A DEADBEAT CONTROLLER FOR BIDIRECTIONAL HIGH-FREQUENCY LINK INVERTER

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To my beloved parents and sister

for their enduring love, encouragement, motivation, and support

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ABSTRACT

This thesis presents a Deadbeat controller for Bidirectional High-Frequency Link (BHFL) inverter. Deadbeat control technique is applied as it exhibits fast dynamic response. The proposed controller consists of inner current loop, outer voltage loop and a feedforward controller. The feedforward controller, which imposes a gain scheduling effect according to the reference signal, is used to compensate steady-state error of the system. The main property of the controller is that the current loop controller and the voltage loop controller have the same structure, and uses the same sampling period. This simplifies design and implementation of the controller. To improve overall performance of the system, disturbance decoupling networks are employed. The design takes into account the model discretisation effect. As such, accurate disturbance decoupling can be achieved. The robustness of the inverter towards load variations is thus increased. To avoid transformer saturation due to low frequency voltage envelope, an equalised Pulse Width Modulation (PWM) technique is proposed. The performances of the BHFL inverter with the proposed controller are investigated using MATLAB/Simulink. The simulation results are compared with the conventional Proportional-Integral (PI) controller and the multirate digital controller. The feasibility of the controller is further validated by a 1kVA laboratory prototype. The DS1104 Digital Signal Processor (DSP) from dSPACE is used to implement the control algorithm. The results show that the BHFL inverter with the proposed Deadbeat controller has excellent dynamic response and low output voltage distortion (1.5%). It also performs well under cyclic step load variations, and good steady-state response under highly nonlinear loads.

ABSTRAK

Tesis ini menyampaikan pengawal *Deadbeat* untuk Penyongsang Dwihala Frekuensi Tinggi. Teknik kawalan *Deadbeat* digunakan kerana ia mempunyai sambutan fana yang pantas. Pengawal yang diusulkan terdiri daripada gelung arus dalaman, gelung voltan luaran dan pengawal suap-depan. Pengawal suap-depan yang mempunyai kesan penjadualan gandaan berdasarkan isyarat rujukan digunakan untuk pampasan ralat sistem pada keadaan mantap. Ciri utama pengawal tersebut ialah pengawal gelung arus dan pengawal gelung voltan mempunyai struktur yang sama, dan menggunakan tempoh sampelan yang sama. Ini memudahkan rekabentuk dan pelaksanaan pengawal tersebut. Demi meningkatkan prestasi keseluruhan sistem, rangkaian nyahgandingan gangguan digunakan. Rekabentuk tersebut mengambil kira kesan pendiskretan model. Dengan ini, nyahgandingan gangguan yang jitu boleh dicapai. Ketegapan penyongsang terhadap perubahan beban turut dapat ditingkatkan. Demi mengelakkan ketepuan pengubah akibat voltan sampul frekuensi rendah, teknik penyamaan modulatan lebar denyut telah diusulkan. Penilaian terhadap prestasi Penyongsang Dwihala Frekuensi Tinggi dengan pengawal yang diusulkan telah dijalankan dengan menggunakan *MATLAB/Simulink*. Keputusan simulasi telah dibandingkan dengan pengawal Kamiran Berkadaran serta pengawal digit berbilang kadar. Kebolehlaksanaan pengawal selanjutnya disahkan melalui satu contoh dasar ujikaji berkadaran 1kVA. Pemproses Isyarat Digit (DSP) DS1104 dari *dSPACE* telah digunakan untuk melaksanakan algoritma pengawal. Keputusan menunjukkan bahawa Penyongsang Dwihala Frekuensi Tinggi yang dikawal oleh pengawal *Deadbeat* mempunyai sambutan fana yang baik, serta herotan voltan keluaran yang rendah (1.5%). Keputusannya juga amat memuaskan bawah perubahan beban langkah berkitar, dan sambutan keadaan mantap yang bagus bawah beban tak lelurus.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

