Compensation of Voltage Sags and Swells Using Z-Source AC-AC Converter

Seyed Hossein Hosseini[1], Farzad Sedaghati[2], Mitra Sarhangzadeh[1]

[1]Islamic Azad University, Tabriz Branch, Tabriz, Iran
hosseini@tabrizu.ac.ir, sarhangzadehm@tabrizu.ac.ir
[2]University of Tabriz, Tabriz, Iran
farzad.sedaghati@gmail.com

Abstract

In this paper Z-source ac-ac converter has been analyzed for compensation of voltage sags and swells and maintenance of continuous regulation in output voltage. A brief discussion about voltage sags and swells is done, and then Z-source ac-ac converter topology, control and operation are reviewed. Finally, simulation analysis has been done using Matlab/Simulink software and its results confirm theoretical discussions.

1. Introduction

Power quality problems have received increasing attention in recent years because of the significant economic impacts that they can impinge on industrial customers [1]. Nowadays, it is common to find disturbances in the amplitude or waveform shape of current and voltage in power systems. These conditions could produce fails in the equipments, raising the possibility of an energy interruption. One of these problems is voltage fast variations that appear in the ac mains and known as voltage sags and swells [2]. It is important to eliminate voltage fast variations because they are the most frequently cause of disrupted operations for many industrial processes, particularly those using modern electronic equipment, which are highly sensitive to short duration source variations [3]. Dynamic Voltage Restorer (DVR) and Uninterrupted Power Supply (UPS) systems had been researched and developed along the last decades and they are capable to compensate voltage sags and swells. Essentially, a DVR functions by injecting a voltage component in series with the load voltage so that the load-side voltage is maintained to its nominal level during a voltage disturbance. Nevertheless, they depend on devices to store energy, like large capacitors or batteries bank. Other option developed, which is able to compensate voltage sags and swells is based on PWM ac-ac converter [4, 5]. This solution uses an autotransformer composed by one primary side and two secondary windings presenting a good performance. The system compensates until 50% voltage sags and swells and can continuously shape the output voltage to be sinusoidal (with low THD). Nevertheless, the autotransformer drives all the load power due to it is connected between the load and the ac mains. In this paper a PWM ac-ac converter is applied in order to compensate voltage sags and swells simultaneously in a distribution network. This converter can maintain a continuous regulation in output voltage. The essential advantages of this compensator are its simple control and sinusoidal output voltage which results in very low voltage THD.

2. Voltage Sags and Swells

2.1. Voltage Sags

Voltage sag is reduction of ac voltage in network main frequency for duration of 0.5 cycles to 1 minute. Sags are usually caused by system faults and are often the result of loads switching with heavy startup currents. Fig. 1 shows voltage sags:

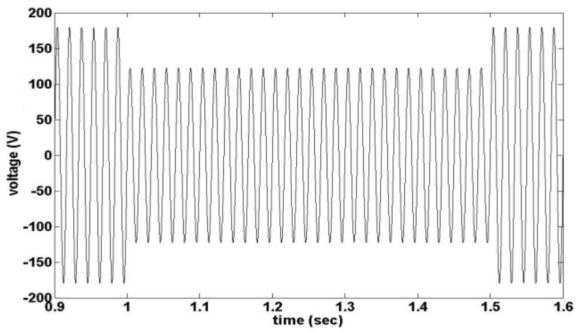

Fig. 1. Voltage sags

Common causes of voltage sags are large loads starting up (such as one might see when they first start up a large air conditioning unit) and remote fault clearing performed by utility equipment. Similarly, large motors starting up inside an industrial facility can result in significant voltage sags. A motor can draw six times as higher as its normal current or more during start up. Existing of such large and sudden electrical loads will likely cause a significant voltage drop to the rest of equipments. Undervoltages can be result of problems which create voltage sags but in longer duration than 1 minute. Fig. 2 shows Undervoltages.

