Z-SOURCE INVERTER IN PV SYSTEM USING SIMPLE BOOST PULSE WIDTH MODULATION

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Thesis submitted in fulfilment of the requirements
for the award of the degree of
Doctor of Philosophy in Electronic Engineering

Faculty of Electrical & Electronics Engineering
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LIST OF ABBREVIATIONS

B	boost factor
D_0	shoot-through duty ratio
f_a	fundamental frequency
f_c	carrier frequency
f_s	switching frequency
f_{sam}	sampling frequency
G	voltage gain
M_i	modulation index
THD	total harmonic distortion
THD_i	current total harmonic distortion
$V_{AC(peak)}$	peak AC output voltage
V_{input}	input DC voltage
$V_{DClink\ (peak)}$	peak voltage stress
V_{ref}	reference voltage
V_{tri}	triangular voltage

LIST OF ACRONYMS

AC	alternating current
ADC	analogue-to-digital converters
CSI	current source inverter
DC	direct current
DSP	digital signal processing
EMI	electro-magnetic interference
IGBT	insulated gate bipolar transistor
MIPS	millions of commands per second
PWM	pulse width modulation
RMS	root mean square
RTW	real time workshop
ST	shoot-through
UPS	uninterruptible power supply
VSI	voltage source inverter
ZS	Z-source
ZSI	Z-source inverter

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ABSTRAK

Galangan-sumber rangkaian atau dikenali sebagai rangkaian Z-sumber adalah satu X gandingan rangkaian dua liang yang terdiri daripada dua pengaruh dan dua kapasitor. Rangkaian Z-sumber disambungkan pada masukan penyongsang H-jambatan membentuk penyongsang Z-sumber (ZSI). Sifat-sifat ZSI yang mengatasi penyongsang konvensional yang boleh diakses, iaitu julat voltan keluaran dalam penyongsang konvensional adalah terhad sama ada besar atau lebih kecil daripada voltan masukan. Ini mendorong ahli akademik dan industri untuk mengkaji kerana sejak penemuannya, banyak penyelidikan dan pembangunan telah dijalankan, seperti meningkatkan topologi yang sedia ada, mencadangkan skim pemanduan baru, membangunkan kawalan gelung dan melaksanakan pada aplikasi baru. Sebaliknya, dalam operasi penyongsang tiga fasa, kaedah enam langkah modulasi lebar denyut (PWM) menghasilkan riak kekerapan tork yang rendah. Masa bagi riak kekerapan penyongsang tork harmonik dalam mesin pada n fasa terjadi disebabkan oleh harmonik masa bekalan kuasa pada $2n \pm 1$. Peningkatan dalam bilangan fasa perintah $2n \pm 1$ mesin dapat menyelesaikan tork frekuensi rendah riak. Oleh itu, tesis ini adalah untuk meningkatkan lagi pengetahuan mengenai skim pemanduan sistem ZSI berbilang kerana perlaksanaannya yang agak terhad. Sistem dengan nombor fasa yang lebih tinggi akan menyebabkan tekanan voltan yang lebih rendah, kebolehpercayaan yang lebih tinggi, meningkatkan kuasa dalam kerangka yang sama dan mengurangkan herotan harmonik. Justeru, cabaran penyelidikan ini adalah untuk mengisi jurang dengan menggunakan rangsangan mudah modulasi nadi-lebar (SBPWM) untuk skim pemanduan sistem ZSI lima fasa. SBPWM adalah skim pemanduan yang dipercayai kerana ia boleh dilaksanakan pada sebarang topologi ZSI, boleh digunakan dalam pengawal digital, mempunyai keteguhan tinggi dan menggunakan persamaan matematik yang mudah. Kajian ini dijalankan dengan membentuk semula SBPWM untuk memenuhi sistem ZSI lima fasa di bawah lima isyarat rujukan dengan isyarat pembawa di pensuisan frekuensi 1.5 kHz. Melalui operasi ini, mod benar-das boleh disusun secara setara. Ini akan menyebabkan sistem boleh mengalak dan meronta. Kajian ini mendapati bahawa pada 0.253 msesaat selang masa penalti sistem memberikan ralat kurang daripada 7%. Kedua, proses simulasi menggunakan MATLAB@Simulink @ dengan perlaksanaan di bawah 2 kWatt dengan kepelbagaian indeks modulasi *(M_i)* dari 0.562 sehingga 1.1 dengan voltan masukan DC 40 V. Pada M_i 0.62, sistem ZSI lima fasa menghasilkan 4.6 % jumlah herotan harmonik *(THD)* arus keluaran untuk Fasa A pada sambungan beban rintangan jenis bintang. Akhir sekali, kajian disahkan lagi dengan menjalankan ujikaji menggunakan pelantar prototaip dengan pengukuran *THD* arus keluaran untuk Fasa A di mana *THD* arus keluaran berkenaan mematuhi piawaian IEEE 519-1992 dan EN 61000-3-2 yang dibenarkan iaitu pada 5% dan 27%.

