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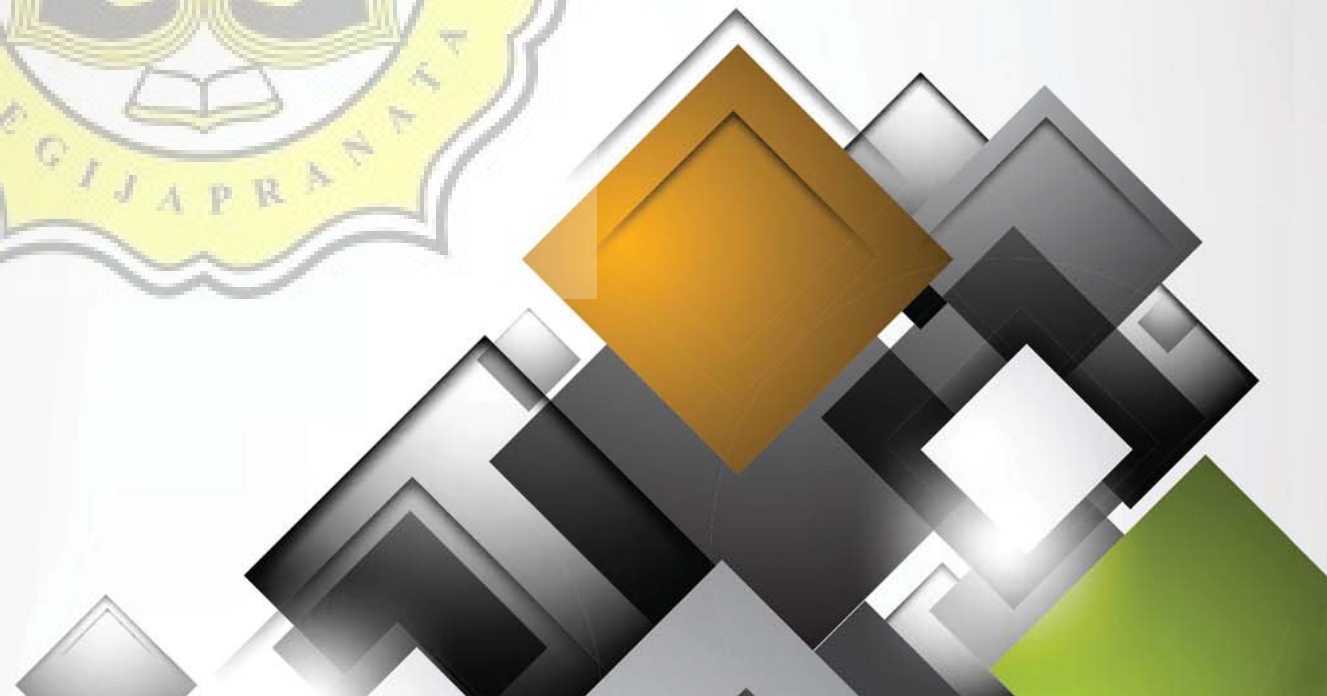

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# The 1st Conference on Information Technology, Computer, and Electrical Engineering (CITACEE 2013)



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## *International Session*

## *National Session*

# Operating a Four-Leg PWM Converter as a Three-Phase Controlled Current Source

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*Abstract*—**Static converters are often used in power electronic fields as power supplies, electric machine drives, active power filters etc. Due to the developments of Pulse Width Modulation (PWM) techniques, the performances of the converters can be improved. This paper describes the analysis of a three-phase four-leg PWM Converter as a controlled current source. By operating the switches, the output voltages can be controlled then the required current waveforms can be obtained. Implementation as a three-phase shunt active power filter is tested to validate the analysis.**

***Keywords : converter, controlled current source, PWM, active power filter***

## I. INTRODUCTION

Rapid progress of power electronics technology takes significant roles in electric energy conversion. Recently, static converters are widely used for their superiority. In the other hand, control strategy that based on pulse width modulation (PWM) has also supported the development of such converters. Some control strategies are also applied in many fields [1]-[2].