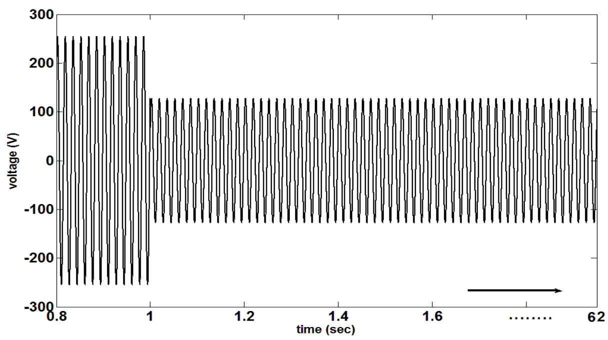

Fig. 2. Undervoltages

2.2. Voltage Swells

Voltage swell, the reverse form of sag, is an increment of ac voltage for duration of 0.5 cycles to 1 minute. High-impedance neutral connections, large load sudden reductions, and a single-phase fault in a three-phase system are common sources which cause voltage swells. Fig. 3 shows voltage swells:

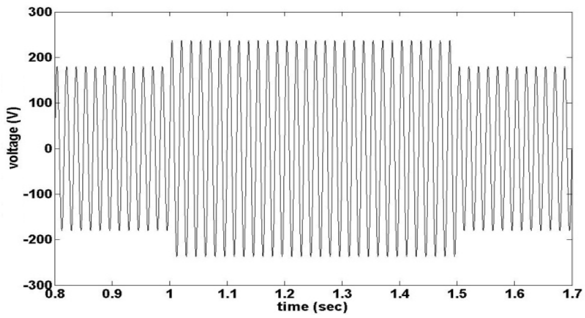

Fig. 3. Voltage swells

Voltage swells results can be data errors, flickering of lights, degradation of electrical contacts, semiconductor damage in electronics, and insulation degradation. Power line conditioners, UPS systems, and ferroresonant "control" transformers are common solutions. Overvoltages can be result of problems which create voltage swells but in longer duration than 1 minute. Fig. 4 shows overvoltages [6].

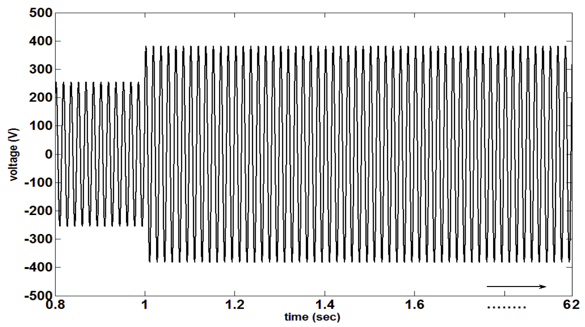

Fig. 4. Overvoltages

3. Z-Source AC – AC Converter

3.1 Z-Source Converter

Impedance source converters are new power electronic converter groups that their main operation depends on their X-shape core. Fig. 5 shows this X-shape core which is named Z-network.

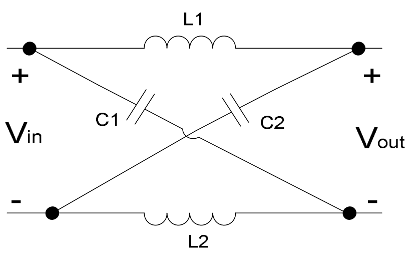

Fig. 5. Z-network

These converters are known as "Z-source converters" because of this Z-network. Z-network associate with semi-conductor switching, can buck and boost input voltage in output side in ac-ac converters and dc-ac converters. Because of various benefits of Z-source inverters, lots of researchers investigated them in recent years. We can point to [7]-[9] which present new researches about Z-source converters. In this paper we use Z-source ac-ac converter to mitigate voltage sags and swells impacts in a distribution network. Xu Peng Fang, Zhao Ming Qian and Fang Zheng Peng have discussed about Z-source ac-ac converters in detail in [10]. First we only review their discussion and then apply it to mitigate voltage sags and swells in next sections.

