The Z-Source Converter as an Introduction to Power Electronics and Undergraduate Research

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Abstract – **This paper presents the undergraduate research experience for electrical engineering students without previous knowledge of the area of power electronics. The paper is divided in two parts: the undergraduate research experience and the analysis of the Z-Source. In the first part of the paper, the dynamic model that describes the operation of the Z-Source under resonance is analyzed. The Z-Source topology is very simple to describe: two-port networks that consist of capacitors C_a and C_b and a split-inductor L_a and L_b connected in X shape. In the paper, the Z-Source is injected with different type of waveforms including square waveforms (produced by inverters or multilevel), harmonic injection, and random noise injected to the fundamental (sine) waveform.**

The second part of the paper present the undergraduate research experience analyzing the Z-Source under resonant conditions. Several goals were obtained: 1) the undergraduate student was exposed to new circuit topologies in the area of power electronics, 2) interest about the new technologies developed in the field of power electronics, and 3) to familiarize the undergraduate student with typical software used in the industry such as Saber, Simulink, P-Spice, etc.

It is important to point that most of the work related to the Z-Source topology had been done in the past by graduate students as their dissertation work. But due the fact of the Z-Source simple configuration, an interesting approach had been done as an introductory topology to undergraduates without previous knowledge of power electronics.

Index Terms – Undergraduate research, Power Electronics, Z-Source, Mentoring.

I. INTRODUCTION

Power electronics is one of the fastest changing and evolutionary areas in electrical engineering in the recent years [1]. As a fact, this area has been an important part of the Power Engineering Curriculum at UPRM for a lot of years. Both graduate and undergraduate research work in power electronics have been performed at UPRM since the 1980s [2]. Additionally, the growth in the undergraduate research works at UPRM had been motivated by the faculty members of the Department of Electrical and Computer Engineering department [3] and the Center for Power Electronics Systems (CPES) [2]. Also, it is important to know that part of the

mission of the ECE Department is the creation of abilities in the undergraduate students such as applying knowledge of mathematics, science and engineering, designing a system, component or process, formulating and solving engineering problems. This mission is in accordance with the Accreditation Board for Engineering and Technology (ABET) criterions [4]. As a result, undergraduate education at UPRM complemented with research in the area of power electronics makes a perfect fit and a win-win situation for the student, faculty and the university.

Now continuing with our definitions, power electronics circuits convert one type or level of voltage or current waveform to another, and hence called converters [5]. But to obtain the desired output, the key component is the switching pattern. Clearly, imperfect switching leads to power loss in converters. In resonant switching circuits, switching takes place when voltage and/or current is zero, thus avoiding simultaneous transitions of voltage and current and thereby eliminating switching losses.

Typically, resonant converters are categorized into three types: series, parallel, and series-parallel [6]-[7]. The series resonant converter contains a resonant circuit in series with the load and the parallel resonant converter contains a resonant circuit in parallel with the load. The series-parallel converter contains a resonant circuit parallel to the load with a series resonant circuit connected between the power source and parallel combination. The three conventional categories of resonant circuits can be viewed as subsets of π-filter and T-filter circuits. Studies have shown that resonant π-filters and T-filters can act as voltage boost circuits or "resonant transformers" [7]. The T filter also shows great result in eliminating noises [8].

An additional topology that has similar properties of the past converters is the Z-Source. The impedance-source power converter (Z-Source) is a new electronic circuit recently recognized because of its applications in power conversion [9]. The Z-Source found to be more efficient than other commonly used power converters [10]. For example, voltage buck-boost capability needed in dc-to-ac fuel cell applications [11] other applications are related to the improvement in the performance of electric drives [12]. The Z-Source can be more reliable than the T-filter when used in utility systems where its large dc inductive current filtering and implicit output short-circuit protection are found to be desirable [13]. Based on the

above mentioned capabilities of the Z-Source converter, this paper presents its topology as a resonant converter.