Static converters have been implemented in single-phase or three-phase systems. For three-phase system with neutral conductor, four-leg converter or three-leg converter with mid-point capacitor can be used [3]-[5]. In the applications as power supplies, a static converter must be capable to provide DC or AC output voltage/current. By using PWM concept, such converters will be able to draw source currents with minimum distortion. Other applications are in adjustable speed drives for electric machines, power conditioners, PV-Grid Connected System, etc.

A static converter can also be operated as a controlled currents source. It is widely used in a shunt active filtering or PV-Grid System. By using a current detection in standard Voltage Source Inverter (VSI), a controlled current source can be designed. This is often used for injecting undesired currents to the system with nonlinear loads to mitigate harmonic contents and solve the power quality problems [6]-[7].

In this paper, a four-leg converter is analyzed. Switching configurations will be controlled to predict the output voltages. To obtain an equivalent circuit, mathematic equations are derived. A PWM strategy is also be described as a basic concept in controlling a controlled current source. Finally, its application on shunt active filtering is chosen. To validate the analysis, simulations and laboratory works were done.

## II. FOUR-LEG PWM CONVERTER

In Figure-1, a converter consisting of eight static switches is shown. This converter has $2^4$ configurations of the switch positions and depicted in Figure-2. The instantaneous voltages of its output are presented in Table-1

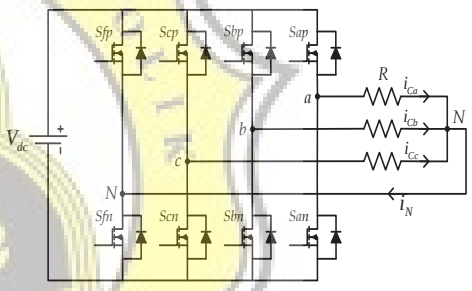


Figure-1 Three-phase four-leg converter

Due to the figure, it can be concluded that the switch position of the fourth leg will influence the phase output voltage polarity of the PWM converter. When $S_f = 0$ then the phase output voltage will be 0 or $V_{dc}$ depending on the value of $S_k$ (where $k$ = $abc$) with respect to $S_f$. When $S_f = 1$ then the phase output voltage will be 0 or $-V_{dc}$, so the equation of the phase output voltage can be expressed as

$$\begin{bmatrix} v_{aN} \\ v_{bN} \\ v_{cN} \end{bmatrix} = \begin{bmatrix} v_{CaN} \\ v_{CbN} \\ v_{CcN} \end{bmatrix} = \begin{bmatrix} S_a - S_f \\ S_b - S_f \\ S_c - S_f \end{bmatrix} . V_{dc} \qquad (1)$$

where

$S_k = 1$ then $S_{kp} \rightarrow ON \Leftrightarrow S_{kn} \rightarrow OFF$

$S_k = 0$ then $S_{kp} \rightarrow OFF \Leftrightarrow S_{kn} \rightarrow ON$

$S_f = 1$ then $S_{fp} \rightarrow ON \Leftrightarrow S_{fn} \rightarrow OFF$

$S_f = 0$ then $S_{fp} \rightarrow OFF \Leftrightarrow S_{fn} \rightarrow ON$

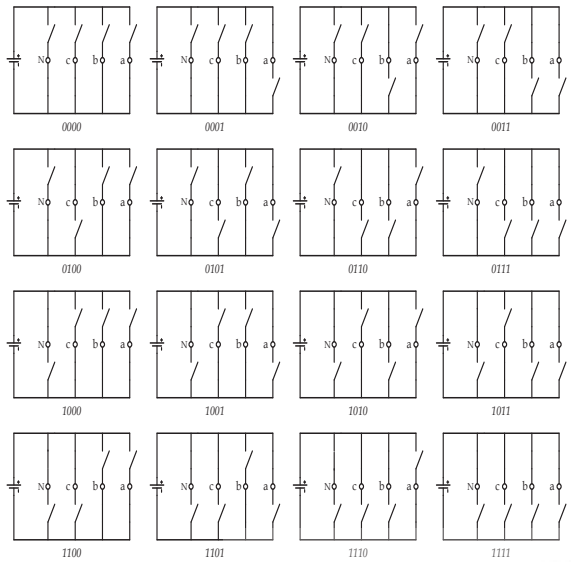


Figure-2. Switching Configurations on a three-phase four-leg PWM converter

By using equations (1), the line voltages can be stated as the following (Table-1)

$$\begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix} = \begin{bmatrix} v_{Cab} \\ v_{Cbc} \\ v_{Cca} \end{bmatrix} = \begin{bmatrix} S_a - S_b \\ S_b - S_c \\ S_c - S_a \end{bmatrix} V_{dc} \qquad (2)$$

