Next Generation Distribution Transformer: To Address Power Quality for Critical Loads

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Abstract— **In this paper a new single phase distribution transformer concept is proposed to improve power quality for critical loads. The secondary of the proposed transformer is composed of two windings, one of them equipped with a power electronic ac-ac converter. With the choice of proper turns ratio and the design of the PWM ac-ac converter, the proposed transformer has the following capabilities: (a) can compensate for 50% voltage sag and swells (b) can continuously shape the output voltage to be sinusoidal (low THD) even when the input voltage is distorted (c) can disconnect the load rapidly under fault conditions. The proposed approach does not employ any energy storage devices, such as large capacitors or inductors. The PWM ac-ac converter consists of four switching devices (IGBT) and is controlled with a four-step switching technique to achieve snubber-less operation. A design example is presented for a 480V/120V, 5 kVA transformer. Simulation results are discussed and experimental results on a 2kVA unit are presented.**

I. INTRODUCTION

Today's society has crossed over into a new era of economics and social experience driven by digitally based technologies. As a result, our society has become more highly interconnected than any in history, utterly dependent on the smooth functioning of complex, interactive networks – including electric power systems, the Internet, telecommunications, and transportation. Such dependence raises a host of unprecedented security, reliability, compatibility and safety issues. Most of all, the new digital society requires a reliable supply of high-quality electricity. A "24-7" economy can only be sustained by providing electric power that is affordable, hardened against disaster, and – at the microprocessor level – free from even momentary disturbances. Meeting these requirements will involve applying a combination of advanced electrical technologies.

A transformer performs many functions such as voltage transformation, isolation, noise decoupling, and is an indispensable component in electric power distribution systems. However, a conventional 60Hz transformer employed in the present day power distribution systems cannot protect digital loads against poor power quality: such as sags/swells/distortion. It is estimated that voltage disturbances cost millions of dollars every year in the United States [13, 14]. Recent surveys have been made throughout North America. These surveys attribute that the ninety-two-percent of the all disturbances in the electrical power distribution systems are due to voltage sags [1]. On the other hand, several voltage compensating techniques have been published in the literature [2-4, 6-8, 15-18]. The approaches are based on conventional rectifier/inverter technology, some are based on energy storage devices, which make them more expensive [7, 8].

In this paper a new single phase distribution transformer concept is proposed to improve power quality for critical loads. The secondary of the proposed transformer is composed of two windings (Fig. 1), one of them equipped with a power electronic ac-ac converter. With the choice of proper turns ratio and the design of the PWM ac-ac converter, the proposed transformer has the following features:

- Can compensate for 50% voltage sags and swells. In other words, the load voltage is regulated and the transformer is capable of providing the ride-through during a momentary disturbance (50% sag/swell).
- Can continuously shape the output voltage to be sinusoidal in shape (with low THD), even when the utility input voltage is distorted due to the presence of nonlinear loads. This feature is particularly attractive when critical electronic loads are sensitive to voltage distortion.
- Can disconnect the load rapidly under fault conditions.
- No bulky or expensive energy storage devices, such as large capacitors or inductors, are required for the proposed approach. The PWM ac-ac converter employs four switching (IGBT) devices and is controlled with a four-step switching technique to achieve snubber-less operation.

Fig. 1 shows the conceptual design for the proposed approach. During normal conditions, the PWM AC-AC converter is operated at low duty cycle in order to maintain the load voltage to 100% of the rated voltage. However, when the utility grid experiences voltage sag, the PWM AC-AC converter increases its duty cycle to maintain rated voltage across the load. On the other hand, during a voltage swell, the PWM AC-AC converter decreases its duty cycle in order to maintain the load voltage at rated value. When the input voltage is distorted (non sinusoidal), the PWM ac-ac converter adds the opposite nonlinear voltage, such that the load voltage is sinusoidal in shape. The paper presents a design example for a 480V/120V, 5 kVA transformer.

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Simulation results are discussed and experimental results on a 2kVA unit are presented.

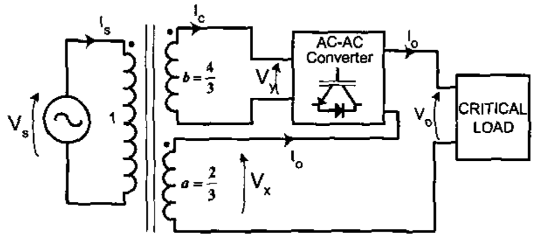

Fig.1. Conceptual design of the approach (NGT).