In the first part of the paper, the dynamic model that describes the operation of the Z-Source under resonance is given. The equations to calculate the resonant frequency using the Z-Source transfer function are presented in the paper and examples will include the Z-Source cleaning the harmonics injected to the load by an inverter. Several tests were done using square waveforms, harmonic injection [15], multilevel waveforms [16] and random noise injected to the fundamental (sine) waveform. The examples and all the simulations were done by the undergraduate researcher.

In summary, the main ideas for this research work are the following: study of the Z-Source converter under resonant conditions, to expose the undergraduate student to new circuit topologies in the area of power electronics, to create in them the interest about the new technologies developed by the power electronics field, and to familiarize the undergraduate student with typical software used in the industry such as Saber, Simulink [17], P-Spice, etc.

II. Z-SOURCE RESONANT MODEL DEVELOPMENT

The Z-Source topology is very simple to describe: two-port networks that consists of a split-inductor L1 and L2 and capacitors C1 and C2 connected in X shape. It is define that C1 is C, C2 is βC, L1 is L and L2 is αL. Figure 1 shows the schematic for a Z-Source converter. Now, it is desired to calculate the dynamic model for a Z-Source. The equations that describe the dynamic model for the Z-Source are given by (1), (2), (3), (4), (5) and (6).

$$\frac{\partial V_{C1}}{\partial t} = \frac{1}{C_1}\left(I_{L2} - I_{in}\right) \tag{1}$$

$$\frac{\partial V_{C2}}{\partial t} = \frac{1}{C_2}\left(I_{L1} - I_{in}\right) \tag{2}$$

$$\frac{\partial V_{L1}}{\partial t} = \frac{1}{L_1}\left(V_{out} - V_{C2}\right) \tag{3}$$

$$\frac{\partial V_{L2}}{\partial t} = \frac{1}{L_2}\left(V_{out} - V_{C1}\right) \tag{4}$$

$$V_{in} = V_{C1} + V_{C2} - V_{out} \tag{5}$$

$$I_{out} = I_{L1} + I_{L2} - I_{in} \tag{6}$$

Using mesh analysis, and considering the initial conditions equal to zero, the transfer function can be obtained using (7), (8) and (9).

$$\left(\frac{1}{sC_1} + sL_2\right)I_{C1} - (sL_2)I_{out} = Vin \tag{7}$$

$$(sL_2)I_{C1} - \left(sL_2 + \frac{1}{sC_1} + R\right)I_{out} + \left(\frac{1}{sC_2}\right)I_{L1} = 0 \tag{8}$$

$$-\left(\frac{1}{sC_2}\right)I_{out} + \left(sL_1 + \frac{1}{sC_2}\right)I_{L1} = -V_{in} \tag{9}$$

After a few calculations, we solve (7), (8) and (9) for *Vo/Vin* and get:

$$\frac{Vo}{Vi} = \frac{s^4\alpha\beta L^2 C^2 - 1}{\left(\alpha\beta RL^2 C^2\right)s^4 + (\beta+1)\alpha L^2 Cs^3 + (\beta+\alpha)RLCs^2 + (\alpha+1)Ls + R} \tag{10}$$

Now, using the given equations in the frequency domain (i.e. $j\omega$) then it is possible to calculate resonance frequency. It is assumed a resistive load. After some simplification, the imaginary part of the Z-Source dynamic model is equal to zero as given by (11-26).

$$\left[\alpha + 1 - \omega^2\left(\alpha\beta LC - \alpha LC\right)\right]j\omega L = 0 \tag{11}$$

Solving for ω, the resonant frequency is given by the expression (12).

$$\omega_0 = \frac{\sqrt{\alpha+1}}{\sqrt{\alpha LC(\beta+1)}} \tag{12}$$

If we substitute the resonant frequency in the transfer function of the Z-Source converter, we get the expression of the circuit when working under resonance, given by (13).

$$\frac{Vout}{Vin} = \frac{\alpha\beta - 1}{\alpha - \beta} \tag{13}$$

Also, the quality factor for the Z-source converter is given by the following two equations (14) and (15).

$$Q = \frac{\omega_0 L\sqrt{\alpha(\beta+1)}}{R\sqrt{(\alpha+1)}} \tag{14}$$

$$Q = \frac{\sqrt{\alpha+1}}{\omega_0 RC\sqrt{\alpha(\beta+1)}} \tag{15}$$

Figure 2 shows that the resonant frequency will create amplification in the voltage output. The graph shows the frequency response with the parameters $\alpha=5$, $\beta=3$ for different values of Q. As can be observed the Z-Source responds with a zero-gain when working approximately at 92.77% of the resonance frequency at this conditions.