Table-1. Output voltages on a three-phase four-leg PWM converter

| $S_f$ | $S_a$ | $S_b$ | $S_c$ | $V_{aN}$ | $V_{bN}$ | $V_{cN}$ |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 1 | 0 | 0 | $V_{dc}$ |
| 0 | 0 | 1 | 0 | 0 | $V_{dc}$ | 0 |
| 0 | 0 | 1 | 1 | 0 | $V_{dc}$ | $V_{dc}$ |
| 0 | 1 | 0 | 0 | $V_{dc}$ | 0 | 0 |
| 0 | 1 | 0 | 1 | $V_{dc}$ | 0 | $V_{dc}$ |
| 0 | 1 | 1 | 0 | $V_{dc}$ | $V_{dc}$ | 0 |
| 0 | 1 | 1 | 1 | $V_{dc}$ | $V_{dc}$ | $V_{dc}$ |
| 1 | 0 | 0 | 0 | $-V_{dc}$ | $-V_{dc}$ | $-V_{dc}$ |
| 1 | 0 | 0 | 1 | $-V_{dc}$ | $-V_{dc}$ | 0 |
| 1 | 0 | 1 | 0 | $-V_{dc}$ | 0 | $-V_{dc}$ |
| 1 | 0 | 1 | 1 | $-V_{dc}$ | 0 | 0 |
| 1 | 1 | 0 | 0 | 0 | $-V_{dc}$ | $-V_{dc}$ |
| 1 | 1 | 0 | 1 | 0 | $-V_{dc}$ | 0 |
| 1 | 1 | 1 | 0 | 0 | $V_{dc}$ | $-V_{dc}$ |
| 1 | 1 | 1 | 1 | 0 | 0 | 0 |

Figure-3 depicts a three-phase four-leg converter operated as a controlled current source and its equivalent circuit is shown in Figure-4. Some equations can be derived due to those

For loop_1:

$$\begin{aligned} &[v_{CaN} - v_{CbN}] - [v_{Sa} - v_{Sb}] \\ &= L\frac{di_1}{dt} - L\frac{d[i_2 - i_1]}{dt} \end{aligned} \qquad (3)$$

The relationship between the loop current and the inductor current is expressed as

$$i_{Ca} = i_1, i_{Cb} = i_2 - i_1, i_{Cc} = i_3 - i_2, i_{CN} = i_3$$

So the equation (3) is able to be simplified as

$$\begin{aligned} &[v_{CaN} - v_{CbN}] - [v_{Sa} - v_{Sb}] \\ &= L\frac{d[i_{Ca} - i_{Cb}]}{dt} \end{aligned} \qquad (4)$$

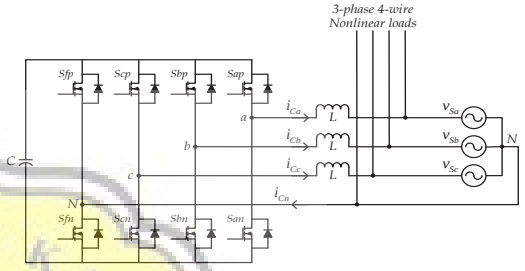


Figure-3. A three-phase four-leg PWM converter as a controlled current source

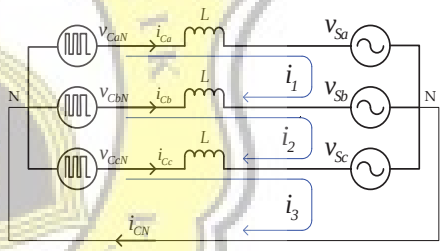


Figure-4. Equivalent circuit of a three-phase four-leg PWM converter as a controlled current source

For loop_2:

$$\begin{aligned} &[v_{CbN} - v_{CcN}] - [v_{Sb} - v_{Sc}] \\ &= L\frac{d[i_{Cb} - i_{Cc}]}{dt} \end{aligned} \qquad (5)$$