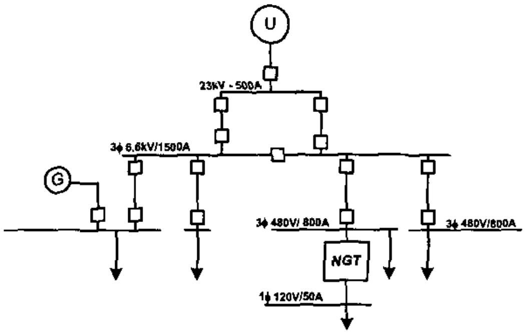

Fig.2 Example of NGT installed in a distribution system.

II. ROPOSED APPROACH

Fig. 1 shows the proposed approach. The transformer is composed of one primary side and two secondary windings. The turns ratio of the main secondary (winding A) is, a=2/3 and the turn ratio of the extra secondary (winding B) is, b=4/3. During normal condition the voltage V_x is equal to 2/3 p.u. and the voltage V_y is equal to 4/3 p.u. Therefore, to keep the rated voltage across the load, the PWM converter sets the duty cycle at 0.25. Thereby, the voltage V_c will be equal to 1/3 p.u. and the load voltage (V_o) will be equal to 1 p.u. When the utility grid (V_s) experiences a 50% momentary voltage reduction (voltage sag), the voltage V_x is equal to 1/3 p.u. and the voltage V_y is equal to 2/3 p.u. Then, the PWM AC-AC converter adjusts its duty cycle from 0.25 to 1, so that the voltage V_c will be 2/3 p.u. and the load voltage (V_o) will be 1 p.u. Similarly, when the utility grid (V_s) experiences a 50% voltage swell the voltage V_x is equal to 1 p.u. and the voltage V_y is equal to 2 p.u. Then, the PWM AC-AC converter sets its duty cycle at 0, so that the voltage V_c will be 0 p.u. and load voltage will be 1 p.u.

The above described operating strategy allows the voltage in the load to be kept constant during all time, under drastic conditions, such as, a 50% voltage sag and a 50% voltage swell of the utility grid.

III ANALYSIS

From Fig. 1 it is possible to establish the following expression for the load voltage.

$$V_o = V_x + V_c \qquad (1)$$

Where:

V_x is the main secondary winding voltage:

$$V_x = a\, V_s \qquad (2)$$

V_c is the compensation voltage provided by the PWM AC-AC converter.

$$V_c = D\, V_y = D\, b\, V_s \qquad (3)$$

Therefore, rewriting (1) yield;

$$V_o = a\, V_s + b\, D\, V_s \qquad (4)$$

Where, a is the turn ratio for the main secondary winding, b is the turn ratio for the additional secondary winding and D is the duty cycle of the PWM AC-AC converter.

For control purposes, the desired load voltage is represented by a constant signal as V_{ref}. The value of V_o is same as V_{ref} during normal conditions. However, during voltage sag, V_s changes to the following value:

$$V_s = (1-n)\, V_{ref} \qquad (5)$$

Where n corresponds to the voltage sag magnitude, in per unit.

Consequently, the voltage V_c, which is a function of the voltage V_y, of the additional secondary winding's turn ratio b and of the PWM AC-AC converter duty cycle D, can be written as:

$$V_c = bDV_s = bD(1-n)V_{ref} \qquad (6)$$

Then, rewriting (4) like a function of n, we have,

$$V_o = a\,(1\text{-}n)\, V_{ref} + b\, D\, (1\text{-}n)\, V_{ref} \qquad (7)$$

Now, in order to keep the voltage V_o constant. V_o must be equal to V_{ref}. Therefore,

$$V_{ref} = a\,(1\text{-}n)\, V_{ref} + b\, D\, (1\text{-}n)\, V_{ref} \qquad (8)$$

$$1 = a\,(1\text{-}n) + b\, D\, (1\text{-}n) \qquad (9)$$

From (9) it is possible to compute the value of D required to keep $V_o = V_{ref}$, like a function of D, a and b. However, in order to optimize the use of the converter, it is possible compute the suitable turn ratios a and b considering two border conditions:

First, when the utility grid experiences a 50% of voltage sag, the converter must works with duty cycle equal to 1, that is;

$$n=0.5 \text{ and } D=1.$$

Therefore, from equation (9) $a + b = 2$

Second, when the utility grid experiences a 50% voltage swell, the converter must works with duty cycle equal to 0, this is;

$$n=-0.5 \text{ and } D=0.$$

Therefore, from equation (9); $a = \frac{2}{3}$ and $b = \frac{4}{3}$

This means the transformer will be able to compensate up to 50% of voltage sag and 50% of voltage swell in the utility grid, as well.