3.2 Z-Source AC-AC Converter

For ac–ac power conversion, which normally requires variable output voltage and variable frequency, the most popular topology is the voltage-source inverter with a dc link, i.e., a pulse width modulation (PWM) inverter with a diode-rectifier front end and dc capacitor link. However, for applications where only voltage regulation is needed, a direct PWM ac–ac converter is a better choice to achieve smaller size and lower cost. AC–AC converters or ac–ac line conditioners can also perform conditioning, isolating, and filtering of the incoming power in addition to voltage regulation. The use of self-commutated switches with PWM control can significantly improve the performance of ac–ac converters. Fig. 6 shows single-phase Z-source, PWM voltage-fed, buck-boost converter. This converter only utilizes two active devices (S_1) and (S_2), each combined with a full diode bridge for bidirectional voltage blocking and bidirectional current paths.

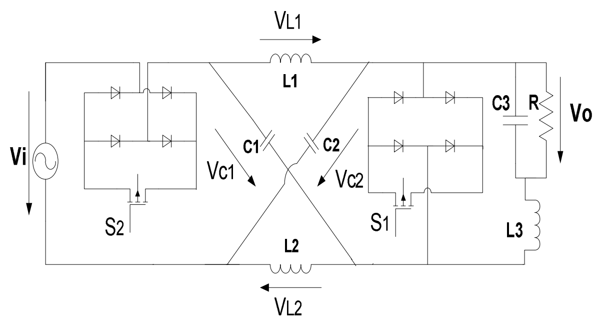

Fig. 6. Z-source ac – ac converter

All of the inductors and capacitors are small. They are used to filter switching ripples. The symmetrical Z-source network, which is combination of two inductors and two capacitors, is the energy storage and filtering element of Z-source ac–ac converter. Since the switching frequency is much higher than ac mains frequency, inductor and capacitor should be small [10].

3.3 Converter Switching Control

Z-source PWM ac-ac converter can be controlled in the same way as a conventional dc-dc converter. This control is complementary for S_1 and S_2. By controlling duty ratio, output voltage can be regulated as desired. For this converter switching frequency is 10 KHz [10].

3.4 Z-Source AC-AC Converter Operation

With respect to control scheme, this converter has two states. Fig. 7 (a) and (b) show states equivalent circuits.

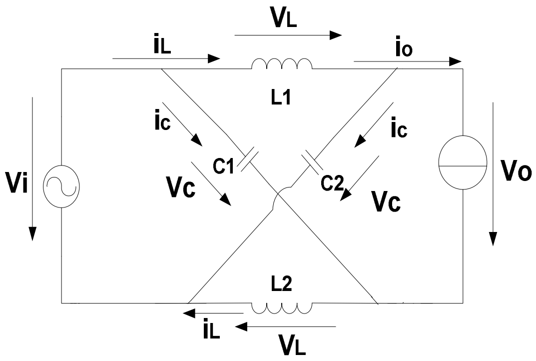

Fig. 7 (a). State 1 equivalent circuit

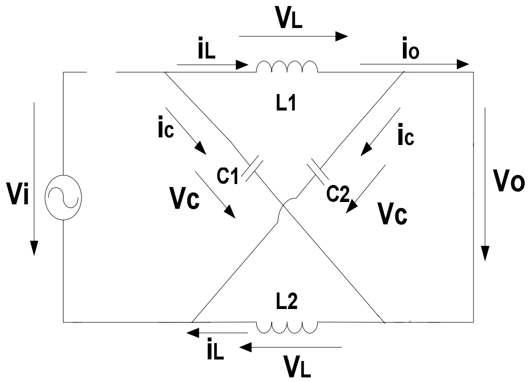

Fig. 7 (b). State 2 equivalent circuit

Since the inductors and capacitors of the Z-network have the same inductances (L) and capacitances (C) in Fig. 7(a) and (b) respectively, the Z-source network is symmetrical, so:

$$\begin{aligned} i_{L1} &= i_{L2} = i_L = I_L \sin(\omega t + \phi_L) \\ v_{C1} &= v_{C2} = v_C = V_C \sin(\omega t + \phi_C) \\ i_{C1} &= i_{C2} = i_C = C\omega \sin(\omega t + \phi_C + 90^{\circ}) \end{aligned} \quad (1)$$