III. SIMULATIONS USING SIMULINK

Figure 3 shows the simulation for the Z-Source model under resonance in Simulink, given $\alpha=4$, $\beta=2000$, Q=5, f=50Hz. Small α is used to minimize the inductances sizes. Note, that with a big difference between the values of α and β, the gain

expression can be approximated by G= –α. The voltage input is a sinusoidal waveform hence the voltage output will be an amplified (i.e. 4 times) sinusoidal waveform shifted by 180°.

Keeping the previous parameters, we proceeded to test the Z-Source with signals that weren't sinusoidal to prove the filter capabilities. As an example, the input signal should be considered as voltage output produced by an inverter. Figure 4 shows the output of the filter with a square wave with Ton > Toff. For our example, a square signal with frequency of 50 Hz and amplitude 100 was produced with Ton=8.1057 and Toff=1.894. Figure 5 shows the voltage output when the voltage input injected to the Z-source is the voltage produced by a multilevel convert. Figure 6 shows the Z-source rejecting the 3rd harmonics injected to the voltage input. Finally, Figure 7 shows the simulation results when the voltage input is injected with random noise. Clearly, for our previous examples, the voltage output looks sinusoidal and in most of the cases the Total Harmonic Distortion was less than 3%. It is important to point that all the simulations were done by an undergraduate student without previous knowledge of power electronics. Clearly, mentoring plays a critical role in the development of these results. Also, the synergy developed between the faculty and the student was vital for the success of this project. The sections will cover the topics of mentoring, task, and skills developed by the student.
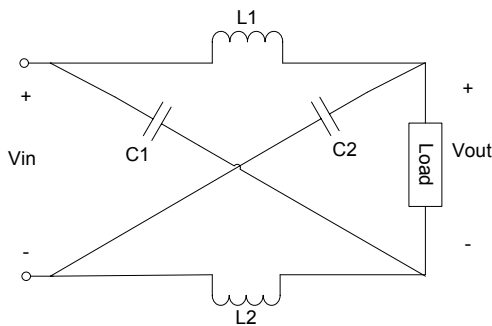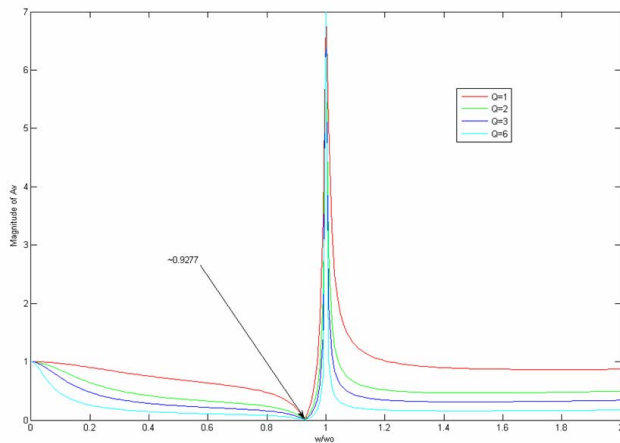

FIGURE 1
Z-SOURCE INVERTER SCHEMATIC.