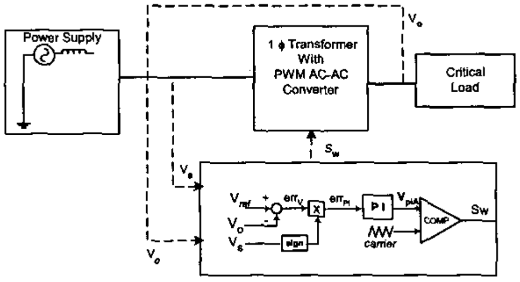

Fig. 3. Control Block Diagram.

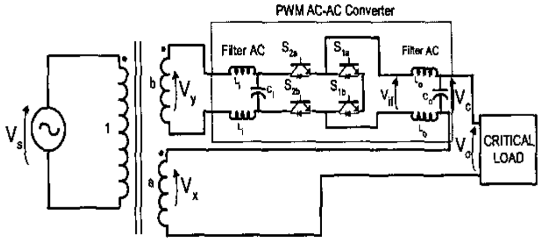

Fig. 4. PWM ac-ac Converter to compensaet voltage sag.

IV PWM AC-AC CONVERTER

The topology of the PWM AC-AC converter is shown in Fig. 4. The output voltage V_c of the PWM converter is given by equation (3). Fig. 4 shows the AC-AC converter, which is composed by four IGBTs (S_{1a}, S_{1b}, S_{2a} and S_{2b}). The proper operation of the converter allows the output voltage V_c to be set at voltage required to compensate the present voltage disturbance. This, is achieved by operating the switches S_{1a} and S_{1b} and S_{2a} and S_{2b} in complementary on/off mode. This operation is reached either during normal condition or during a voltage disturbance.

The duty cycle D sets the time that the switches $S1_{a,b}$ and $S2_{a,b}$ are closed or open. When it is necessary to increase the duty cycle the switches $S2_a$ and $S2_b$ are closed for more time than the switches $S1_a$ and $S1_b$. On the other hand, when it is necessary to decrease the duty cycle, the switches $S2_a$ and $S2_b$ are closed for less time than the switches $S1_a$ and $S1_b$. Thereby, this converter always works like AC buck converter.

The proper control strategy (Fig. 3) allows the converter to shape the output voltage V_c (Fig. 6) in order to make V_o (Fig. 7) sinusoidal. The voltage V_c is added to the voltage of the main secondary winding V_x (Fig. 5).

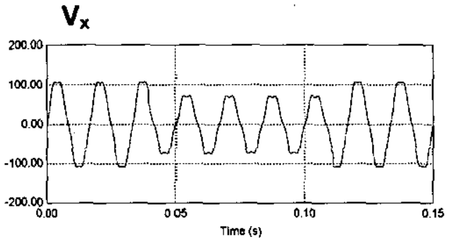

Fig. 5. Main secondary winding voltage V_x, when the utility experience harmonic distortion and a voltage sag.

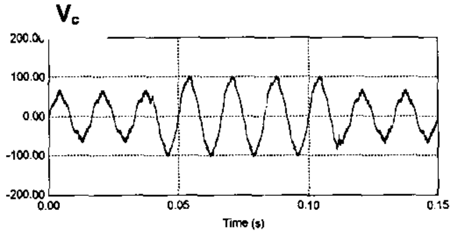

Fig. 6. Converter's output voltage V_c, when the utility experience harmonic distortion and a voltage sag.

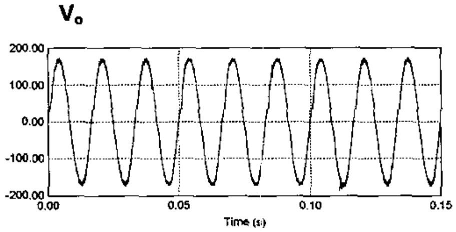

Fig. 7. Output voltage V_o, when the utility experience harmonic distortion and a voltage sag.

Furthermore, the $IGBT_s$ are driven by using a suitable gate signal pattern which incorporates a for four-step switching strategy. This technique allows for the reduction of switching losses and the elimination of snubber circuits [9]. The topology shown in Fig. 4 allows for the use of conventional IGBT modules widely available for inverter applications.