ABSTRACT

Impedance-source network or known as Z-source network is an X form coupling of the two-port network consists of two inductors and two capacitors. The Z-source network is connected to the input of the H-bridge inverter forming into a Z-source inverter (ZSI). The attributes of ZSI that overcome the conventional inverter, which their accessible of output voltage range in the conventional inverter is restricted to either greater or smaller than the input voltage. This quickly brought interest to the academicians and industry since its inception, a lot of research and development were carried out to improve the existing topology, proposing a new driving scheme, developing control loop and implementing new application. On the other hand, in three-phase inverter operation, the six-step modes of pulse width modulation (PWM) produce the low-frequency torque ripple. Since the lowest frequency torque ripple harmonic in an n-phase machine is caused by the time harmonics of the supply of the order $2n \pm 1$, an increase in the number of phases of the order $2n \pm 1$, then the machine is able to resolve the low-frequency torque ripple. Thus, this thesis is to further enhance the body of knowledge on the driving scheme of multiphase ZSI system since the implementation is rather limited. A system with a higher number of phases would result in lower voltage stress, higher reliability, increase power in the same frame and reduced harmonic distortions. Thus, the research challenge is to fill the gap by using simple boost pulse-width modulation (SBPWM) for the driving scheme of the five-phase ZSI system. SBPWM is a trusted driving scheme since it can be implemented at any ZSI topology, can be embedded in a digital controller, has high robustness and has low mathematics complexity. The research is carried out by remodelling SBPWM to suit the five-phase ZSI system specification under five reference signals that is compared with a carrier signal at switching frequency of 1.5 kHz. The equally contributed at the shoot-through mode in the operation make the system capable of both boosting and bucking operation. It is found that at the 0.253 msec shoot-through time interval gives less than 7% error. The remodelled SBPWM is then implemented on operations below 2 kW via MATLAB@Simulink simulation, where the modulation index (Mi) varied from 0.562 until 1.1 and input DC voltage fixed at 40 V. At Mi 0.62, the five-phase ZSI system offers 4.6% total harmonic distortion (THD) output current for resistive load at the star formation connection. Finally, the result verification is carried out with hardware experiment prototype, where the output current's THD is compiled to the IEEE 519-1992 and EN 61000-3-2 standards.

REFERENCES

A. Kouzou, & Abu-rub, H. (2013). Multiphase Z-source inverter using maximum constant boost control. In *Archives of Control Sciences* (Vol. 23, pp. 107–126).

Ali, U. S. (2011). Double Carrier Pulse Width Modulation Control of Z-Source Inverter. *European Journal of Scientific Research*, *49*(2), 168–176.

Ali, U. S., & Kamaraj, V. (2012). Z-Source Inverter with Minimization of Total Harmonic Distortion on Output Voltage for Photovoltaic Applications. *International Journal of Electrical Engineering.*, *5*(5), 587–601.

Anderson, J., & Peng, F. Z. (2008). A Class Of Quasi-Z-Source Inverters. *2008 IEEE Industry Applications Society Annual Meeting*, 1–7. http://doi.org/10.1109/08IAS.2008.301

Au, U. S., & Priya, A. H. (2013). A Novel Carrier Based Pulse Width Modulation Technique for Quasi-Z-Source Inverter with Improved Voltage Gain. In *International Conference on Circuits, Power and Computing Technologies* (pp. 199–202).

