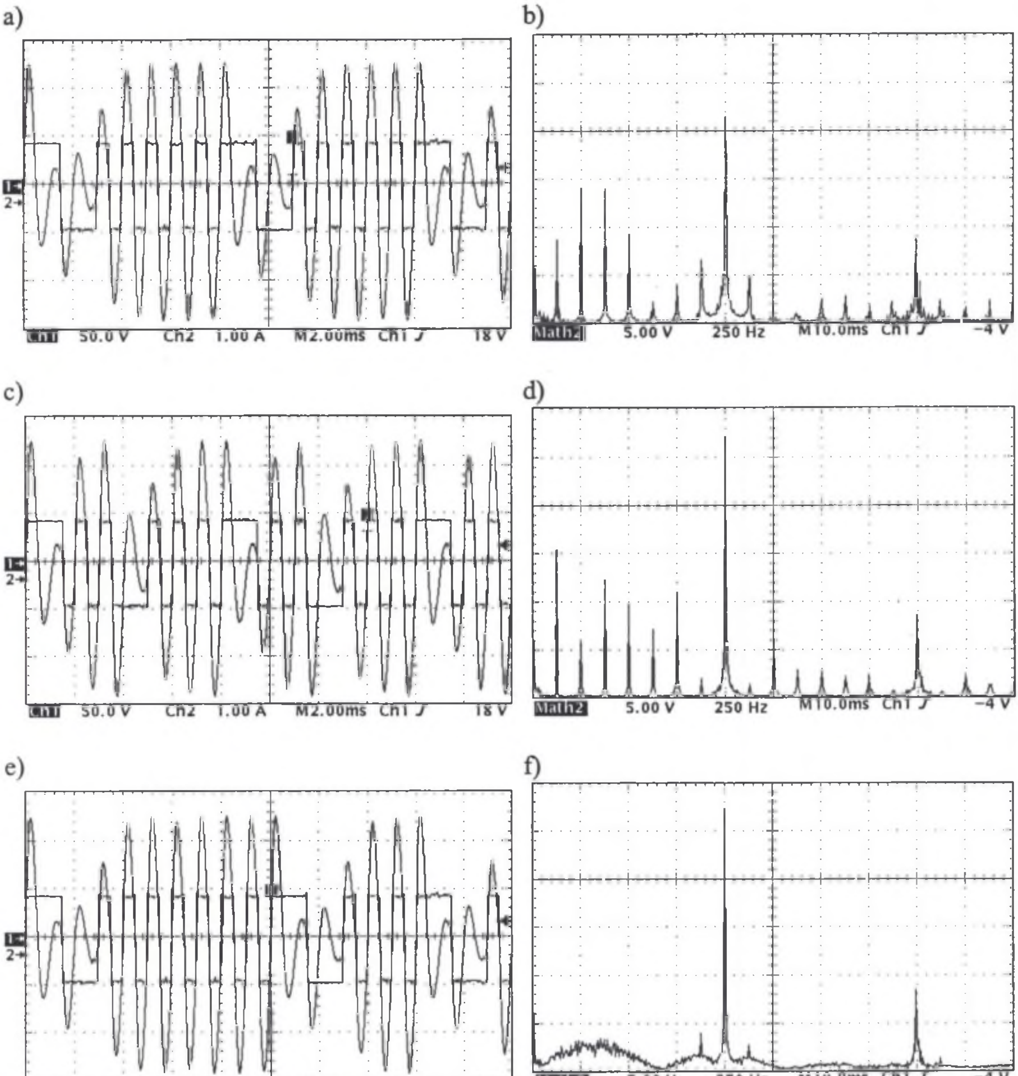

Fig. 6. Comparison of output voltage and current of the inverter (Left Side) and spectrum of the output current (scale - 1A/div); *Q*=5, *fo*=1 kHz
a, b) IPDM strategy (*6+10*), Combined Integral Pulse;
c, d) IPDM strategy (*6+10*), Split Integral Pulse;
e, f) random r-IPDM strategy (*6+10*), Combined Integral Pulse

Rys. 6. Porównanie napięć i prądów wyjściowych falownika (lewa kolumna) oraz widm harmonicznych prądu odbiornika (prawa kolumna, skala 1A/dz), *Q*=5, *fo*=1 kHz;
a, b) standardowa metoda IPDM (*6+10*), Puls Zintegrowany Zespolony;
c, d) standardowa metoda IPDM (*6+10*), Puls Zintegrowany Rozdzielony;
e, f) stochastyczna metoda r-IPDM (*6+10*), Puls Zintegrowany Zespolony

4. LABORATORY INVESTIGATION

Measurements were carried out in IGBT based laboratory inverter (1 kW, 1 kHz). The supply voltage of the inverter $2E_S$=100 V, the resonant frequency of the *RLC* load f_0=1 kHz, the load quality factor Q=5.

Tektronix oscilloscope TDS620B with FFT module was used for current and noise harmonics analysis. For noise analysis the *Brüel & Kjaer 2238 Mediator* analyser with microphone *Brüel & Kjaer 4148* (16 Hz - 12 kHz) was used.