V TRANSFORMER POWER RATING

During normal conditions the additional secondary winding B will drive some amount of power, which will be proportional to the duty cycle and the voltage across winding B. The total input power S_T is equal to the sum of the two secondary windings power.

That is,

$$S_T = S_A + S_B \tag{10}$$

where;

S_T : Total Input Power.

S_A : Output power in winding A.

S_B : Output power in winding B.

$$V_s I_s = V_x I_o + V_y I_c \tag{11}$$

Since,

$$V_x = \frac{2}{3} V_s \ , \ V_y = \frac{4}{3} V_s \text{ and } I_c = D I_o$$

and during normal condition D=0.25, the equation (11) can be re-written as;

$$V_s I_s = \frac{2}{3} V_s I_o + \frac{4}{3} V_s (0.25\ I_o) \tag{12}$$

$$V_s I_s = \frac{2}{3} V_s I_o + \frac{1}{3} V_s I_o \tag{13}$$

$$Is = Io \tag{14}$$

Then, from equation (10), (13) and (14);

$$S_T = V_s I_s = \frac{2}{3} V_s I_s + \frac{1}{3} V_s I_s \qquad (15)$$

therefore,

$$S_A = \frac{2}{3} S_T \quad \text{and} \quad S_B = \frac{1}{3} S_T$$

Despite the fact that during a voltage sag the winding B will drive more than 33.3% of S_T, this condition will last only for a short duration (during the disturbance). Considering that a transformer can handle more than 5 times its nominal current during one minute, it is not necessary to increase the transformer's size any further than its rated value [19].

VI DESIGN EXAMPLE AND SIMULATION RESULTS

For simulation purposes a system with the following specifications is considered; 5 kVA, 120V 1ϕ, 60Hz, PWM switching frequency, f_s =10 kHz. The filter values are given by L_i=50μH, C_i=15uF, L_o=50μH and C_o=30μF. The turn ratios of the transformer are ***a***= 0.66 and ***b***=1.33. The system shown in Fig. 3 is chosen to test a single-phase system under various drastic voltage disturbances.

A. Single-phase voltage sag (feeding linear load).

Fig. 8 (below) shows the utility voltage undergoing a 35% voltage sags and notching. Its corresponding output voltage is shown in Fig. 8 (above), where it is possible to see that the compensation is keeping the load voltages constant.

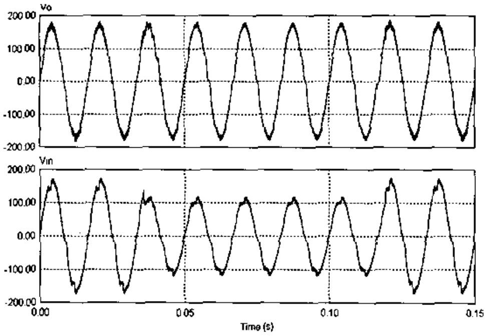

Fig. 8. Output and Input Volatge during a 35 % voltage.(Notching in utility grid).

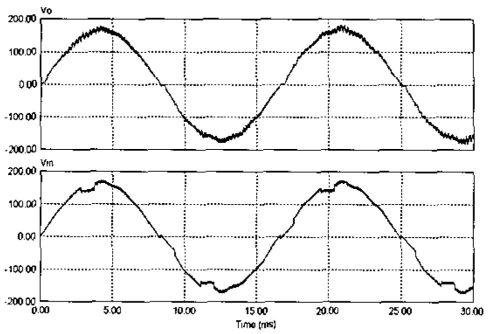

Fig. 9. Detail of Output and Input voltage during normal condition (Notching in utility grid).

A detail of the output and input voltage during normal condition is shown in Fig. 9. The output voltage's THD_v is kept less than 4%.

B. 30% voltage sag with utility experiencing voltage distortion and notching (feeding linear load).

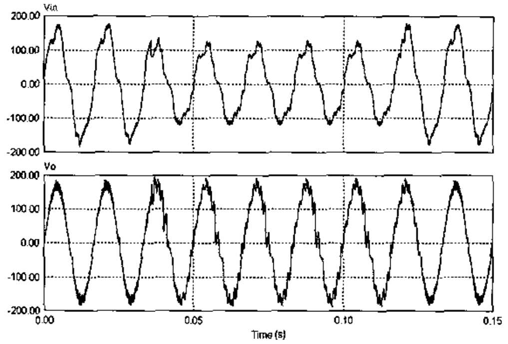

Fig. 10. Input and Output voltage during 30% voltage sag. (Harmonic Distortion and Notching in utility grid).