Barati, A. R., Moslehi, M., & Khaburi, D. A. (2013). Z-Source Five Leg Inverter. In *4th Power Electronics, Drive Systems & Technologies Conference (PEDSTC2013)* (Vol. 2, pp. 205–211).

C.R.Robertson. (2008). *Further Electrical And Electronic Principles. Newnes* (3rd Editio). Newnes.

Chuang Hong Zhao, & Kolar, J. . (2004). A Novel Three-Phase Three-Port UPS Employing A Single High Frequency Isolation Transformer. In *IEEE Power Electronics Specialists Conference* (pp. 4135–4141).

D.P.Hartmann, R.P.Stratford, C. K. D. etl. (1993). IEEE Std 519-1992 Recommended Practices and Requirements for Harmonic Control in Power Systems. *IEEE Std 519-1992.*

Dahono, P. A. (2010). Analysis and Minimization of Output Current Ripple of Multiphase Carrier-based PWM Inverters. *ITB J. Eng. Sci.*, *42*(1), 53–64.

Dahono, P. a., Akbarifutra, C. P., & Rizqiawan, A. (2009). Input ripple analysis of five-phase pulse width modulated inverters. *IET Power Electronics*, *3*(5), 716–723. http://doi.org/10.1049/iet-pel.2009.0129

Dahono, P. A., Member, S., & Supriatna, E. G. (2009). Output Current-Ripple Analysis of Five-Phase PWM Inverters. *IEEE Transactions on Industry Applications*, *45*(6), 2022–2029.

Dang, C., Liu, H., & Zhang, X. (2013). The new and precise control base on Z-source inverter. In *Control and Decision Conference (CCDC), 2013 25th Chinese* (pp. 5183–5188).

Daniyal, H., Borle, L. J., Iu, H. H. C., & Member, S. (2013). Design and Development of Digital Ramptime Current Control Technique. *IEEE Transactions on Industrial Informatics*, *9*(2), 992–1002.

Ding, X., Zhang, C., & Qian, Z. (2013). X-source inverter: A generic Z-source inverter structure. In *2013 IEEE Energy Conversion Congress and Exposition* (pp. 5341–5348). IEEE http://doi.org/10.1109/ECCE.2013.6647425

Drazen Dujic, M. J., & SlobodanN. Vukosavic, and E. L. (2009). A General PWM Method for a (2n + 1) -Leg Inverter Supplying n Three-Phase Machines. *IEEE Transactions on Industrial Electroncis*, *56*(10), 4107–4118. Retrieved from about:blank

Ellabban, O., Member, S., Mierlo, J. Van, & Lataire, P. (2009). Voltage Mode and Current Mode Control for a 30 kW High-Performance Z-Source Inverter. In *Electrical Power & Energy Conference*.

Ellabban, O., & Mierlo, J. Van. (2012). Z-Source Inverter for Automotive Applications.

Ellabban, O., Mierlo, J. Van, & Lataire, P. (2011). Control of a Bidirectional Z-Source Inverter for Electric Vehicle Applications in Different Operation Modes. *Journal of Power Electronics*, *11*(2), 120–131. http://doi.org/10.6113/JPE.2011.11.2.120

Ellabban, O., Van Mierlo, J., & Lataire, P. (2012). A DSP-Based Dual-Loop Peak DC-link Voltage Control Strategy of the Z-Source Inverter. *IEEE Transactions on Power Electronics*, *27*(9), 4088–4097. http://doi.org/10.1109/TPEL.2012.2189588

Ellabban, O., Van Mierlo, J., Lataire, P., Mierlo, J. Van, Lataire, P., & Elsene, B.-. (2009). Comparison between Different PWM Control Methods for Different Z-Source Inverter Topologies. In *13th European Conference on Power Electronics and Applications (2009)* (pp. 1–11).

EPSMA. (2010). *Harmonic Current Emissions Guidelines to the standard EN 61000-3-2 Revision Date : 2010-11-08*.