C	-	Filter capacitor
E, e	-	Error signal
f_c	-	Filter cut-off frequency
f_{net}	-	Transfer function of artificial neuron
f_s	-	Sampling frequency
f_{sw}	-	Switching frequency
i_c	-	Filter capacitor current
i_d	-	Current disturbance
i_{dc}	-	DC source current
i_L	-	Filter inductor current
i_o	-	Output current
i_{or}	-	Rectified output current
i_{ref}	-	Current reference
K_D	-	Derivative gain of PID controller
K_i	-	Current loop controller gain
K_I	-	Integral gain of PID controller
K_P	-	Proportional gain of PID controller
K_v	-	Voltage loop controller gain
L	-	Filter inductor
$N1$, $N2$	-	Transformer winding
O_j	-	Output of artificial neuron
$\mathrm{P_o}$, p_o	-	Output power
R, r	-	Reference signal
r_c	-	Equivalent Series Resistance of filter capacitor
R_j	-	Net input of artificial neuron
r_L	-	Equivalent Series Resistance of filter inductor

T, T_s	-	Sampling period
t_d	-	Dead-time
T_i	-	Current loop sampling period
t_{on}	-	Switch on period
T_{sw}	-	Switching period
T_v	-	Voltage loop sampling period
U, u	-	Control signal or control variable
v_{cl}	-	Output voltage of cycloconverter
$\mathrm{V_d}$	-	DC link voltage
v_d	-	Voltage disturbance
$\mathrm{V_{dc}}$	-	DC source voltage
v_{HF}	-	High-frequency voltage
v_i	-	Input voltage of converter
v_o	-	Output voltage
v_{or}	-	Rectified output voltage
v_{pwm}	-	Gate signal for high-frequency PWM bridge
v_{pwm_rect}	-	Rectified PWM voltage
v_r	-	High-frequency rectified voltage
v_{rect}	-	Rectified sinusoidal voltage
v_{ref}	-	Voltage reference
v_s	-	Gate signal for active rectifier
v_u	-	Gate signal for polarity-reversing bridge
W_{ij}	-	Weighting elements of artificial neuron
x_i	-	Input of artificial neuron
Y, y	-	System output
Z	-	Output impedance
z^{-1}	-	Unit delay
δ	-	Sliding surface or sliding line
θ_j	-	Bias in artificial neuron
ω	-	Cut-off frequency of low-pass filter
ω_o	-	Oscillating frequency

LIST OF ABBREVIATIONS

ADC	-	Analogue-to-Digital Converter
BHFL	-	Bidirectional High-Frequency Link
COA	-	Centre of Area
DSMC	-	Discrete-time Sliding Mode Control
DSP	-	Digital Signal Processor
EMF	-	Electromotive Force
EMI	-	Electromagnetic Interference
GUI	-	Graphical User Interface
IGBT	-	Insulated Gate Bipolar Transistor
IIR	-	Infinite Impulse Response
MOM	-	Mean of Maximum
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
MPPT	-	Maximum Power Point Tracking
PI	-	Proportional-Integral
PID	-	Proportional-Integral-Derivative
PLL	-	Phase Lock Loop
PV	-	Photovoltaic
PWM	-	Pulse Width Modulation
RTI	-	Real-Time Interface
SMC	-	Sliding Mode Control
SPWM	-	Sinusoidal Pulse Width Modulation
THD	-	Total Harmonic Distortion
TTL	-	Transistor-Transistor Logic
UPS	-	Uninterruptible Power Supply
VSC	-	Variable Structure Control
VSI	-	Voltage Source Inverter

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

With the growing energy demand, increasing global environmental issues, and depleting energy resources (coal, oil and gas), the need to develop and utilise new sources of energy seems inevitable. For these reasons, renewable energy resources such as solar, wind, biomass and geothermal, appear as important alternative energy options. Solar energy, one of the few clean and abundant renewable energy resources, has come into the limelight in recent years. Research in this area is going on progressively, even in countries with limited sunshine days per year. Blessed with year-rounded sunshine, the solar energy is particularly a feasible energy source in Malaysia. It is important to note that the Ministry of Science, Technology and Innovation, Malaysia (MOSTI)[1] has classified the solar power for residential application as the high priority energy research area [1].

To harness the solar energy, various energy conversion technologies are required. Photovoltaic (PV) panels, or commonly known as solar panels, are devices used to convert sunlight into electricity. The acronym PV stands for photo (light) and voltaic (electricity), whereby sunlight photons free electrons from the atoms of the panels and creates a voltage difference. Since the PV panels convert sunlight into electricity in the form of direct current (dc), while most electrical devices for residential applications require alternating current (ac), dc-ac power conversion is

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[1] Formerly known as the Ministry of Science, Technology and the Environment, Malaysia (MOSTE).

needed. This can be realised by power converter known as inverter. In solar energy systems, PV inverter is the power converter used specifically to convert the dc power obtained from PV panels into ac power.