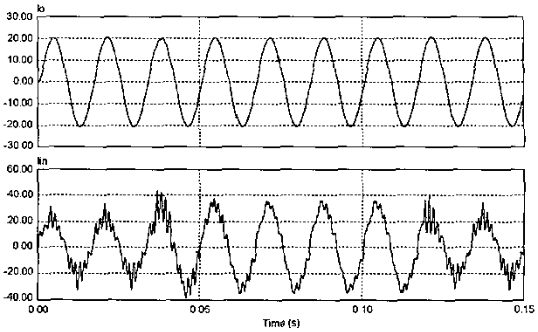

Fig. 11. Output and Input current during 30% voltage sag (Notching in utility grid).

The input and output voltages are shown in Fig. 10, meanwhile the utility voltage experiences a 30% voltage sag, some harmonic distortion and notching. The harmonic distortion is satisfactorily compensated during normal condition. However, during the voltage sag, the voltage is compensated showing some harmonic distortion.

C. 30% voltage sag with utility experiencing voltage distortion and notching. (feeding a Non-linear load)

The approach was also tested feeding a non linear load while the utility grid experienced a 30% voltage sag. The THD_v was kept less than 4% during normal condition and it increased during the voltage sag. However, the rms value of the voltage fundamental component was kept constant. Fig. 12 shows the output and input voltage for this case and Fig. 13 shows the voltage waveforms in detail during normal condition.

VII EXPERIMENTAL RESULTS

In order to validate the proposed approach, experimental results were obtained on a 120V/2KVA single-phase prototype (Table I). The obtained results were the input voltage, output voltage and input current.

The laboratory proto-type was tested in the TAMU power electronics & power quality laboratory on programmable ac power source. The PWM AC-AC converter was controlled via a four-step switching technique [9].

TABLE I: EXPERIMENTAL RESULTS PARAMETERS

Voltage	120V
Load Power	2 kVA
f_s	10kHz
L_i	50μH
C_i	12μF
L_o	55μH
C_o	50μF
a	2/3
b	4/3

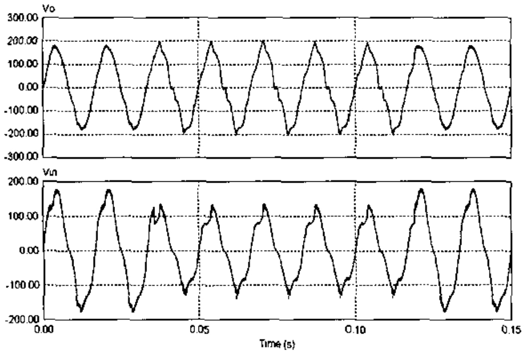

Fig. 12. Output and Input voltage during a 30% voltage sag (feeding a non-linear load).

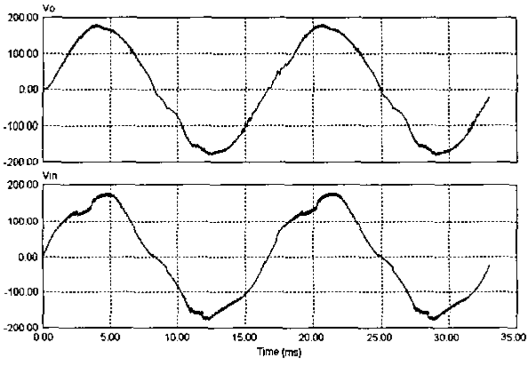

Fig.13. Output and Input Voltage Detail, during normal condition. (feeding a non-linear load)

Fig. 14 shows the performance of the approach on a linear load, for 25% voltage sag and 25% voltage swell.