For loop_3:

$$\begin{aligned} &[v_{CcN} - v_{ScN}] \\ &= L\frac{di_{Cc}}{dt} \end{aligned} \qquad (6)$$

By substituting (6) into (5) then we get

$$\begin{aligned} &\left(v_{CbN}(t) - v_{SbN}(t)\right) - L\frac{di_{Cc}(t)}{dt} \\ &= L\frac{di_{Cb}(t)}{dt} - L\frac{di_{Cc}(t)}{dt} = L\frac{di_{Cb}(t)}{dt} \end{aligned} \qquad (7)$$

The same step can be done by substituting (7) into (4)

$$\left\{v_{CaN}(t)-v_{SaN}(t)\right\}-L\frac{di_{Cb}(t)}{dt} = L\frac{di_{Ca}(t)}{dt}-L\frac{di_{Cb}(t)}{dt}=L\frac{di_{Ca}(t)}{dt} \quad (8)$$

The relationship between the currents flowing in the neutral and the phase conductors can be written as

$$i_{CN}(t)=-\left(i_{Ca}(t)+i_{Cb}(t)+i_{Cc}(t)\right) \quad (9)$$

Equations (6)-(9) shows that a three-phase four-wire PWM converter as a controlled current source connected to the grid can be regarded as single phase circuit (Figure-5)

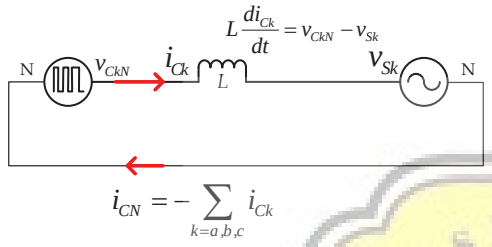


Figure-5. Simplification of equaivalent circuit for a three-phase four-leg PWM converter as a controlled current source

## III. PWM BASED CONTROL STRATEGY

Pulse Width Modulation is a strategy that is often applied in power electronics to obtain certain waveforms with higher power rating. A static converter with its nonlinear characteristics implements PWM technique to produce the required waveforms. By modulating the continuous signal in the control circuit, a digital signal will operates static switches to generate output voltages/currents. One of these is classic one, that is carrier based PWM. By comparing a modulating signal and a high frequency carrier waveform then a high frequency pulses are generated. Implementing these pulses to the switches of the converter causes ON/OFF state of the switches. Figure-6 shows a scheme of such a concept. Due to the figure, the spectrum consists of the waveforms whose frequencies are at modulating frequency followed by other frequencies at carrier multiple frequencies.

To make analysis, two legs of the four-leg converter are taken as a leg for neutral conductor and another for phase conductor (Figure-8). The deviation of the converter output currents are expressed as

$$\frac{di_{Ck}(t)}{dt}=\frac{V_{dc}-V_{Sk}}{L} \quad (10)$$

During the conduction states of the lower switches $S_{kn}$ and $S_{fn}$ ($t_{off}$) then the current $i_{Ck}(t)$ decreases, stated as

$$\frac{di_{Ck}(t)}{dt}=-\frac{V_{Sk}}{L} \quad (11)$$

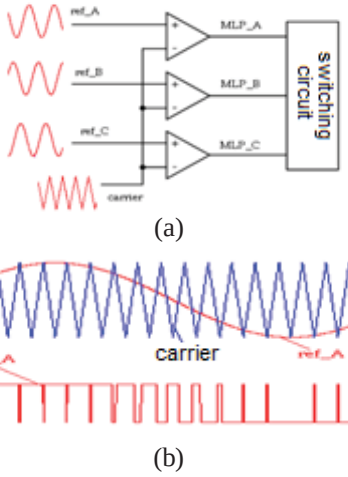


Figure-6. A carrier based PWM (a) scheme (b) PWM pulses

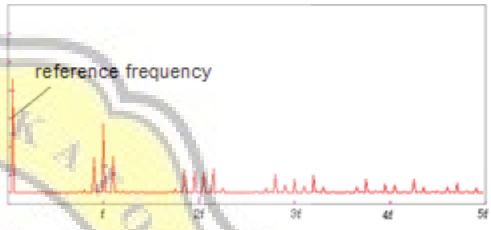


Figure-7. Spectrum of a carrier based PWM

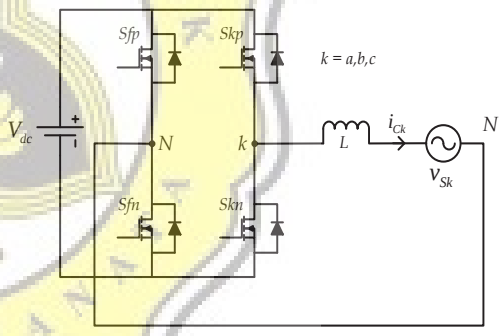


Figure-8. Two legs of the four-leg converter act as a single phase full bridge converter