Erginer, V., & Sarul, M. H. (2013). Modulation Techniques for Z-Source Inverter used in Photovoltaic Systems. In *4th Power Electronics, Drive Systems & Technologies Conference (PEDSTC2013)* (pp. 459–464).

Fang, X. P., Qian, Z. M., & Peng, F. Z. (2005). Single-Phase Z-Source PWM AC-AC Converters. *IEEE Power Electronics Letters*, *3*(4), 121–124.

Gajanayake, C. J., Vilathgamuwa, D. M., & Poh Chiang, L. (2006). Modeling And Design Of Multi-loop Closed Loop Controller For ZSI For Distributed Generation. In *Power Electronics Specialists Conference, 2006. PESC '06. 37th IEEE* (pp. 1–7).

Gao, F., Loh, P. C., Blaabjerg, F., & Gajanayake, C. J. (2008). Operational analysis and comparative evaluation of embedded Z-Source inverters. In *Power Electronics Specialists Conference, 2008. PESC 2008. IEEE* (pp. 2757–2763).

Huang, Y., Shen, M., Member, S., Peng, F. Z., & Wang, J. (2006). Z -Source Inverter For Residential Photovoltaic Systems. *IEEE Transactions on Power Electronics*, *21*(6), 1776–1782.

Husodo, B. Y., Anwari, M., & Ayob, S. M. (2010). Analysis and simulations of Z-source inverter control methods. *2010 Conference Proceedings IPEC*, (1), 699–704. http://doi.org/10.1109/IPECON.2010.5697016

Iqbal, A., Levi, E., Jones, M., & Vukosavic, S. N. (2006). Generalised Sinusoidal PWM with Harmonic Injection for Multi-Phase VSIs. In *37th IEEE Power Electronics Specialists Conference* (pp. 1–7). http://doi.org/10.1109/PESC.2006.1712206

Ji, J.-K., Kim, J.-H., Sui, S.-K., & Kim, H. S. (2004). A Novel Three-Phase Line-Interactive UPS System With Parallel-Series Active Power Line Conditioning Capabilities Using AC Line Reactor. In *IEEE Industrial Electronics Society Annual Conference* (pp. 1861–1866).

Jiang, S., & Peng, F. Z. (2012). Modular single-phase trans-Z-source inverter for multi-input renewable energy system. In *2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)* (pp. 2107–2114). http://doi.org/10.1109/APEC.2012.6166112

Jung, J. W., & Keyhani, A. (2007). Control Of a Fuel Cell based Z-source converter. *Energy Conversion, IEEE Transactions on*, *22*(2), 467–476.

Jung, S. K. Y., & Wu, Y. L. Y. (2012). Output Voltage Constant Control of Three-Phase Z- Source Inverter. In *Industrial Electronics (ISIE), 2012 IEEE International Symposium* (pp. 425–430).

Karugaba, S., & Ojo, O. (2012). A carrier-based PWM modulation technique for balanced and unbalanced reference voltages in multiphase voltage-source inverters. *IEEE Transactions on Industry Applications*, *48*(6), 2102–2109. http://doi.org/10.1109/TIA.2012.2226421

Khera, F. A., & Rashad, E. E. M. (2013). Performance Analysis of Z-Source Inverter Considering Inductor Resistance. In *International Conference on Electrical Machines and Systems* (pp. 1–7).

Kirubakaran, A., Jain, S., & Nema, R. K. (2011). DSP-Controlled Power Electronic Interface For Fuel-Cell-Based Distributed Generation. *IEEE Transactions on Power Electronics*, *26*(12), 3853–3864. http://doi.org/10.1109/TPEL.2011.2138162

Levi, E. (2008). Multiphase Electric Machines for Variable-Speed Applications. *Industrial Electronics, IEEE Transactions on*, *55*(5), 1893–1909. http://doi.org/10.1109/TIE.2008.918488

Levi, E., Bojoi, R., Profumo, F., Toliyat, H. A., & Williamson, S. (2007). Multiphase Induction Motor Drives - A Technology Status Review. *Electric Power Applications, IET*, *1*(4), 489–516. http://doi.org/10.1049/iet-epa:20060342

Li, Yuan, Anderson, J. etc. (2011). Quasi-Z-Source Inverter for Photovoltaic Power Generation Systems. In *2011 TwentySixth Annual IEEE Applied Power Electronics Conference and Exposition APEC (2011)* (pp. 918–924).