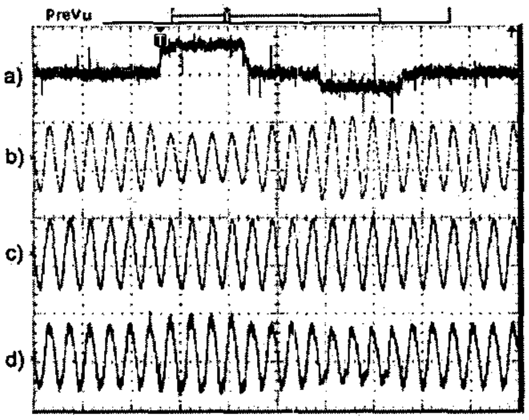

Fig. 14. Performance during a 25% voltage sag and 25% voltage swell, when the utility voltage is sinusoidal. a) Control Signal VpiA. b) Transformer's Input voltage. c) Transformer's Output voltage. d) Transformer's input current. (250V/div, 20A/div, 40ms/div).

Fig. 15 shows a detail of Fig. 14, when the utility experiences the voltage sag. Fig. 16 shows the performance when the utility experience a 10% THDv because of 3rd and 5th harmonic contamination. Fig. 17 shows the performance on a non-linear load, during a 20% voltage sag. The results are summarized in table II

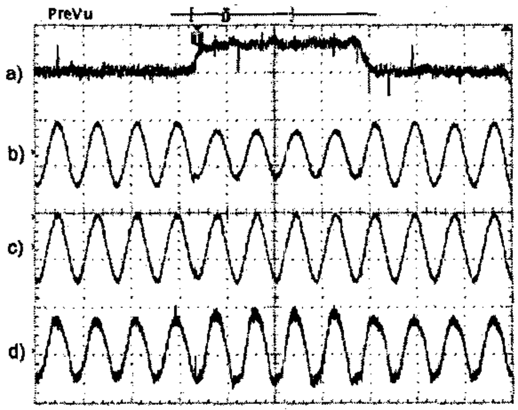

Fig. 15. Detail Fig. 14 during 25% voltage sag. a) Control Signal VpiA. b) Transformer's Input voltage during a 25% voltage sag. c) Transformer's Output voltage. d) Transformer's input current. (250V/div, 20A/div, 40ms/div)

TABLE II: EXPERIMENTAL RESULTS

	Output Voltage THDv	
	Load type	
Utility Voltage	***Linear***	***Non-Linear (28% THDi)***
Normal	1% THDv	3% THDv
10% THDv	3.5% THDv	-

Table II. Output voltage THDv during several conditions at nominal load

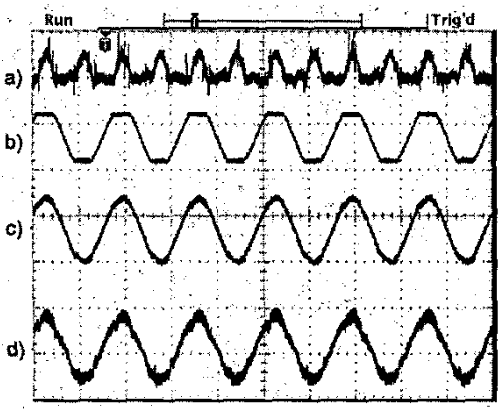

Fig. 16. Performance when the utility experiences a 10% voltage distortion. a) Control Signal VpiA. b) Transformer's Input voltage. c) Transformer's Output voltage. d) Transformer's input current. (250V/div, 20A/div, 40ms/div).

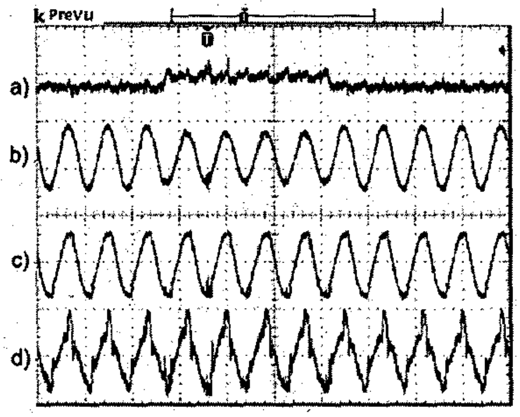

Fig. 17. Performance on non-linear load, during a 20% voltage sag. a) Control Signal VpiA. b) Transformer's Input voltage. c) Transformer's Output voltage. d) Transformer's input current. (250V/div, 20A/div, 40ms/div).

VIII CONCLUSIONS

In this paper a new single phase distribution transformer concept has been proposed to enhance power quality for critical loads. The scheme employs a single-phase transformer with two secondary windings and a PWM ac-ac converter using four IGBTs per phase. The PWM ac-ac converter has been shown to compensate up to 50% voltage sag / swells and voltage distortion. Simulation and experimental results confirm the high speed operation of the control strategy and a good performance.

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