From the economic point of view, although the cost of PV power is relatively high as compared to other renewable energy sources such as wind and biomass, it has decreased from more than \$50/W in the early 1980s to about \$5/W today [2]. This can be attributed to the economics of scale and subsidies from the government, as that of Japan and Germany [2], [3]. The future plan from utility providers to “purchase” electricity (“buy back” policy) generated by users, for example the Net Metering System [4], has further encouraged the development of grid-connected PV systems. Besides, the PV panels can be designed as part of the roof structure, replacing the conventional ceramic or concrete-based roof tiles. In view of these advantages, PV is envisaged as a viable economics proposition of the future.

As the solar energy for residential application is gaining considerable interest, there have been numerous PV inverter topologies proposed in the literature [5]-[12]. Basically, there are two types of PV inverters, namely the stand-alone PV inverter and the grid-connected PV inverter. In the stand-alone mode, the inverter operates independently of the grid, and is normally equipped with batteries for energy storage. On the other hand, the grid-connected PV inverter operates in parallel with the grid without battery storage. If one were to consider the application of PV for residential, it is desired that the inverter be able to operate in both operation modes, together with the Uninterruptible Power Supply (UPS) features. Furthermore, the future trend of inverter design is high efficiency, light weight, small size and low cost. In order to achieve these requirements, high-frequency link inverters with bidirectional power flow capability have been proposed [13]-[17].

In residential PV applications, the types of loads connected to the PV inverter are rather uncertain. Nonlinear loads such as rectifiers in computer systems could cause intense distortion in the output current and voltage waveform. Therefore, a high performance inverter is required to maintain the desired sinusoidal output voltage waveform over all loading conditions and transients. This is especially important if the PV inverter is operated in the stand-alone mode. Generally, the performance of an inverter is evaluated in terms of its dynamic response over sudden load changes and steady-state output voltage waveform distortion. The requirements can only be achieved by employing closed-loop control. Over the past decades, several control techniques have been proposed for closed-loop regulation of inverters [18]-[40]. Although most of the control techniques were developed based on line-frequency inverters, they can be adopted in high-frequency link inverters. In addition, a complete PV system may be incorporated with Maximum Power Point Tracking (MPPT) controller [8], [11], which is used to transfer maximum available power from the PV panels to the PV inverter.

Traditionally, closed-loop inverter systems have been implemented using analogue components, such as resistors, capacitors and operational amplifiers. Today, with the explosive growth and expanding efficiency of digital technology, digital-based inverter system is getting more prevalent over its analogue-based counterpart. Microprocessors and Digital Signal Processors (DSPs) have been used for Pulse Width Modulation (PWM) pulse generation and real-time controller of inverter systems. In fact, digital-based systems have many advantages over analogue-based systems. For instance, digital-based systems are programmable thus offering flexibility in system modifications. In contrast, analogue-based systems depend on the variation of constant condition of parts. Hence, the complicated parameters tuning is avoided in digital-based systems. This makes the design process of closed-loop controller for inverter systems much easier, enabling shorter time of system development. Moreover, digital-based systems are robust towards environmental effects and ageing drift, tangibly enhance the system performance. Therefore, adopting digital technique is an extra motivation to the design and development of closed-loop inverter systems.

1.2 Objective, Scope and Importance of Research

1.2.1 Objective of Research

The objective of this research is to propose, design and implement a digital controller for closed-loop regulation of Bidirectional High-Frequency Link (BHFL) inverter. The BHFL inverter topology was originally proposed by Ramli *et al.* [17]. The controller scheme chosen is Deadbeat control, to provide fast dynamic response and good steady-state output voltage waveform.