Equations (10) and (11) are generally written based on switching function $[S_{sw}]$ as the following

$$\frac{di_{Ck}(t)}{dt}=\frac{[S_{sw}]V_{dc}-V_{Sk}}{L} \quad (12)$$

$$i_{Ck}(t)=\int\frac{[S_{sw}]V_{dc}-V_{Sk}}{L}dt+I_{Ck0} \quad (13)$$

The converter output currents will fluctuate $\Delta i$ around the reference value (Figure-9) so the relationship between the reference and the actual currents can be presented as

$$\frac{\Delta I_{Ck}}{2}=i^{*}_{Ck}(t)-i_{Ck}(t) \quad (14)$$

Substituting (14) into (12) will results in

$$v_{Ck}(t) = L\frac{i^*_{Ck}(t) - \frac{\Delta I_{Ck}}{2}}{dt} + v_{Sk}(t) \qquad (15)$$

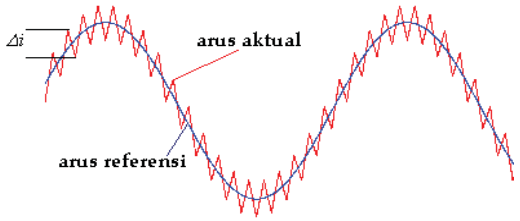


Figure-9. Fluctuation of the actual current around the reference value

Equation (15) shows that the output voltage of a PWM converter needed to force the actual current tracks the reference is the summation of the instantaneous value of source voltage and the inductor voltage. The output voltage $v_{Ck}$ (where $k$ = $abc$) is locally average of a PWM waveform. A current controller will force the value of $\Delta i$ tends to zero.

## IV. Application on Shunt Active Filtering

To solve the power quality problems caused by harmonics, a shunt active power filter can be applied. It commonly uses Voltage Source Inverter as its core and operated as a controlled current source. Harmonic and reactive power compensation are done by injecting undesired currents to the grid so the source currents will be nearly sinusoidal with unity power factor.

For a three-phase system with neutral wire, it is required a controlled current source which is capable to inject currents into neutral conductor. A four-leg converter can be chosen as an alternative way. Figure-10 depicts such a converter that is implemented as a shunt active power filter. It is installed to mitigate the harmonic contents generated by nonlinear loads. Its equivalent circuit is shown in Figure-11.

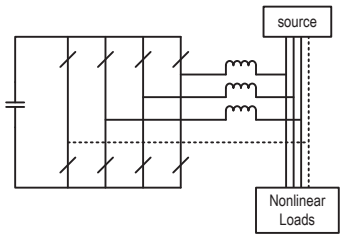


Figure-10. A four-leg PWM converter operated as a shunt active power filter

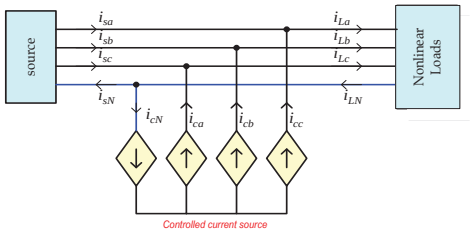


Figure-11. A controlled current source represents a shunt active power filter in three-phase four-wire system

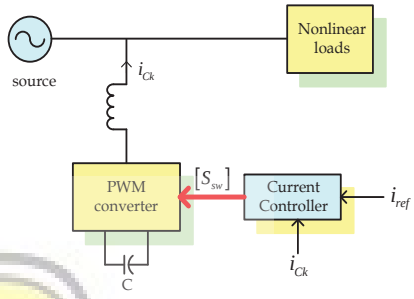


Figure-12. A current controller on PWM converter as a shunt active power filter

## V. Simulation and Laboratory Works

To validate the analysis, simulations of a four-leg PWM converter as a shunt active power filter are done based on Figure-10. Three-phase four-wire nonlinear loads are implemented by using three single-phase thyristor rectifiers with inductive loads. Distorted currents drawn by such a rectifier is depicted in Figure-13. The compensation done by injecting the compensating currents as shown in Figure-14 and finally the source currents will be nearly sinusoidal (Figure-15).