Li, J., Liu, J., & Zeng, L. (2009). Comparison of Z-source inverter and traditional two-stage boost-buck inverter in grid-tied renewable energy generation. *2009 IEEE 6th International Power Electronics and Motion Control Conference*, *3*, 1493–1497. http://doi.org/10.1109/IPEMC.2009.5157623

Loh, F. G. P. C., Teodorescu, F. B. R., & Vilathgamuwa, D. M. (2010). Five-level Z-source diode-clamped inverter. *IET Power Electronics*, *3*(January 2009), 500–510. http://doi.org/10.1049/iet-pel.2009.0015

Loh, P. C., Duan, N., Liang, C., Gao, F., & Blaabjerg, F. (2007). Z-Source B4 Inverters. *2007 IEEE Power Electronics Specialists Conference*, 1363–1369. http://doi.org/10.1109/PESC.2007.4342193

Loh, P. C., Vilathgamuwa, D. M., Gajanayake, C. J., Wong, L. T., & Ang, C. P. (2005). Z-source Current-type Inverters: Digital Modulation And Logic Implementation. In *Industry Applications Conference, 2005. Fourtieth IAS Annual Meeting. Conference Record of the 2005* (Vol. 2, p. 940–947 Vol. 2).

Loh, P. C., Vilathgamuwa, D. M., Lai, Y. Sen, & Chua, G. T. (2005). Pulse-Width Modulation Of Z -Source Inverters. *IEEE Transactions on Power Electronics, 20*(6), 1346–1355.

Loh, P. C., Vilathgamuwa, D. M., & Member, S. (2007). Transient Modeling And Analysis of Pulse-Width Modulated ZSI. *IEEE Trasnsaction On Power Electronics, 22*(2), 498–507.

M. Abdullah, A., Abu Talib, N., Mohd Suradi, A., Mokhtar, N. J., & Zainuddin, M. (2006). K-Chart: Research Planning And Monitoring Tool For Engineering And Technology Applications. In *FEIIC Seminar on Engineering and Technology* (pp. 1–6).

Mansor, M., & Rahim, N. A. (2011). Three-Phase PWM-Switched Autotransformer Voltage-Sag Compensator Based on Phase Angle Analysis. *Journal of Power Electronics, 11*(6), 897–903. http://doi.org/10.6113/JPE.2011.11.6.897

Meenakshi, T. (2010). Identification of an Effective Control Scheme for Z-source Inverter . *Asian Power Electronics, 4. No.1.*

Mohan, N. (2012). *Power Electronics: A First Course*. John Wiley and Sons;

Mohd. Radzi, M. A. (2009). *Switched Capacitor Active Power Filter With New Control Algorithms*. University Malaya.

Muhammmad H Rashid. (2011). *Power Electronics Handbook - Devices, Circuits and Applications*. (M. H. Rashid, Ed.) (Third Edit). Elseivier.

Mummadi, V. (2011). Design of Robust Digital PID Controller for. *IEEE Transactions on Industrial Electroncis, 58*(7), 2883–2897.

Muruganandham, N., Lavanya, G., & Babu, R. S. (2013). Simulation of SPWM based Z-Source Inverter. *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE), 6*(3), 53–60.

Nayak, B., Dash, S. S., & Kumar, S. (2014). Proposed Method for Shoot-Through in Three Phase ZSI and Comparison of Different Control Techniques. *International Journal of Power Electronics and Drive System (IJPEDS), 5*(1), 32–40.

Pan, L., Sun, H., Wang, B., Dong, Y., & Gao, R. (2014). ESL-Γ-Z- Source Inverter. *J Electr Eng Technol, 9*(2), 589–599.