1.2.2 Scope of Research

There are many control functions in a PV inverter system, such as inverter voltage regulation, power factor control, phase synchronisation with grid voltage, MPPT, and other protection functions. As the developed BHFL inverter is meant for both grid-connected mode and stand-alone mode with UPS features, a high performance closed-loop controller is needed. The controller must fulfil the stringent requirements of voltage regulation under all loading conditions, particularly in stand-alone mode. A high performance controller can also be operated in grid-connected mode by incorporating the MPPT controller, Phase Lock Loop (PLL) [8], [41] and islanding function. The scope of this research is limited to the following items for closed-loop regulation of the BHFL inverter:

i. Study of various control techniques for PWM inverters

   Prior knowledge of control systems, such as design considerations, analysis methods and practical implementation aspects is acquired [42]-[46]. Several previous works on closed-loop control techniques for high performance inverters are reviewed [18]-[40]. The critical loads in residential PV applications are also identified and their characteristics are studied.

ii. Selecting appropriate control technique for the BHFL inverter

Deadbeat control technique has been selected as it exhibits fast dynamic performance and good steady-state response of the output voltage.

iii. Analytical modelling of the BHFL inverter and controller design

A dynamic model of the BHFL inverter has been derived using the state-space averaging method [47]. The Deadbeat controller is then designed based on the state-space model.

iv. Computer simulation

To verify the performance of the designed controller, a complete simulation model of the closed-loop BHFL inverter is developed. The computer simulation package used is MATLAB/Simulink[2]. The system performance is verified under various loads and conditions.

v. Hardware implementation

To validate the feasibility of the proposed control technique, a hardware prototype is constructed. The tasks include selecting the appropriate digital processor, designing the power circuit, gate drivers, feedback and signal conditioning circuits, and implementing the control algorithm. The selected digital processor is the DS1104[3] DSP board. The critical load test-rigs are also constructed.

vi. System verification and improvement

Laboratory experiments are carried out on the system under various loads and conditions. Necessary modifications and fine-tuning are made to further improve the performance of the system.

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[2] MATLAB is the trademark of The MathWorks, Inc.

[3] DS1104 is provided by dSPACE GmbH.

1.2.3 Importance of Research

The decreasing cost of PV power has been the main impetus of developing PV systems. Looking at the full potential of residential PV system in Malaysia, research and development investment has been made by the government. Some of the early PV systems are being applied for rural electrification and telecommunication [3], [48]. The PV is anticipated to play a more prominent role once the grid-connected system is well-established with the legal framework for users selling power to the utility provider is in place.

In a complete PV system, the inverter is normally equipped with closed-loop controller. The controller plays a vital role in maintaining the sinusoidal output voltage waveform over all loading conditions. Hence, there is a need to develop a high performance controller for the BHFL inverter. Although many modern control techniques have been proposed in the literature, they are mainly developed for line-frequency inverters [25]-[38]. On the other hand, the published works on high-frequency link inverters only utilising conventional control techniques [7], [8], [13], [14], [16]. As the inverter and closed-loop controller work together as a complete system, it is of preference to apply the modern control techniques into high-frequency link inverters. In this research, the Deadbeat control technique, which has been applied in line-frequency PWM inverters since 1980s [33], is adopted for closed-loop regulation of the BHFL inverter. Besides verifying the feasibility of the control technique on high-frequency link inverter, it also bridges the gap between researches in these two areas.

Deadbeat control is selected for closed-loop regulation of the BHFL inverter because it provides excellent dynamic response. The proposed controller consists of inner current loop controller, outer voltage loop controller and feedforward controller. The controller has same structure for the current and voltage loop controllers, which simplifies design and implementation. To improve overall performance of the system, additional decoupling networks are employed. A voltage disturbance decoupling network is added to the voltage loop controller. Similarly, a current disturbance decoupling network is added to the current loop controller. The decoupling networks take into account the model discretisation effect. Therefore, improved system robustness towards load variations is envisaged. In the proposed control technique, there is no observer or estimator applied. This is an advantage because inclusion of observer might introduce estimation errors. The implemented controller possesses fast dynamic response with good steady-state response under all loading conditions. This paves a way to Deadbeat control to be applied in high-frequency link inverters, which hitherto have not been applied. With necessary modifications, the BHFL inverter with Deadbeat controller is suitable for stand-alone and grid-connected residential PV applications.

1.3 Organisation of Thesis

This thesis is organised into seven chapters. The content of these chapters are outlined as follows:

- Chapter 2 provides an overview of various line-frequency and high-frequency link inverter topologies. Closed-loop control techniques for inverters are also presented. The merits and drawbacks of the control techniques are discussed.

- Chapter 3 describes the BHFL inverter and its operating principle. The analysis and design of the proposed Deadbeat controller are explained in considerable detail. The robustness of the designed controller against parameter mismatches is also investigated.

