A Digitally Controlled Switch Mode Power Supply Based on Matrix Converter

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***Abstract*—High power telecommunication power supply systems consist of a three-phase switch mode rectifier followed by a dc/dc converter to supply loads at −48 V dc. These rectifiers draw significant harmonic currents from the utility, resulting in poor input power factor with high total harmonic distortion (THD). In this paper, a digitally controlled three-phase switch mode power supply based on a matrix converter is proposed for telecommunication applications. In the proposed approach, the matrix converter directly converts the low frequency (50/60 Hz, three-phase) input to a high frequency (10/20 kHz, one-phase) ac output without a dc-link. The output of the matrix converter is then processed via a high frequency isolation transformer to produce −48 V dc. Digital control of the system ensures that the output voltage is regulated and the input currents are of high quality under varying load conditions. Due to the absence of dc-link electrolytic capacitors, power density of the proposed rectifier is expected to be higher. Analysis, design example and experimental results are presented from a three-phase 208-V, 1.5-kW laboratory prototype converter.**

***Index Terms*—Three-phase switch mode rectifier, total harmonic distortion (THD).**

I. Introduction

Modern telecommunication power systems require several rectifiers in parallel to obtain higher current dc output at −48 V dc [1]–[4]. Commercially available telecom-rectifiers [1] employ ac to dc conversion stage with a boost converter, followed by a high frequency dc/dc converter to produce −48 V dc (see Fig. 1). This type of rectifier draws significant fifth and seventh harmonic currents resulting in near 40% total harmonic distortion (THD). In addition, the rectifier dc-link capacitor stage is bulky, contributes to weight and volume. Furthermore, the presence of multiple power conversion stages contributes to lower efficiency.

In response to these concerns, this paper proposes a digitally controlled switch mode power supply based on a matrix converter for telecommunication applications (Fig. 2). Matrix converter topology employs six bidirectional switches to convert lower frequency (50/60 Hz) three-phase input directly to a high frequency (10/20 kHz) one-phase output. The output is then processed via an isolation transformer and rectified to −48 V dc. Digital control of the matrix converter stage ensures that the output voltage is regulated against load changes as well as input supply variations while maintaining sinusoidal input current shape at near unity power factor.

Advantages of the proposed topology are:

- no dc-link capacitor required;
- capable of operation over a wide input voltage range;
- low total harmonic distortion (THD) in line current;
- proper switching modulation results in smaller input filter;
- unity input power factor over a wide load range;
- higher efficiency with increased power density;
- digital control facilitates external communication; enable parallel operation of several stages and implementation of complex closed loop control functions.

The paper present a detailed analysis of the modulation scheme, discusses a design example and experimental results on a three-phase 208-V, 1.5-kW laboratory prototype converter.

II. Proposed Switch Mode Power Supply

The proposed digitally controlled switch mode power supply based on matrix converter is shown in Fig. 2. Matrix converter topology employs six bidirectional switches to convert lower frequency (50/60 Hz) three-phase input directly to a high frequency (10/20 kHz) one-phase output. The output is then processed via an isolation transformer and rectified to −48 V dc. Digital control of the matrix converter stage ensures that the output voltage is regulated against load changes as well as input supply variations.

Matrix converter is a direct ac/ac converter and operates without a dc-link [5]. It has the advantage of bidirectional power flow, controllable input power factor, high reliability, and compact design. High operating frequency of the system allows the size and weight of the transformer to be reduced. In this paper, space vector modulation technique applied to a matrix converter is employed. For hardware implementation, a three-phase to three-phase matrix converter module based on 1200-V IGBT introduced by EUPEC [6] is used.

III. Matrix Converter PWM Modulation

In the proposed topology a three-phase to one-phase matrix converter (Fig. 3) employing twelve IGBT switches is employed.

The PWM modulation is divided to two modes, rectifier mode and inverter mode, respectively. Fig. 4 illustrates the modulation modes of matrix converter as traditional ac/dc/ac conversion system. Due to the absence of dc-link, V_{pn} is presented as a fictitious dc voltage for analysis purposes.