Park, S.-J. (2008). Psim and Matlab simulations analysis on 3-Phase Z-Source inverter. *2008 7th International Caribbean Conference on Devices, Circuits and Systems*, 1–5. http://doi.org/10.1109/ICCDCS.2008.4542662

Peng, F. Z. (2003). Z-Source Inverter. *IEEE Transactions on Industry Applications, 39*(2), 504–510.

Peng, F. Z. (2008). Analysis and design of Bi-directional Z-source inverter for electrical vehicles. *2008 Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition*, 1252–1257. http://doi.org/10.1109/APEC.2008.4522883

Peng, F. Z., Shen, M., Member, S., Qian, Z., & Member, S. (2005). Maximum Boost Control of the Z-Source Inverter. *IEEE Transactions on Power Electronics, 20*(4), 833–838.

Peng, F. Z., Xiaoming, Y., Xupeng, F., & Zhaoming, Q. (2003). ZSI For Adjustable Speed Drives. *Power Electronics Letters, IEEE, 1*(2), 33–35.

Ping, L., & He-ping, L. (2011). Application of Z-source Inverter for Permanent-magnet Synchronous Motor Drive System for Electric Vehicles. *Procedia Engineering*, *15*, 309–314. http://doi.org/10.1016/j.proeng.2011.08.060

Rąbkowski, J. (2007). The Bidirectional Z-source Inverter As An Energy Storage/Grid Interface. In *The International Conference on "Computer as a Tool"* (pp. 1629–1635).

Rabkowski, J., Barlik, R., & Nowak, M. (2008). Pulse Width Modulation methods for bidirectional/high-performance Z-source inverter. *2008 IEEE Power Electronics Specialists Conference*, 2750–2756. http://doi.org/10.1109/PESC.2008.4592361

Rahim, N. A. (1995). *Closed-Loop Control Of A Current-Mode AC/DC BUCK Converter In 4 Quadrant P-Q Operation*. Heriot-Watt University.

Rajaei, A. H., Mohamadian, M., Dehghan, S. M., & Yazdian, A. (2010). Single-phase induction motor drive system using z-source inverter. *Electric Power Applications, IET*, *4*(1), 17–25. http://doi.org/10.1049/iet-epa.2008.0304

Rajakaruna, S. (2008). Experimental studies on a novel single-phase Z-Source inverter for grid connection of renewable energy sources. In *Power Engineering Conference, 2008. AUPEC '08. Australasian Universities* (pp. 1–6).

Rajakaruna, S., & Jayawickrama, Y. R. L. (2005). Designing Impedance Network Of Z-source Inverters. In *Power Engineering Conference, 2005. IPEC 2005. The 7th International* (p. 962–967 Vol. 2).

Rao, K. P. P., Veni, B. K., & Ravithej, D. (2012). Five-Leg Inverter for Five-Phase Supply. *International Journal of Engineering Trends and Technology-*, *3*(2), 144–152.

Renukadevi, G., & Rajambal, K. (2013). Modeling and Analysis of Multi-Phase Inverter Fed Induction Motor Drive with Different Phase Numbers. In *Wseas Transc on Systems and Control* (Vol. 8, pp. 73–80).

Rostami, H., & Khaburi, D. a. (2010). Neural networks controlling for both the DC boost and AC output voltage of Z-source inverter. *2010 1st Power Electronic & Drive Systems & Technologies Conference (PEDSTC)*, 135–140. http://doi.org/10.1109/PEDSTC.2010.5471841

Shen, M. (2006). *Z-source inverter design, analysis, and its application in fuel cell applications*. Michigan State University.

Shen, M., Jin, W., Joseph, A., Peng, F. Z., Tolbert, L. M., & Adams, D. J. (2004). Maximum Constant Boost Control Of The Z-source Inverter. In *Industry Applications Conference, 2004. 39th IAS Annual Meeting. Conference Record of the 2004 IEEE* (Vol. 1, p. 147).

Shen, M., Joseph, A., Huang, Y., Peng, F. Z., & Qian, Z. (2006). Design And Development of a 50kW ZSI for Fuel Cell Vehicles. In *IPEMC 2006*.