FIGURE 2
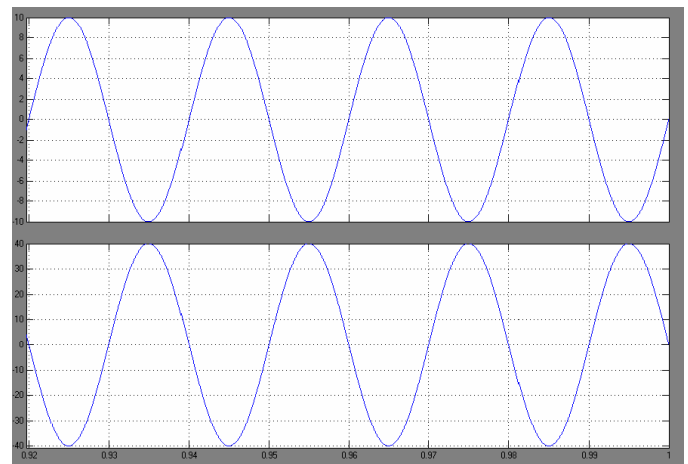Z-SOURCE FRECUENCY RESPONSE FOR DIFFERENT VALUES OF Q

FIGURE 3
SIMULATION RESULTS FOR A SINUSOIDAL INPUT WITH ALPHA=4, BETA= 2000, Q=5 AND GAIN=4.
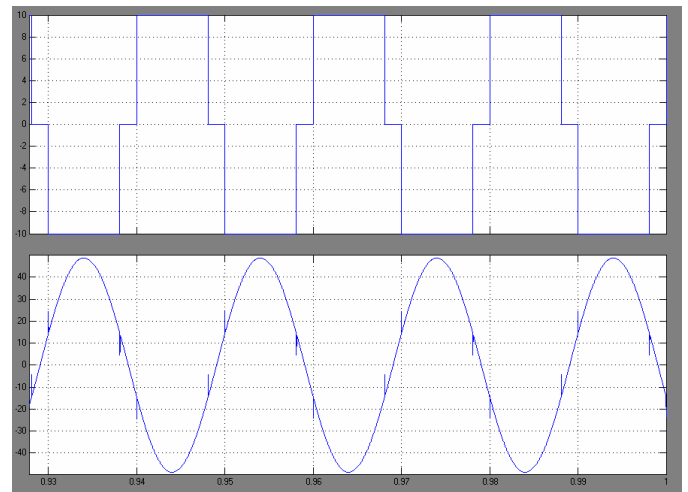

FIGURE 4
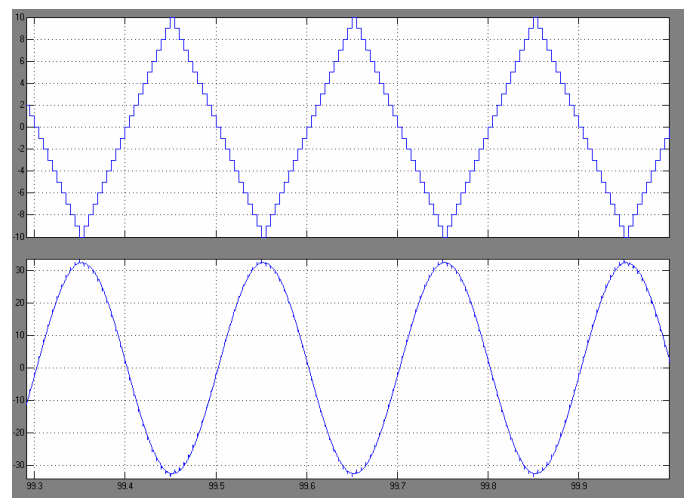SIMULATION RESULTS FOR A SQUARE WAVEFORM USING THE Z-SOURCE.

FIGURE 5
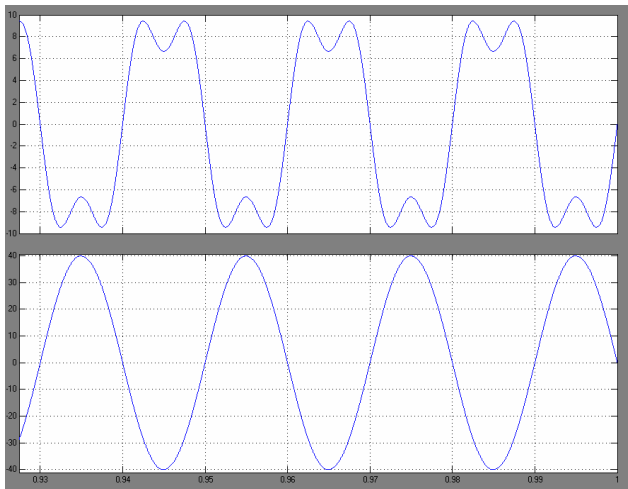SIMULATION RESULTS FOR A MULTILEVEL WAVE INPUT.