- Chapter 4 presents the system modelling of the BHFL inverter with the proposed Deadbeat controller using MATLAB/Simulink simulation package. Descriptions are given on the modelling procedures using blocksets from MATLAB/Simulink libraries.

- Chapter 5 describes the laboratory experimental set-up. Brief explanation is given on the power circuit and gate drives. Detailed description is provided on the implementation of the proposed controller using DS1104 DSP. This includes the design and realisation of digital filters, and introduction of pulse equalisation technique into the proposed Deadbeat controller.

- Chapter 6 evaluates the performances of the proposed controller. This is performed in comparison with the conventional PI controller and the multirate digital controller. Various types of loads are tested on the system. The simulation and experimental results are provided.

- Chapter 7 concludes the works undertaken and highlights the contributions of this research. Several suggestions are provided as possible directions for future work.

REFERENCES

1. MOSTE. Energy Research Program for Malaysia in the Next Five Years and Beyond. *Final Report.* 1995.

2. Bull, S. R. Renewable Energy Today and Tomorrow. *Proceedings of the IEEE.* 2001. 89(8): 1216-1226.

3. Sopian, K. Likely Initiatives for Renewable Technology Development in Malaysia. *Energy Smart.* Selangor, Malaysia: Malaysia Energy Centre. 2003. 12: 4-20.

4. Washington Utilities and Transportation Commission. *Relating to the Definition of Net Metering System.* Washington, EHB 2334. 2000.

5. Fiorello, R. M. and Salameh, Z. M. Stand-Alone Transformerless Sinusoidal Inverter for PV Systems. *Proceedings of the 6th Annual Applied Power Electronics Conference and Exposition, APEC'91.* March 10-15, 1991. Dallas, Texas: IEEE. 1991. 484-490.

6. Hinga, P. K., Ohnishi, T. and Suzuki, T. A New PWM Inverter for Photovoltaic Power Generation System. *25th Annual Power Electronics Specialists Conference Record, PESC'94.* June 20-25, 1994. Taipei: IEEE. 1994. vol. 1: 391-395.

7. Myrzik, J. M. A. Novel Inverter Topologies for Single-Phase Stand-Alone or Grid-Connected Photovoltaic Systems. *Proceedings of the 4th IEEE International Conference on Power Electronics and Drive Systems, PEDS'01.* October 22-25, 2001. Indonesia: IEEE. 2001. vol. 1: 103-108.

8. Cocconi, A., Cuk, S. and Middlebrook, R. D. High-Frequency Isolated 4kW Photovoltaic Inverter for Utility Interface. *Proceedings of the 7th Power Conversion International Conference, PCI'83.* September 13-15, 1983. Geneva, Switzerland: Intertec Communications, Inc. 1983. 325-345.

9. Bhat, A. K. S. and Dewan, S. D. Resonant Inverters for Photovoltaic Array to Utility Interface. *IEEE Transactions on Aerospace and Electronic Systems.* 1988. 24(4): 377-386.

10. Saha. S. and Sundarsingh V. P. Novel Grid-Connected Photovoltaic Inverter. *IEE Proceedings on Generation, Transmission and Distribution.* 1996. 143(2): 219-224.

11. Chiang, S. J., Chang, K. T. and Yen, C. Y. Residential Photovoltaic Energy Storage System. *IEEE Transactions on Industrial Electronics.* 1998. 45(3): 385-394.

12. Jung, Y. S., Yu, G. J., Choi, J. H. and Choi, J. Y. High-Frequency DC Link Inverter for Grid-Connected Photovoltaic System. *29th Photovoltaic Specialists Conference Record.* May 19-24, 2002. IEEE. 2002. 1410-1413.

13. Pressas, S. A. and Makios, V. A Light Weight, Four Quadrant, High Switching Frequency Modular, Photovoltaic DC/AC Inverter, with Sinusoidal Output and High Efficiency. *20th Photovoltaic Specialists Conference Record.* September 26-30, 1988. IEEE. 1988. vol. 2: 1304-1308.

14. Fujimoto, H., Kuroki, K., Kagotani, T. and Kidoguchi, H. Photovoltaic Inverter with a Novel Cycloconverter for Interconnection to a Utility Line. *Conference Record of the 30th Industry Applications Society Annual Meeting.* October 8-12, 1995. Orlando, Florida: IEEE. 1995. vol. 3: 2461-2467.