Shen, M., Joseph, A., Wang, J., Peng, F. Z., & Adams, D. J. (2005). Comparison Of Traditional Inverters And Z-Source Inverter. *IEEE 36th Conference on Power Electronics Specialists, 2005.*, 1692–1698. http://doi.org/10.1109/PESC.2005.1581858

Shen, M., Member, S., Wang, J., Joseph, A., Peng, F. Z., Tolbert, L. M., ... Adams, D. J. (2006). Constant Boost Control Of The ZSI To Minimize Current Ripple And Voltage Stress. *IEEE Transactions on Industry Applications*, *42*(3), 770–778.

Shen, M., & Peng, F. Z. (2008). Operation Modes and Characteristics of the Z-Source Inverter With Small Inductance or Low Power Factor. *IEEE Transactions on Industrial Electronics*, *55*(1), 89–96. http://doi.org/10.1109/TIE.2007.909063

Shen, W. X. X., Zhi Jian, Z., Xing, Z., Po, X., & Shen, W. X. X. (2008). Single-Phase Uninterruptible Power Supply Based on Z-Source Inverter. *IEEE Transactions on Industrial Electronics*, *55*(8), 2997–3004. http://doi.org/10.1109/TIE.2008.924202

Sikorski, A., & Citko, T. (1998). Current Controller Reduced Switching Frequency For VS-PWM Inverter Used With AC Motor Drive Applications. *IEEE Transactions on Industrial Electronics*, *45*(5), 792–801.

Sumedha Rajakaruna, L. J., Rajakaruna, S., Member, S., & Jayawickrama, L. (2010). Steady-State Analysis and Designing Impedance Network of Z-Source Inverters. *IEEE Transactions on Industrial Electronics*, *57*(7), 2483–2491.

Tang, Y., Xie, S., & Ding, J. (2014). Pulsewidth Modulation of Z-Source Inverters With Minimum Inductor Current Ripple. *IEEE Transactions on Industrial Electroncis*, *61*(1), 98–106.

Tang, Y., Xie, S., Zhang, C., & Xu, Z. (2009a). Improved Z-Source Inverter With Reduced Z-Source Capacitor Voltage Stress and Soft-Start Capability. *IEEE Transactions on Power Electronics*, *24*(2), 409–415. http://doi.org/10.1109/TPEL.2008.2006173

Tang, Y., Xie, S., Zhang, C., & Xu, Z. (2009b). Improved Z-Source Inverter With Reduced Z-Source Capacitor Voltage Stress and Soft-Start Capability. *IEEE Transactions on Power Electronics*, *24*(2), 2005–2008.

Thangaprakash, S., & Krishnan, A. (2010a). Comparative evaluation of modified pulse width modulation schemes of Z-source inverter for various applications and demands. *International Journal of Engineering, Science and Technology*, *2*(1), 2005–2008.

Thangaprakash, S., & Krishnan, A. (2010b). Implementation and Critical Investigation on Modulation Schemes of Three Phase Impedance Source Inverter. *Iranian Journal of Electrical & Electronic Engineering*, *6*(2), 84–92.

Thangaprakash, S., & Krishnan, A. (2012). A new switching scheme for Z-source inverter to minimize ripples in the Z-source elements. *International Journal of Automation and Computing*, *9*(2), 200–210.

Thangaprakash, S., Krishnan, A., & S. Thangaprakash, A. K. (2010). Implementation and Critical Investigation on Modulation Schemes of Three Phase Impedance Source Inverter. *Iranian Journal of Electrical & Electronic Engineering*, *6*(2), 84–92.

Thangaprakash, S., Krishnan, A., & Thangaprakash†, S. (2010). Current Mode Integrated Control Technique for Z-Source Inverter Fed Induction Motor Drives. *Journal of Power Electronics*, *10*(3), 285–292. http://doi.org/10.6113/JPE.2010.10.3.285

Tran-Quang, V., Tae-Won, C., Kim, H.-G., & Nho, E.-C. (2009). Minimization of Voltage Stress Across Switching Devices in The ZSI by Capacitor Voltage Control. *Journal of Power Electronics*, *9*(3), 335–342.