FIGURE 6
SIMULATION RESULTS USING A SINE WAVE WITH HARMONICS INPUT.

FIGURE 7
SIMULATION RESULTS INSERTING A RAMDOM NOISE TO A SINUSOIDAL
WAVEFORM AS INPUT.

IV. ORGANIZATION AND MENTORING

A critical part for the success of this project was the mentoring provided by the professor to the student. Several steps were done to provide the correct mentoring to the student. First, the student met with the professor at least one hour per week, making an oral presentation in which the student showed the past, present and future work of the research project to the professor and other undergraduate and graduate students. Every month, the student was asked to handle a report including the work done during that period and expressing himself about the experience doing that work. At the end of the semester, the student made a final report, summarizing all the work done during the semester, and describing the experience of working on a graduate level research at undergraduate level. One of the most important outcomes using this mentoring strategy was that the undergraduate student published as first author a paper presenting the research results in the 2007 Center for Power Electronics General Meeting.

V. STUDENT'S TASKS

It is important to recognize that the student responsibility and interest in the project play an important role in the success of this project. After 24 weeks of mentoring, training, research and experimentation, the work done by the student included the following tasks:

- **Searching of literature**: At first, the student started looking for past information and works done with the Z-Source topology.
- **Simulation of the circuit in P-Spice:** The student made some simulations with random parameters as first approach to the Z-Source topology.
- **Calculation of transfer function:** In this task, the student found the 4th order transfer function of the Z-Source
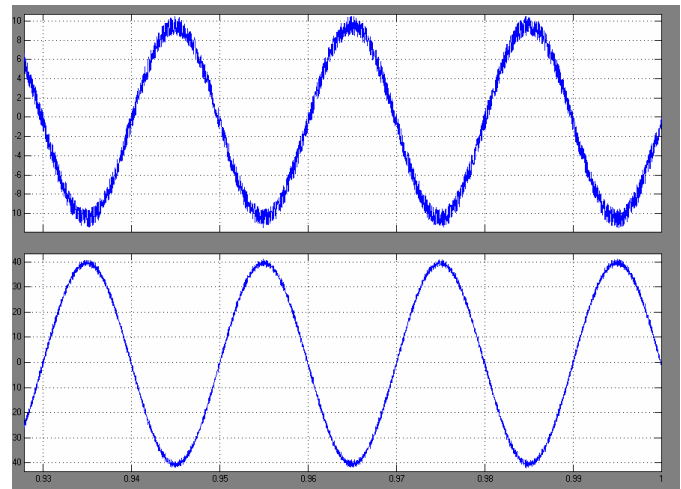
considering a resistive load. MATLAB's symbolic toolbox was used to prove the results.
- **Calculation of Quality factor and resonance frequency expressions:** The parameters were substituted in the transfer function in order to make the circuit work at its resonance frequency.
- **Simulation using Simulink:** State variables approach was used to simulate the Z-Source in resonant mode. Several inputs were used to represent different voltage outputs produced by an inverter. Also, the parameters of the Z-Source were changed to find the more efficient parameters. At last, inductive and capacitive effects were added to the load to find out the effectiveness of the Z-Source filter at these conditions.
- **Applications:** The student simulated several examples including utility applications and induction motors.
- **Final Project Report:** This report included all the research results and an evaluation of the impact of the research in his early career.

VI. SKILLS DEVELOPED AND BENEFITS GAINED BY THE STUDENT

For the undergraduate student, working in this type of research experience was a very challenging process especially for a student without previous knowledge in the area of power electronics. First of all, the student had the obligation to search and learn outside of the classroom because he had no preview experience working in that kind of project. This process vastly improved the student's ability to search, understand, and discuss journal articles and publications concerning the area of power electronics.