We assume input and output voltages are as mentioned below:

$$\begin{aligned} v_i &= V_i \sin(\omega t) \\ v_o &= V_o \sin(\omega t + \phi_o) \end{aligned} \quad (2)$$

Where Φ_L, Φ_C, Φ_o are phase angles of Z-network inductor current, capacitor voltage and output voltage, respectively. In state 1, S_1 is turned off and S_2 is turned on, so input ac voltage charges the Z-network capacitors while inductors discharge and transfer energy to the load. Interval of the converter operating in this state is *(1-D) T*, where D is duty ratio of S1 switch and T is switching period. So in this state:

$$\begin{aligned} v_C &= v_i - v_L \\ v_o &= v_i - 2v_L \end{aligned} \quad (3)$$

In state 2, S_1 is turned on and S_2 is turned off, so Z-network capacitors discharge while inductors charge and store energy. Interval of converter operating in this state is *DT*. So in this state:

$$v_C = v_L \quad , \quad v_o = 0 \quad (4)$$

The average voltage of inductors during one ac line period in steady state should be zero, by ignoring the fundamental voltage drop and from (3) and (4), the following is results:

$$V_L = \bar{v}_L = \int [v_C.DT + (v_i - v_C).(1-D)T] \ dt \quad (5)$$

And this equation results in:

$$\frac{V_C}{V_i} = \left| \frac{1-D}{1-2D} \right| \quad \begin{cases} \phi_C = 0 & D < 0.5 \\ \phi_C = \pi & D > 0.5 \end{cases} \quad (6)$$

We assume filter inductor and the inductor in the Z-network are very small and there is not line frequency voltage drop across the inductor, so voltage across the load and V_C, the voltage across the capacitor of the Z-network, should be equal, therefore:

$$V_O = \left| \frac{1-D}{1-2D} \right| V_i \quad (7)$$

And in summary:

$$v_O = \frac{1-D}{1-2D} \ v_i \quad (8)$$

Fig. 8 shows voltage gain versus duty cycle [10].

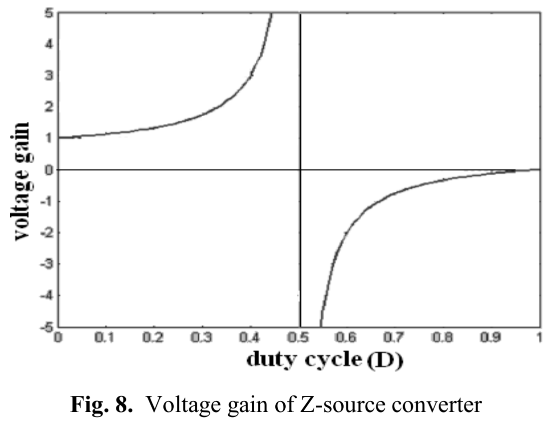

Fig. 8. Voltage gain of Z-source converter

4. Simulation Results

Z-source ac-ac converter capability in voltage continuous regulation creates idea of voltage sags and swells mitigation in a distribution network via this converter. Fig. 9 shows a distribution network which has been analyzed to prove our discussion.