15. Matsui, M., Nagai, M., Mochizuki, M. and Nabae, A. High-Frequency Link DC/AC Converter with Suppressed Voltage Clamp Circuits – Naturally Commutated Phase Angle Control with Self Turn-Off Devices. *IEEE Transactions on Industry Applications.* 1996. 32(2): 293-300.

16. Koutroulis, E., Chatzakis, J. Kalaitzakis, K. and Voulgaris, N. C. A Bidirectional, Sinusoidal, High-Frequency Inverter Design. *IEE Proceedings on Electric Power Applications.* 2001. 148(4): 315-321.

17. Ramli, M. Z., Salam, Z., Toh, L. S. and Nge, C. L. A Bidirectional High-Frequency Link Inverter Using Center-Tapped Transformer. *35th Annual Power Electronics Specialists Conference Record, PESC'04.* June 20-25, 2004. Aachen, Germany: IEEE. 2004. vol. 5: 3883-3888.

18. Ryan, M. J. and Lorenz, R. D. A High Performance Sine Wave Inverter Controller with Capacitor Current Feedback and "Back-EMF" Decoupling. *26th Annual Power Electronics Specialists Conference Record, PESC'95.* June 18-22, 1995. Atlanta, Georgia: IEEE. 1995. vol. 1: 507-513.

19. Abdel-Rahim, N. M. and Quaicoe, J. E. Analysis and Design of a Multiple Feedback Loop Control Strategy for Single-Phase Voltage-Source UPS Inverters. *IEEE Transactions on Power Electronics.* 1996. 11(4): 532-541.

20. Choudhury, S. Implementing Triple Conversion Single-Phase On-Line UPS Using TMS320C240. *Application Report SPRA589A.* September, 1999. Texas Instruments. 1999.

21. Kawamura, A. and Hoft, R. G. Instantaneous Feedback Controlled PWM Inverter with Adaptive Hysterisis. *IEEE Transactions on Industry Applications.* 1984. IA-20(4): 769-775.

22. Tripathi, A. and Sen, P. C. Comparative Analysis of Fixed and Sinusoidal Band Hysteresis Current Controllers for Voltage Source Inverters. *IEEE Transactions on Industrial Electronics.* 1992. 39(1): 63-73.

23. Bowes, S. R. and Grewal, S. Three-Level Hysteresis Band Modulation Strategy for Single-Phase PWM Inverters. *IEE Proceedings on Electric Power Applications.* 1999. 146(6): 695-706.

24. Sonaglioni, L. Predictive Digital Hysteresis Current Control. *Conference Record of the 30th Industry Applications Society Annual Meeting.* October 8-12, 1995. Orlando, Florida: IEEE. 1995. vol. 3: 1879-1886.

25. Jezernik, K. and Zadravec. D. Sliding Mode Controller for a Single Phase Inverter. *Proceedings of the 5th Annual Applied Power Electronics Conference and Exposition, APEC'90.* March 11-16, 1990. Los Angeles, California: IEEE. 1990. 185-190.

26. Jung, S. L. and Tzou, Y. Y. Sliding Mode Control of a Closed-Loop Regulated PWM Inverter under Large Load Variations. *24th Annual Power Electronics Specialists Conference Record, PESC'93.* June 20-24, 1993. Seattle, Washington: IEEE. 1993. 507-513.

27. Tai, T. L. and Chen, J. S. UPS Inverter Design Using Discrete-Time Sliding-Mode Control Scheme. *IEEE Transactions on Industrial Electronics.* 2002. 49(1): 67-75.

28. Haneyoshi, T., Kawamura. A. and Hoft. R. G. Waveform Compensation of PWM Inverter with Cyclic Fluctuating Loads. *IEEE Transactions on Industry Applications.* 1988. 24(4): 582-589.

29. Yeh, S. C. and Tzou, Y. Y. Adaptive Repetitive Control of a PWM Inverter for AC Voltage Regulation with Low Harmonic Distortion. *26th Annual Power Electronics Specialists Conference Record, PESC'95.* June 18-22, 1995. Atlanta, Georgia: IEEE. 1995. vol. 1. 157-163.