The comparison of measurements and analytical results for normalised output power characteristics of standard IPDM *6+kp* control strategy are depicted in fig. 4. The analytical results were obtained using piecewise linear model and they show good conformity compare to measurement results.

Two method IPDM and r-IPDM were compared based on: a) shape of the inverter output voltage/current, b) spectrum of output current, c) spectrum of noise. The results of comparison for p=*6+4* strategy shows fig. 5. Transistors *ZCS* conditions are satisfied. The comparison shows that r-IPDM method characterized in spread output current spectrum but the fundamental harmonic of 1kHz is dominated (compare fig. 5c and fig. 5d).

The comparison of spectrum of noise shows, that r-IPDM method characterized in broadband character of the noise (fig. 5e and fig. 5f). Such character of noise is more acceptable for a human ear.

Another comparison results show fig. 6. Three IPDM method (p=*6+10*) were compared based on output current spectrum: a) IPDM with Combined Integral Pulse, b) IPDM with Split Integral Pulse, c) r-IPDM with Combined Integral Pulse. Like in previous comparison, r-IPDM method characterizes in spread output current spectrum with domination of 1 kHz harmonic.

5. CONCLUSIONS

The proposed control strategy allows the control of the output power of the high frequency, half bridge class D and DE resonant inverters. The control is realised inside the inverter, the DC/DC chopper is not required.

Transistors ZCS conditions and the low switching losses allow to reach high switching frequencies over 1 MHz. The proposed control method can be applied to high frequency class DE inverters.

The output power control range is about (10-100)% of full output power.

The half bridge series resonant inverter together with the proposed r-IPDM control strategy is attractive solution in case there is no need to keep the frequency content within narrow limits, e.g. high frequency induction heating applications. Additionally, the current harmonics content is possible to be partially controlled. It means possibility of the control of the heating rate and relevant distribution of heating sources.

The analysis of harmonics spectrum of the output current shows that r-IPDM is characterised by spread of current spectrum (e.g. compare fig. 6b, d, f). It is results in broadband character of the noise more acceptable for a human ear.

REFERENCES

1. Fujita H., Akagi H.: *Pulse-Density-Modulated Power Control of a 4 kW, 450 kHz Voltage-Source Inverter for Induction Melting Application.* IEEE Trans. on Industry Applications, Vol.32, No.2, March/April 1996, pp.279-286.
2. Nagai S., Kim Y., Nakaoka M.: *Development of Advanced Soft-Switching PWM&PFM Hybrid Control-Based Series Load-Resonant Inverter Topologies for High-Frequency Applications.* PEMC'94, Warsaw, September 1994, pp.474-479.
3. Chibani A., Nakaoka M., Maruhashi T.: *New High-Frequency Resonant PWM Inverter-Linked DC-DC Converter Using Insulated Gate Transistors*, 2nd European Conference on Power Electronics and Applications, Grenoble, Sept. 1987, Vol. 1, pp. 213-218.
4. Kazimierczuk M.K., Czarkowski D.: *Resonant Power Converters*, John Wiley & Sons, Inc., USA 1995.
5. Matysik J.: *Integration control methods for class D transistor source inverters with series resonant circuit*, (title of original: Metody sterowania integracyjnego tranzystorowych falowników napięcia klasy D z szeregowym obwodem rezonansowym), publishing house of the Warsaw University of Technology, ELEKTRYKA z.114, ISSN 0137-2319, Warsaw 2001.
6. Kasprzak M.: *Analysis of selected high frequency Mosfet inverters devoted for induction heating applications*, PhD thesis, Silesian University of Technology, Gliwice, Poland, 1997.
7. Grzesik B., Kaczmarczyk Z., Kasprzak M.: *Integral Pulse Modulation - new strategy for series resonant half bridge inverter of Class D and DE*, International Conference on Electrical Drives and Power Electronics EDPE'99, 5-7 October 1999, the High Tatras, Slovakia, pp. 100-104.
8. Górka S.: *Project and Realisation of Microprocessor Random PDM Controller for Series Resonant Inverter*, M.Sc. Thesis, Silesian University of Technology Gliwice 2001.
9. Hube J.M., Flieller D. and all: *Phase Locking Control of a Resonant DC-AC Converter*, EPE'97, Trondheim, pp. 2.303-2.308.
10. Trzynadlowski A.M., Blaabjerg F., Pedersen J.K., Kirlin R.L., Legowski S.: *Random Pulse Width Modulation Techniques for Converter-Fed Drive Systems - A Review,* IEEE Tran. On Ind. Appl., vol.30, no.5, Sep/Oct 1994, pp.1166-1175.
11. Bech M.M., Pedersen J.K., Blaabjerg F.: *Random Modulation Techniques in Power Conversion - An Update,* Proceedings of the 7th International Power Electronics & Motion Control Conference, Budapest Hungary, 2-4 Sep. 1996, pp.3/357-3/365.
12. Wieczorkowski R., Zieliński R.: *Computers Random-number Generators*, published by WNT Warszawa 1997 (title of original: Komputerowe Generatory Liczb Losowych).
13. H8/3048 Series, H8/3048F-ZTAT Hardware Manual - Hitachi, January 1995.

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