Also, this experience gave the opportunity to the student to apply previous knowledge of courses taken before, and during the process. The use of mathematics in this research helped the student to improve his ability and quickness to work complex equations. Also, the student learned how to use

computer aided analysis to verify his results. Basic circuit theory was reviewed and applied, thus providing the student an application to his past courses. Also, the student applied knowledge of the courses he was currently taking, like dynamic systems and state variables given in the control systems course. This process gave him a deep understanding and practice of the material, giving an advantage over other students taking the courses. In top of that, the student acquired practice in the usage of P-Spice, and then started learning typical software that can be found in industry such as MATLAB, Simulink, and Saber. Clearly, the experience gained by the student, is a valuable tool and prepared him to bigger challenges in the area of power electronics.

The knowledge gained during the research work served as an introduction to courses like electric machinery and power electronics. Also the student was motivated to explore and to take the course of introduction power electronics given in the UPRM's curriculum. As well, the experience and close interaction with a faculty member has left the student a confidence in his research skills and a feeling of capability to contribute to society, giving the spark to the student to pursue in the nearest future an advance education in the graduate school.

Another asset of this research was the oral and writing skills developed by the student during this process. Oral skills were developed because of the constant power point presentations. The oral presentations helped the student to feel confidence when talking in a crowded place, and also created an atmosphere of mutual confidence between the undergraduate, the other presenting students and the professor to express, question and discuss about the work done.

Progress reports and the making of the paper lead to an increase in writing skills. Making a paper introduced the student to a new writing form, in which the student learned how to present a work correctly, follow a specific format, and submit this kind of work into conferences.

Another improved area was social skills. The student met and worked with other students at different levels of education. The group of students that presented each week included 2nd to 5th year undergraduate students from electrical and computer engineering departments, and graduate students from the electrical engineering department. This core of students created a supportive and helping atmosphere during the whole process.

At last, the student learned how to meet a project's expectations. The expected outcomes were given since the first week of work. During the entire semester, the mentor asked for results each week according with the student's capabilities. The student felt a responsibility to present concrete results each week, even when the student was busy studying or working in other courses. During the final weeks of the research, the professor demanded and motivated the student into presenting certain results, applications, and the paper of the project, leading the student to raise his productivity to a very high level.

VI. CONCLUSION

We have shown that the Z-Source, when working under resonance conditions, can work as an integrated filter-transformer. This integration permits the elimination of noises and changing the voltage level of the input, and also it reduces the cost compared to usually used transformers. It is important to point that most of the work related to this topology had been done in the past by graduate students as their dissertation work. But due the fact of the Z-Source simple configuration, an interesting approach had been done using the Z-Source as an introductory topology to undergraduates without previous knowledge of power electronics. As prove of the last statement, this work was completely done by an undergraduate student without previous experience in the area of power electronics. As a closing remark and proving the excellent results obtained in the last six months using this methodology, the undergraduate student has two publications in peer review conferences and right now, the student is writing a third publication in the area of power systems with his professor, a young faculty member at University of Puerto Rico.

In conclusion, this research work served the student as a motivating and learning experience. The experience has also given the student new tools and confidence to solve engineering problems. During the process the student obtained an improvement in his analytical, oral, writing and social skills. It has been observed that when making this kind of work it is effective involving other students at different levels of education to make the researcher raise his working level and create a confidence atmosphere between the professor and the students.

REFERENCES

[1] Bose, B.K.; "Advances in power electronics-its impact on the environment", *Industrial Electronics, 1998. Proceedings. ISIE '98. IEEE International Symposium*, Volume 1, 7-10 July 1998 pp. 28 – 30.

[2] O'Neill-Carrillo, E.; Irizarry-Rivera, A.; Velez-Reyes, M.; "Curriculum improvements in power engineering" *Frontiers in Education Conference, 2001. 31st Annual.* Volume 1, 10-13 Oct. 2001 pp. T4A - 15-20.