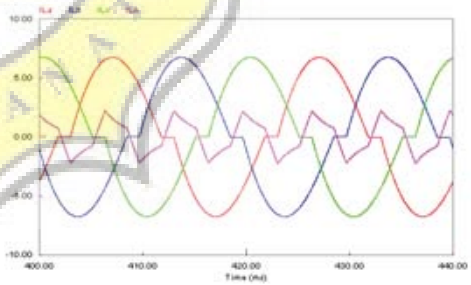

Figure-13. Simulation results of the load currents drawn by thyristor rectifiers

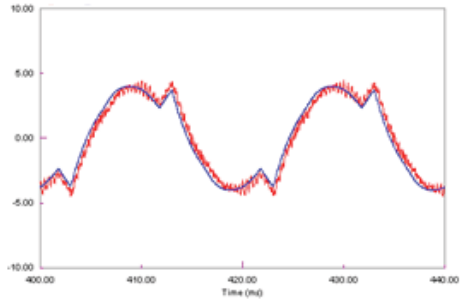

Figure-14. Simulation results of the current injected by the shunt active power filter

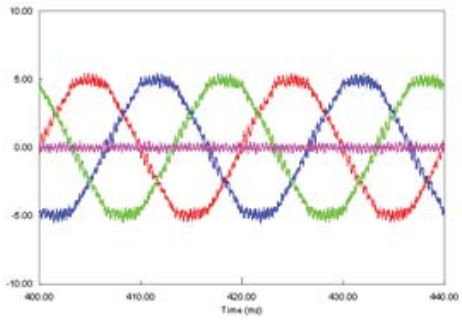

Figure-15. Simulation results of the source after the shunt active power filter installed

The laboratory works were also done to verify the analysis and simulation results. Figure-16 depicts the distorted load currents caused by nonlinear loads. Implemeting a shunt active power filter will inject the compensating current (Figure-17b) then the source currents will be nearly sinusoidal and the neutral current tends to zero (Figure-18).

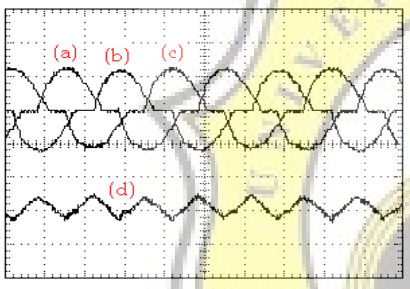


Figure-16. Experimental results of the load currents drawn by thyristor rectifiers (a)-(c) phase load currents (d) neutral load current

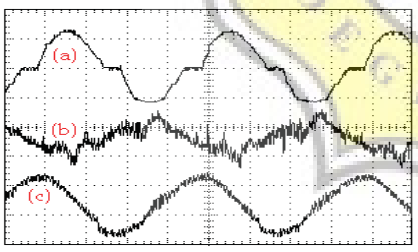


Figure-17. Experimental results of the load currents drawn by thyristor rectifiers (a) phase load current (b) phase injected current (c) phase source current

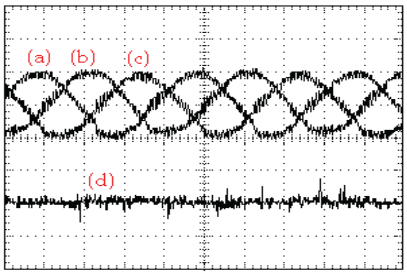


Figure-18. Experimental results of the source currents after the shunt active power filter installed (a)-(c) phase source currents (d) neutral source current

## VI. CONCLUSION

A four-leg PWM converter is capable to be operated as a controlled current source. By choosing certain switches to be ON or OFF, the output voltages of such a converter can be controlled. This converter is also able to act as a shunt active power filter. By using the proper control strategy, compensation can be done so the distorted currents can be reduced.

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Semarang, November 16th, 2013

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