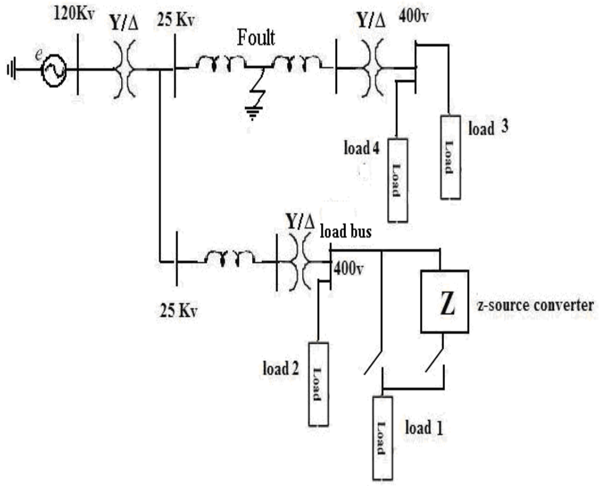

Fig. 9. Distribution network

To produce pulse signals for switches, following equations are resultants of solving $G=V_o/V_{in}$ with respect to D using (8) and (4): For boost mode

$$D=\frac{1-G}{1-2G} \tag{9}$$

And for buck mode

$$D=\frac{1+G}{1+2G} \tag{10}$$

Three phases to ground fault happened in feeder 1, from 0.1s to 0.2s which causes 25% voltage sags in feeder 2. Load 1 is sensitive load which has two paths to receive electric energy. One of the paths is normal path and the other one is converter path. Converter transmits energy when voltage sags or voltage swells occur. In this estate load bus voltage RMS is compared with reference (desired) voltage RMS. If there is any difference, load must be fed from converter path while normal path is open. Fig. 10 shows Control blocks, which is applied to regulate converter output voltage.

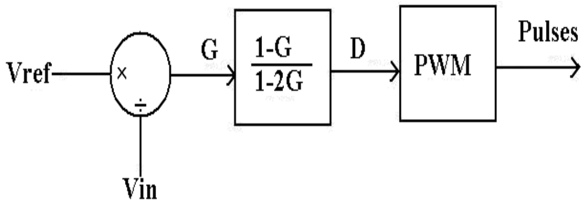

Fig. 10. Z-source converter control blocks

Fig. 11 shows load voltage when load is fed from normal path and Fig. 12 shows load voltage when load is fed from converter path. Fig. 13 shows load current when load is fed from normal path and Fig. 14 shows load current when load is fed from converter path.

These figures show Z-source ac-ac converter has mitigated voltage sags in load bus. As we can see from Fig. 12 and Fig.14, this compensation has not distorted voltage and current waveform, so this compensation has not bad effect on power quality.