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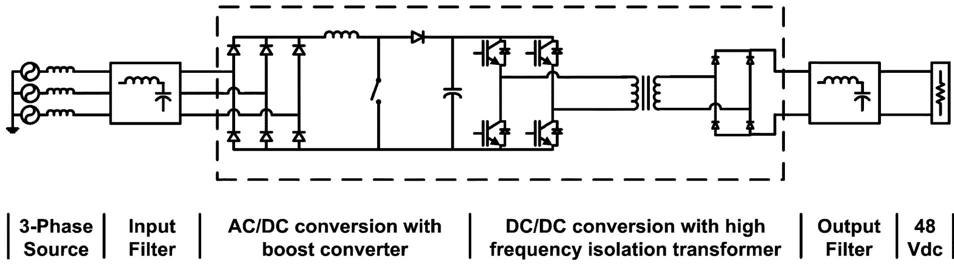

Fig. 1. Conventional telecommunication switch mode power supply [1].

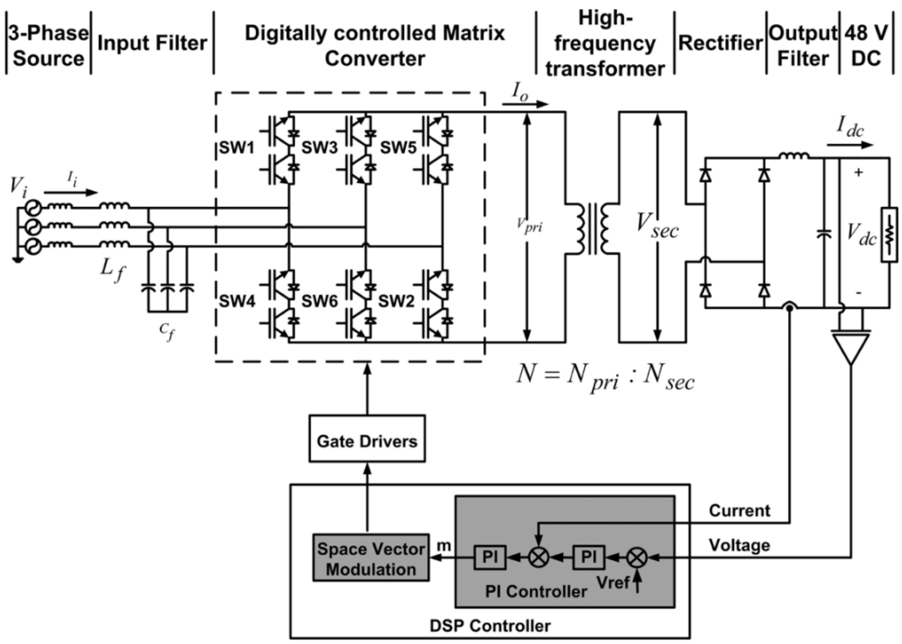

Fig. 2. Proposed digitally controlled switch mode power supply based on matrix converter.

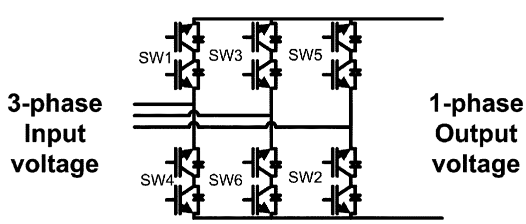

Fig. 3. Figure of three-phase to one-phase matrix converter.

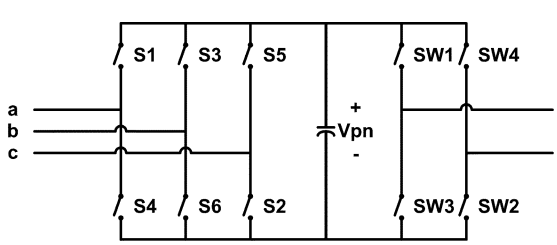

Fig. 4. Illustration of matrix converter operation.