Tran, Q.-V., Chun, T.-W., & Kim, H.-G. (2009). Minimization of Voltage Stress across Switching Devices in the Z-Source Inverter by Capacitor Voltage Control . *Journal of Power Electronics*, 335–342.

Tran, Q., Chun, T., Ahn, J., & Lee, H. (2007). Algorithms For Controlling Both The DC Boost And AC Output Voltage Of Z-Source Inverter. *IEEE Transactions on Industrial Electronics*, *54*(5), 2745–2750. http://doi.org/10.1109/TIE.2007.895146

Vasanthi, V., & Ashok, S. (2013). Performance of Simple Boost Controlled ZSI Fed Three Phase Locomotives In The Motoring Region. *International Journal of Electrical Engineering Engineering Research*, *3*(5), 127–132.

Vukosavic, S. N., Jones, M., Dujic, D., & Levi, E. (2008). An improved PWM method for a five-leg inverter supplying two three-phase motors. In *2008 IEEE International Symposium on Industrial Electronics* (pp. 160–165). http://doi.org/10.1109/ISIE.2008.4676881

Welchko, B. ., Lipo, T. A., Jhans, T. ., & Schulz, S. . (2004). Fault Tolerance Three-Phase AC Motor Drive Topologies: A Comparison Of Feature, Cost and Limitations. *IEEE Transactions on Power Electronics*, *19*(4), 1108–1116.

Xie, S., Tang, Y., & Zhang, C. (2009). Research on third harmonic injection control strategy of improved Z-source inverter. *2009 IEEE Energy Conversion Congress and Exposition*, 3853–3858. http://doi.org/10.1109/ECCE.2009.5316222

Yamanaka, M., & Koizumi, H. (2009). A Bi-directional Z-source inverter for electric vehicles. In *2009 International Conference on Power Electronics and Drive Systems PEDS.*

Zhu, Miao, Kun Yu, F. L. L. (2010). Topology Analysis of a Switched-Inductor Z-Source Inverter. In *Industrial Electronics and Applications (ICIEA), 2010 the 5th* (pp. 364–369).

Zhu, M., Yu, K., & Luo, F. L. (2010). Switched Inductor Z-Source Inverter. *IEEE Transactions on Power Electronics*, *25*(8), 2150–2158.

LIST OF PUBLICATIONS

Conference Papers and Journals:

1. **M.S.BAKAR**, N.A.RAHIM, H.DANIYAL, K.H.GHAZALI "Experimental Study Of SBPWM For Z-Source Inverter Five Phase" in International Journal of Power Electronics & Drives (IJPEDS – Scopus Cited), Vol 6, No 1: March 2015.
2. **M.S.BAKAR**, N.A.RAHIM, K.H.GHAZALI, H.DANIYAL "Evaluation on Performances of Carrier-Based PWM for Z-Source Five Leg Inverter" in The 2nd Power and Energy Conversion Symposium (PECS2014), 2014.
3. **M.S.BAKAR**, N.A.RAHIM, K.H.GHAZALI, H.DANIYAL, "An Open Loop Evaluation Of Five-Phase Z-Source Inverter" in Journal of International Review Of Automatic Control, 2013(IREACO – Scopus Cited) , Vol. 6.No. 5. pp. 607-611.
4. **M.S.BAKAR**, N.A.RAHIM, K.H.GHAZALI, A.H.M.HANAFI, "Feasibility Study On Z-Source Inverter Topologies" in International Conference on Electrical, Control and Computer Engineering 2013 (InECCE), 2013, pp.14-18.
5. **M.S.BAKAR**, N.A.RAHIM, K.H.GHAZALI, A.H.M.HANAFI, "Z-source inverter pulse width modulation: A Survey" in International Conference on Electrical, Control and Computer Engineering 2011 (InECCE), 2011, pp. 313-3316.
6. **M.S.BAKAR**, N.A.RAHIM, K.H.GHAZALI, "Analysis of various PWM controls on single-phase Z-source inverter" in 2010 IEEE Student Conference on Research and Development (SCOReD), 2010, pp. 448-451.