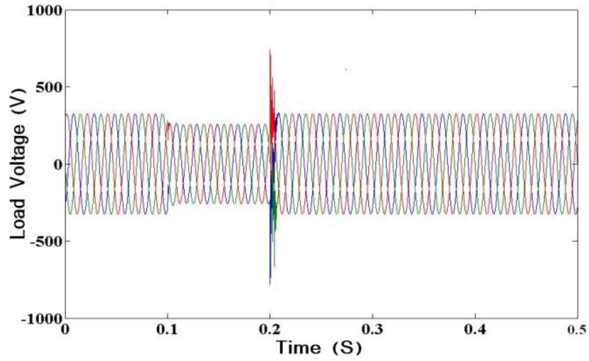

Fig. 11. Load voltage sags

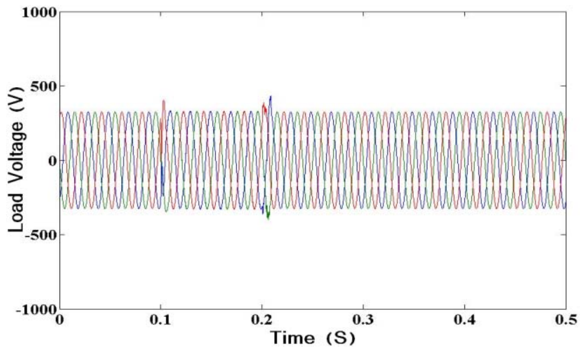

Fig. 12. Compensated load voltage

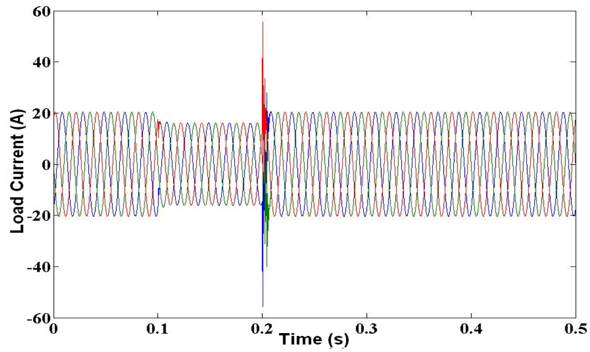

Fig. 13. Load current under voltage sag condition

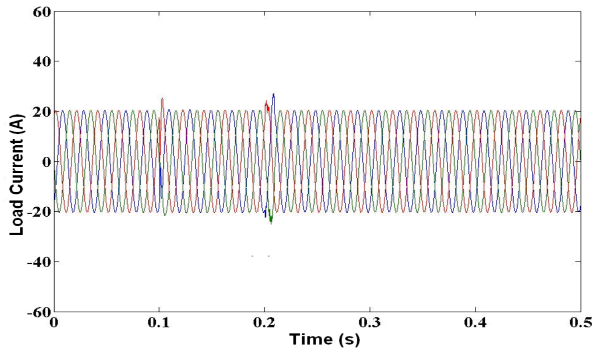

Fig. 14. Compensated load current

Load 2 and load 3 desertion causes voltage swell on load 1 from 0.1s to 0.2s. So, power transmission path replaces from normal path to converter path. Fig. 15 shows load voltage when load is fed from normal path and Fig. 16 shows load voltage when load is fed from converter path. Fig. 17 shows load current when load is fed from normal path and Fig. 18, shows load current when load is fed from converter.