The operation of the matrix converter can be expressed mathematically in a matrix formation. The fictitious dc voltage, V_{pn}, is derived from the rectifier mode of operation

$$V_{pn} = F_r * V_i \tag{1}$$

where F_r is rectifier mode transfer function and V_i is the input voltage vector. Matrix converter output voltage, V_o, is derived from the inverter mode of operation as

$$V_o = F_i * V_{pn} \tag{2}$$

where F_i is the inverter mode transfer function. The line current I_i can be expressed in terms of rectifier and inverter mode transfer functions as

$$I_i = F_r^T * F_i^T * I_o. \tag{3}$$

The three-phase input voltage vector V_i is given by

$$V_i = \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} V_m \sin(\omega_i t) \\ V_m \sin(\omega_i t - 120^\circ) \\ V_m \sin(\omega_i t + 120^\circ) \end{bmatrix} \tag{4}$$

where V_m is amplitude of input voltage and ω_i is input angular frequency.

A. *Rectifier Mode of Operation*

As detailed in the earlier section, matrix converter analysis is simplified by separating the rectifier and inverter mode of operations. The objective of the rectifier mode of operation is to

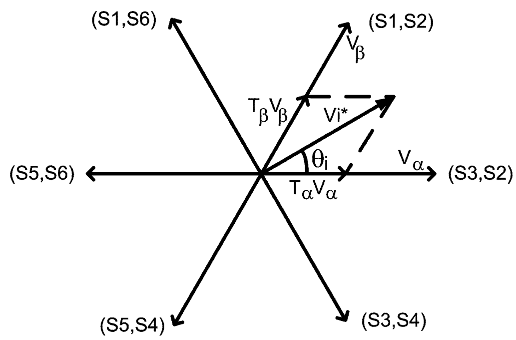

Fig. 5. Rectifier space vector hexagon.

create a fictitious dc voltage V_{pn} from input voltage and to maintain unity input power factor. Rectifier space vector hexagon is shown in Fig. 5.

The switching vectors in the hexagon in Fig. 5 are indicated by the switches from rectifier part in Fig. 4. The placement of space vector reference vector, V_i^*, within one sector is defined by adjacent the switching vectors, V_α and V_β. The angle θ_i is angle of space vector reference vector. The duty cycles of the active switching vectors are calculated with rectifier mode modulation index, m_c

$$T_\alpha = m_c \sin\left(\frac{\pi}{3} - \theta_i\right) \tag{5}$$

$$T_\beta = m_c \sin(\theta_i) \tag{6}$$

$$T_o = 1 - T_\alpha - T_\beta. \tag{7}$$

Rectifier mode matrix, F_r, can be set up from switching functions S1 to S6 established by space vector method. Number of elements in F_r depends on the number of input phases

$$F_r = [F_{r1} \quad F_{r2} \quad F_{r3}] \tag{8}$$

$$F_{r1} = \mathrm{S}_1 - \mathrm{S}_4 \tag{9}$$

$$F_{r2} = \mathrm{S}_3 - \mathrm{S}_6 \tag{10}$$

$$F_{r3} = \mathrm{S}_5 - \mathrm{S}_2. \tag{11}$$

It can be stated that F_{r2} and F_{r3} are the same function as F_{r1} with phase shifting of $-2\pi/3$ and $+2\pi/3$, respectively. From (1) and (4), the fictitious dc voltage

$$V_{pn} = 1.5 * m_c * V_m. \tag{12}$$

B. Inverter Mode of Operation

The objective of this mode of operation is to generate a high frequency single phase output voltage. The operating frequency in this mode is the same as desired output frequency.