[3] Jimenez, M.; Santiago, N.S.; "The supporting role of CAD/CAM tools in undergraduate research education in electrical and computer engineering", *Information Technology Based Higher Education and Training, 2005. ITHET 2005. 6th International Conference*, 7-9 July 2005 pp. S3C/23 - S3C/26.

[4] The Accreditation Board for Engineering and Technology (ABET): www.abet.org.

[5] Hart, D. W.; "Introduction to Power Electronics", 1997, Prentice Hall Inc., Upper Saddle River, NJ 07458.

[6] Wu Xiang; Yan Xiangwu; Zhang Lixia; "Analysis of filter circuit of DC side in high-frequency current transformer based on battery performance measurement", *Electrical Machines and Systems, 2005.* ICEMS 2005. *Proceedings of the Eighth International Conference.* Volume 2, 27-29 Sept. 2005 pp. 1219 - 1222

[7] Thibodeaux, R.J., "Analysis of DC/DC converters with resonant filters", *Energy Conversion Engineering Conference, 1997. IECEC-97. Proceedings of the 32nd Intersociety.* Volume 4, 27 July-1 Aug. 1997 pp. 2217 - 2221 vol.4

[8] Masoud, K.; Ledwich, G., "Sampling averaging for inverter control" *Power Electronics Specialists Conference, 2002. pesc 02. 2002 IEEE 33rd Annual.* Volume 4, 23-27 June 2002 pp.1699 – 1704

[9] F.Z. Peng, "Z-Source inverter", *IEEE Trans. Ind. Applicant.* Volume 39, pp. 504-510, Mar/Apr. 2003

[10] Rajakaruna, S.; Jayawickrama, Y.R.L., "Designing impedance network of Z-source inverters", Power Engineering Conference, 2005. IPEC 2005. The 7th International. Volume 2, 29 Nov.-2 Dec. 2005 pp. 962 - 967

[11] Xu Peng Fang; Zhao Ming Qian; Fang Zheng Peng, "Single-phase Z-source PWM AC-AC converters", *Power Electronics Letters, IEEE.* Volume 3, Issue 4, Dec. 2005, pp.121 – 124

[12] Fang Zheng Peng,, Alan Joseph, JinWang,, Miaosen Shen, Lihua Chen, Zhiguo Pan, Eduardo Ortiz-Rivera, and Yi Huang, "Z-Source Inverter for Motor Drives". *IEEE Transactions on Power Electronics*, Volume 20, NO. 4, July 2005, pp. 1-7.

[13] Loh, P.C., Gajanayake, C.J., Vilathgamuwa, D.M., Blaabjerg F.;"Evaluation of Resonant Damping Techniques for ZSource Current-Type Inverter", *Applied Power Electronics Conference and Exposition, 2006. APEC '06. Twenty-First Annual IEEE*, 19-23 March 2006, pp. 7

[14] Miaosen Shen; Peng, F.Z., "Operation modes and characteristics of the Z-source inverter with small inductance"**,** *Industry Applications Conference, 2005. Fourtieth IAS Annual Meeting. Conference Record of the 2005*, Volume 2, 2-6 Oct. 2005 pp. 1253 – 1260.

[15] Pereira, L.; Kosterev, D.; Mackin, P.; Davies, D.; Undrill, J.; Wenchun Zhu; "An interim dynamic induction motor model for stability studies in the WSCC", Power Systems, IEEE Transactions on Volume 17, Issue 4, Nov. 2002 Pages:1108 - 1115

[16] Bojoi, R.; Lazzari, M.; Profumo, F.; Tenconi, A., "Digital field oriented control for dual three-phase induction motor drives", Industry Applications Conference, 2002. 37th IAS Annual Meeting. Conference, Vol.: 2, On pages: 818- 825 vol.2, 2002.

[17] Marti, J.R.; Myers, T.O.; "Phase-domain induction motor model for power system simulators", WESCANEX 95. Communications, Power, and Computing. Conference Proceedings. IEEE, Volume 2, 15-16 May 1995 Page(s):276 - 282 vol.2.