30. Lin, B. R. and Hoft, R. G. Power Electronics Converter Control Based on Neural Network and Fuzzy Logic Methods. *24th Annual Power Electronics Specialists Conference Record, PESC'93.* June 20-24, 1993. Seattle, Washington: IEEE. 1993. 900-906.

31. Wu, T. F, Yang, C. H., Chen, Y. K. and Liu, Z. R. Photovoltaic Inverter Systems with Self-Tuning Fuzzy Control Based on an Experimental Planning Method. *Conference Record of the 34th Industry Applications Society Annual Meeting.* October 3-7, 1999. Phoenix, Arizona: IEEE. 1999. vol. 3: 1887-1894.

32. Sun, X., Xu, D. H., Leung, F. H. F., Wang, Y. S. and Lee, Y. S. Design and Implementation of a Neural-Network-Controlled UPS Inverter. *Proceedings of the 25th Annual Conference of the Industrial Electronics Society, IECON'99.* November 29-December 3, 1999. San Jose, California: IEEE. 1999. vol. 2: 779-784.

33. Gokhale, K. P, Kawamura, A. and Hoft, R. G. Dead Beat Microprocessor Control of PWM Inverter for Sinusoidal Output Waveform Synthesis. *IEEE Transactions on Industry Applications.* 1987. IA-23(5): 901-910.

34. Kawamura, A., Haneyoshi, T. and Hoft, R. G. Deadbeat Controlled PWM Inverter with Parameter Estimation Using Only Voltage Sensor. *IEEE Transactions on Power Electronics.* 1988. 3(2): 118-125.

35. Hua, C. C. High Switching Frequency DSP Controlled PWM Inverter. *2nd IEEE Conference on Control Applications.* September 13-16, 1993. Vancouver, British Columbia: IEEE. 1993. vol. 1. 273-283.

36. Jung, S. L., Chang, M. Y., Jyang, J. Y., Yeh, L. C. and Tzou, Y. Y. Design and Implementation of an FPGA-Based Control IC for AC-Voltage Regulation. *IEEE Transactions on Power Electronics.* 1999. 14(3): 522-532.

37. Mihalache, L. DSP Control Method of Single-Phase Inverters for UPS Applications. *Proceedings of the 17th Annual Applied Power Electronics Conference and Exposition, APEC'02.* March 10-14, 2002. Dallas, Texas: IEEE. 2002. 590-596.

38. Kawamura, A. and Yokoyama, T. Comparison of Five Different Approaches for Real Time Digital Feedback Control of PWM Inverters. *Conference Record of the 1990 Industry Applications Society Annual Meeting.* October 7-12, 1990. Seattle, Washington: IEEE. 1990. vol. 2: 1005-1011.

39. Kawabata, T., Miyashita, T. and Yamamoto, Y. Dead Beat Control of Three Phase PWM Inverter. *IEEE Transactions on Power Electronics.* 1990. 5(1): 21-28.

40. Kukrer, O. Deadbeat Control of a Three-Phase Inverter with an Output LC Filter. *IEEE Transactions on Power Electronics.* 1996. 11(1): 16-23.

41. Arruda, L. N., Silva, S. M. and Filho, B. J. C. PLL Structures for Utility Connected Systems. *Conference Record of the 36th Industry Applications Society Annual Meeting.* September 30-October 4, 2001. Chicago, Illinois: IEEE. 2001. vol. 4: 2655-2660.

42. Nise, N. S. *Control Systems Engineering.* 2nd ed. Menlo Pak, California: Addison-Wesley Publishing Company. 1995.

43. Philips, C. L. and Harbor, R. D. *Feedback Control Systems.* 4th ed. Upper Saddle River, New Jersey: Prentice Hall, Inc. 2000.

44. Kuo, B. C. *Digital Control Systems.* New York: Holt, Rinehart and Winston, Inc. 1980.

45. Ogata, K. *Discrete-Time Control Systems.* 2nd ed. Englewood Cliffs, New Jersey: Prentice Hall, Inc. 1995.

46. Nekoogar, F. and Moriarty, G. *Digital Control Using Digital Signal Processing.* Upper Saddle River, New Jersey: Prentice Hall, Inc. 1999.

47. Mohan, N., Undeland, T. M. and Robbins, W. P. *Power Electronics – Converters, Applications, and Design.* 3rd ed. Hoboken, New Jersey: John Wiley & Sons, Inc. 2003.