From the rectifier mode, fictitious dc voltage, V_{pn}, is found. It is used as the input of single phase inverter part in Fig. 2. Due to only one phase for the matrix converter output, the inverter mode matrix, F_i, has single element

$$F_i = [F_{i1}] \tag{13}$$

$$F_{i1} = \mathrm{SSW}_1 - \mathrm{SSW}_3 = \mathrm{SSW}_2 - \mathrm{SSW}_4. \tag{14}$$

The switching function, F_{i1}, can be generated as shown in Fig. 6. The control signal, m, is varied to obtain desired matrix converter output voltage. The switching function can be expressed as

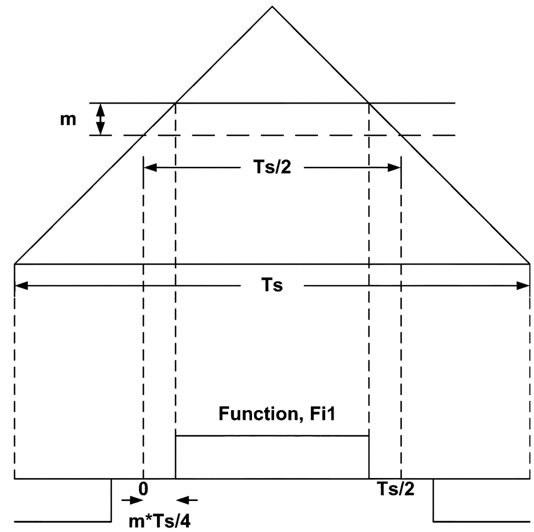

Fig. 6. Inverter mode switching function.

$$F_{i1} = \sum_{n=odd}^{\infty} B_n \sin(n\omega_o t) \tag{15}$$

$$B_n = \frac{4}{n * \pi} \sin\left(\frac{n\pi}{2}\right) \cos(n\pi) \sin\left(\frac{(m-1)n\pi}{2}\right). \tag{16}$$

From (2) and (12) and let m_v be inverter mode modulation index

$$V_o = 1.5 * m_c * m_v * V_m. \tag{17}$$

C. Proposed PWM Switching Modulation

From (1) and (2), it can be shown that matrix converter output can be found from

$$V_o = F_i * F_r * V_{\text{in}} = F_T * V_{\text{in}}. \tag{18}$$

Equation (18), the transfer function, F_T, is representing the matrix converter switching function. Thus, switching function of matrix converter switches can be realized as follows.

From (8)–(11), (13), and (14) we have

$$\begin{aligned} F_T &= \begin{bmatrix} SSW_1 & SSW_3 \\ SSW_4 & SSW_2 \end{bmatrix} \times \begin{bmatrix} S_1 & S_3 & S_5 \\ S_4 & S_6 & S_2 \end{bmatrix} \\ &= \begin{bmatrix} SW_1 & SW_3 & SW_5 \\ SW_4 & SW_6 & SW_2 \end{bmatrix} \end{aligned} \tag{19}$$

$$\begin{aligned} SW_1 &= SSW_1 \times S_1 + SSW_3 \times S_4 \\ SW_2 &= SSW_4 \times S_5 + SSW_2 \times S_6 \\ SW_3 &= SSW_1 \times S_3 + SSW_3 \times S_6 \\ SW_4 &= SSW_4 \times S_1 + SSW_2 \times S_4 \\ SW_5 &= SSW_1 \times S_5 + SSW_3 \times S_2 \\ SW_6 &= SSW_4 \times S_3 + SSW_2 \times S_6. \end{aligned} \tag{20}$$

Block diagram of the proposed matrix converter modulation is shown in Fig. 7. Each switch can be implemented with the logic gates as shown in Fig. 8.