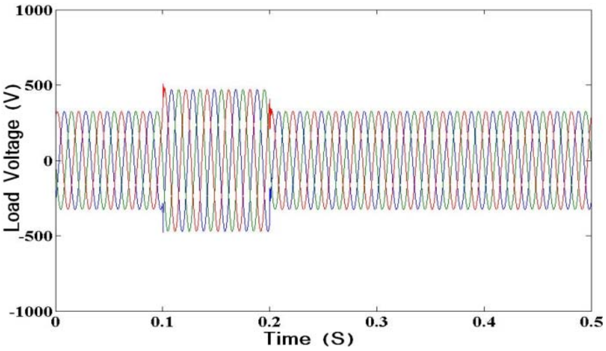

Fig. 15. Load voltage swells

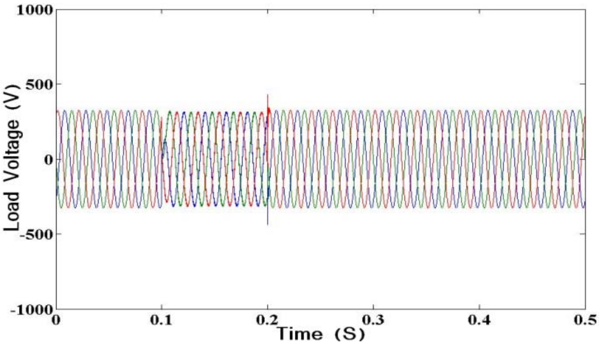

Fig. 16. Compensated load voltage

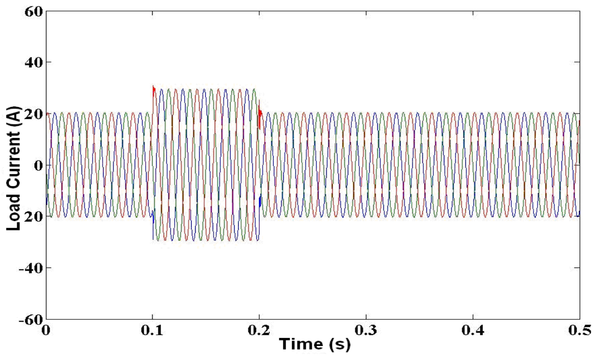

Fig. 17. Load current under voltage swells condition

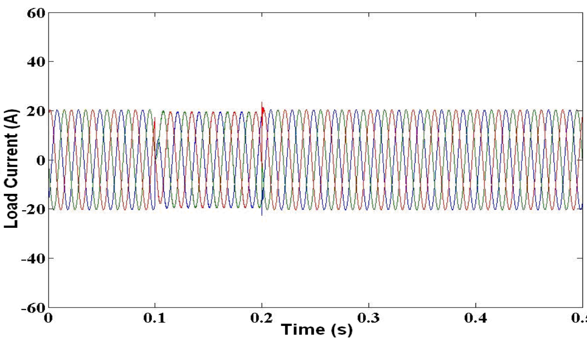

Fig. 18. Compensated load current

These figures show Z-source ac-ac converter has mitigated voltage swells in load bus. Same as for voltage sags, Fig. 16 and Fig. 18 show voltage swell compensation has not distorted voltage and current waveform, so this compensation has not bad effect on power quality too.

5. Conclusion

In this paper Z-source ac-ac converter has been analyzed for compensation of voltage sags and swells in a typical distribution network. This scheme has used three single-phase ac-ac converters. In this converter, duty cycle of each switch is produced from comparing load bus voltage with reference voltage. This converter has some especial advantages such as, simple control and sinusoidal output voltage which results in very low THD. Also it doesn't require energy storage system. Simulation results confirm good performance of PWM Z-source ac-ac converter in voltage sags and swells compensation.

6. References

[1] S.Choi, J. D. Li, and D. Mahinda Vilathgamuwa, "A Generalized Voltage Compensation Strategy for Mitigating the Impacts of Voltage Sags/Swells*", IEEE Transactions on power delivery*, vol. 20, no. 3, July 2005.

[2] D. Sabin, "An Assessment of Distribution System Power Quality", *vol 2: Statistical Summary Report, Palo Alto, CA. EPRl Final Report* TR-106294-V2, May 1996.

[3] E. Randolph Collins Jr and Arshad Mansoor, "Effects of Voltage Sags on AC Motor Drives", *IEEE Annual Textile Fiber and Film Industry Technical Conference,* 6-8 May 1997.

[4] E. C. Aeloiza, P. N. Enjeti, L. A. Morin and I. Pitel, "Next Generation Distribution Transformer: To Address power Quality for Critical Loads", *Power Electronics Specialists Conference PESC 2003*, Vol. 3pp. 1266-1271, June 2003.

[5] E. C. Aeloiza, P. N. Enjeti, 0.C. Montero and L. A. Morin, "Analysis and Design of a New Voltage Sag Compensator for Critical Loads in Electrical Power Distribution Systems", *Industrial Application Conference LAS*, Vol.2, 13-18de, pp. 911-916, Oct.2002.

[6] M. H. J. Bollen, Understanding Power Quality Problems: Voltage Sags and Interruptions, New York: IEEE Press, 2000.

[7] Jingbo Liu, Jiangang Hu, and Longya Xu, "Dynamic Modeling and Analysis of Z Source Converter—Derivation of AC Small Signal Model and Design-Oriented Analysis", *IEEE Transactions on Power Electronics*, vol.22, no.5, September 2007.

[8] Miaosen Shen and Fang Zheng Peng, "Operation Modes and Characteristics of the Z-Source Inverter with Small Inductance or Low Power Factor", *IEEE Transactions on Industrial Electronics*, vol.55, no.1, January 2008.

[9] Poh Chiang Loh, Chandana Jayampathi Gajanayake,D. Mahinda Vilathgamuwa, and Frede Blaabjerg, " Evaluation of Resonant Damping Techniques for Z-Source Current-Type Inverter", *IEEE Transactions On Power Electronics*,vol.23, no.4, July 2008.

[10] Xu Peng Fang, Zhao Ming Qian, , and Fang Zheng Peng, "Single-Phase Z-Source PWM AC-AC Converters", *IEEE power electronics letters*, vol. 3, no. 4, December 2005.