48. Ismail, I. S. S., Omar, A. and Hassan, H. Pilot Centralized Solar Power Station in Remote Village, Rompin, Pahang. *The Ingenieur.* Kuala Lumpur, Malaysia: Board of Engineers Malaysia. 2005. vol. 26: 26-30.

49. Rashid, M. H. *Power Electronics – Circuits, Devices and Applications.* 2nd ed. Englewood Cliffs, New Jersey: Prentice Hall, Inc. 1993.

50. Hung, J. Y., Gao, W. B. and Hung, J. C. Variable Structure Control: A Survey. *IEEE Transactions on Industrial Electronics.* 1993. 40(1): 2-22.

51. Francis, B. A. and Wonham, W. M. The Internal Model Principle for Linear Multivariable Regulators. *Applied Mathematics and Optimisation.* 1975. 2(2): 170-194.

52. Harris, C. J., Moore, C. G. and Brown, M. *Intelligent Control – Aspects of Fuzzy Logic and Neural Nets.* Singapore: World Scientific Publishing Co. Pte. Ltd. 1993.

53. Vaccaro, R. J. *Digital Control – A State-Space Approach.* New York: McGraw-Hill, Inc. 1995.

54. Saranli, U., Schwind, W. J. and Koditschek, D. E. Toward the Control of a Multi-Jointed, Monoped Runner. *Proceedings of the International Conference on Robotics and Automation.* May 16-20, 1998. Leuven: IEEE. 1998. vol. 3: 2676-2682.

55. Iwashiro, M., Yatsu, M. and Suzuki, H. Time Optimal Track-to-Track Seek Control by Model Following Deadbeat Control. *IEEE Transactions on Magnetics.* 1999. 35(2): 904-909.

56. Endo, S., Konishi, M. and Imabayasi, H. Water Level Control of Small-Scale Hydroelectric Power Plant by Deadbeat Control Method. *Proceedings of the 26th Annual Conference of the Industrial Electronics Society, IECON 2000.* October 22-28, 2000. Nagoya: IEEE. 2000. vol. 2: 1123-1128.

57. Yamada, E., Tsuji, M., Izumi, K., Tanimoto, M. and Oyama, J. Dead Beat Control of DC Chopper System with Nonlinear Load. *Proceedings of the 1991 International Conference on Industrial Electronics, Control and Instrumentation, IECON'91.* October 28-November 1, 1991. Kobe: IEEE. 1991. vol. 1: 581-586.

58. Yang, S, M. and Lee, C. H. A Deadbeat Current Controller for Field Oriented Induction Motor Drives. *IEEE Transactions on Power Electronics.* 2002. 17(5): 772-778.

59. Nishida, K., Rukonuzzman, M. and Nakaoka, M. Advanced Current Control Implementation with Robust Deadbeat Algorithm for Shunt Single-Phase Voltage-Source Type Active Power Filter. *IEE Proceedings on Electric Power Applications.* 2004. 151(3): 283-288.

60. Irvine, R. G. *Operational Amplifier – Characteristics and Applications.* 3rd ed. Englewood Cliffs, New Jersey: Prentice Hall, Inc. 1994.

61. Orfanidis, S. J. *Introduction to Signal Processing.* Englewood Cliffs, New Jersey: Prentice Hall, Inc. 1996.

62. dSPACE GmbH. *DS1104 R&D Controller Board – Hardware Installation and Configuration.* Germany: User Manual. 2004.

63. dSPACE GmbH. *dSPACE Solutions for Control – Software Installation and Management Guide.* Germany: User Manual. 2004.

64. dSPACE GmbH. *Real-Time Interface (RTI and RTI-MP) – Implementation Guide.* Germany: User Manual. 2004.

65. dSPACE GmbH. *DS1104 R&D Controller Board – RTLib Reference.* Germany: User Manual. 2004.

66. dSPACE GmbH. *ControlDesk – Experiment Guide.* Germany: User Manual. 2004.

67. Deitel, H. M. and Deitel, P. J. *C: How to Program.* 4th ed. Upper Saddle River, New Jersey: Prentice Hall, Inc. 2004.

68. IEEE. *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.* New York, IEEE Std 519-1992. 1993.

69. Leggate, D. and Kerkman, R. J. Pulse-Based Dead-Time Compensator for PWM Voltage Inverters. *IEEE Transactions on Industrial Electronics.* 1997. 44(2): 191-197.