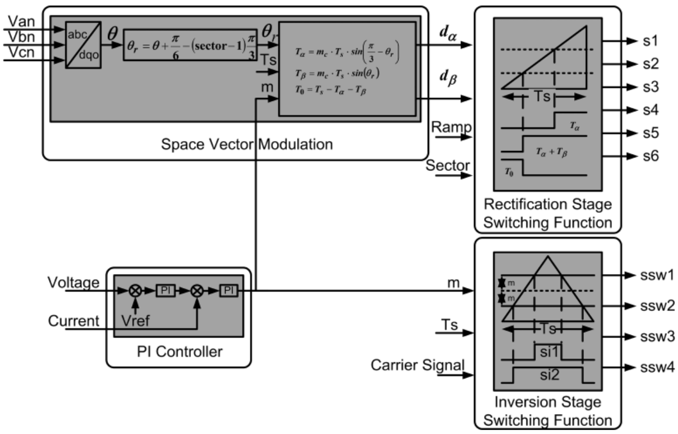

Fig. 7. Block diagram of the proposed matrix converter modulation.

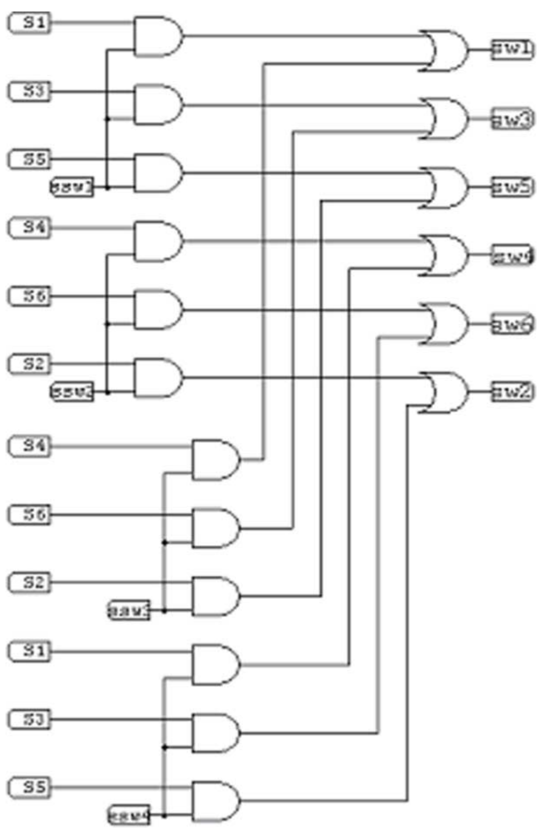

Fig. 8. Matrix converter switch gating signals generating through logic gates.

IV. Analysis of the Proposed Power Conversion Stage

A. Voltage Analysis

In the proposed topology, input source voltage is converted to high frequency voltage through operation of three-phase to one-phase matrix converter. From (1) and (2), the matrix converter output voltage is given by

$$V_o = F_i * F_r * V_i. \tag{21}$$

From (4), (8), and (13) we have

$$V_o(\omega_o t) = F_i * (F_{r1} * V_{ab} + F_{r2} * V_{bc} + F_{r3} * V_{ca}) \tag{22}$$

where

$$F_{r1} = A_1 \sin(\omega_i t) + \sum_{n=3,5,7,\ldots} A_n \sin(n\omega_i t) \tag{23}$$

$$F_{r2} = A_1 \sin\left(\omega_i t - \frac{2\pi}{3}\right) + \sum_{n=3,5,7,\ldots} A_n \sin\left(n\omega_i t - \frac{2\pi}{3}\right) \tag{24}$$

$$F_{r3} = A_1 \sin\left(\omega_i t + \frac{2\pi}{3}\right) + \sum_{n=3,5,7,\ldots} A_n \sin\left(n\omega_i t + \frac{2\pi}{3}\right). \tag{25}$$

Then

$$\begin{aligned} V_o(\omega_o t) &= 1.5 * A_1 * B_1 * V_m \sin(\omega_o t) + V_{o,h}(\omega_o t) \\ V_{o,h}(\omega_o t) &= (1.5 * A_1 * V_m) \sum_{n=odd}^{\infty} B_n \sin(n\omega_o t) \\ &\quad + (1.5 * B_1 * V_m) \sin(\omega_o t) \sum_{n=odd}^{\infty} A_n \sin(n\omega_i t) \\ &\quad + (1.5 * V_m) \sum_{n=odd}^{\infty} A_n \sin(n\omega_i t) \\ &\quad \times \sum_{n=odd}^{\infty} B_n \sin(n\omega_o t). \end{aligned} \tag{26}$$

Equation (26) shows no dc component in the matrix converter output voltage. The high frequency ac output voltage is connected to isolation transformer stage.

In order to generate −48 V dc, the high frequency transformer performs step-down operation with suitable turn ratio, N. The selected N depends on value of input voltage and range of matrix converter modulation index and is detailed in the design example section.

B. Line Current and Harmonics Analysis

In this section the input line current is analyzed. Equation (3) shows the input current I_i as a function of I_o and the rectifier/inverter mode transfer functions. Now assuming the output current I_o to be sinusoidal

$$I_o = I_m \sin(\omega_o t) \tag{27}$$

where I_m is amplitude of output current and ω_o is output angular frequency. The input current can be expressed as

$$I_i = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} F_{r1} \\ F_{r2} \\ F_{r3} \end{bmatrix} * F_{i1} * I_o. \tag{28}$$

From (28), line current I_a can be expressed as

$$I_a = F_{r1} * F_i * I_m \sin(\omega_o t). \tag{29}$$

Substitute (14) and (24)–(29) yields

$$\begin{aligned} I_a =& \left(\frac{A_1 * B_1 * I_m}{2}\right)\sin(\omega_i t) \\ &- \left(\frac{A_1 * B_1 * I_m}{4}\right)\sin\left((\omega_i \pm 2\omega_o)t\right) + I_{a,h} \\ I_{a,h} =& B_1 * I_m \sin^2(\omega_o t)\sum_{n=odd}^{\infty} A_n \sin(n\omega_i t) \\ &+ A_1 * I_m \sin(\omega_o t)\sin(\omega_i t)\sum_{n=odd}^{\infty} B_n \sin(n\omega_o t) \\ &+ I_m \sin(\omega_o t)\sum_{n=odd}^{\infty} A_n \sin(n\omega_i t) \\ &\times \sum_{n=odd}^{\infty} B_n \sin(n\omega_o t) \end{aligned} \tag{30}$$

where ω_i is the input frequency in rad/s ($\omega_i = 2\pi f_i$, $f_i = 60$ Hz) and ω_o is the output frequency in rad/s ($\omega_o = 2\pi f_o$, $f_o = 10$ kHz). Substituting ω_i and ω_o in (30), it is clear that the input current does not have any low frequency harmonic components and is of high quality. The high frequency components in I_i are to be filtered by the input put filter stage of the converter.

V. Design Example

In this section, a design example is presented for the following input/output specifications.

To facilitate calculation in per-unit, the following base quantities are defined

$$\begin{aligned} P_{\text{base}} &= P_o = 1.5 \ \text{kW} \\ V_{\text{base}} &= V_{\text{dc}} = 48 \ \text{V} \\ I_{\text{base}} &= I_{\text{dc}} = 31.25 \ \text{A} \\ Z_{\text{base}} &= \frac{V_{\text{base}}}{I_{\text{base}}} = 1.536 \ \Omega. \end{aligned}$$

Input line voltage $V_i = 4.33$ per– unit.

The matrix converter output current I_o is given by

$$I_o = \frac{1}{N} * I_{\text{dc}} \tag{31}$$

where N is the transformer turn ratio.

Select $N = 4$, $I_o = 0.25$ per unit.

Neglecting losses, the utility line current can be expressed as

$$I_a = \frac{P_o}{\sqrt{3} * V_i}. \tag{32}$$

And the input current $I_a = 0.133$ per-unit.

A. Input Filter Design

High frequency current components in the input current of matrix converter can be filtered via a LC filter. The value of filter capacitor is selected by the following equation [7]:

$$C_F \approx \frac{2 * P}{3 * V_m^2 * \omega_i} \tag{33}$$

where P is the power rating, V_m is the peak of input voltage, and ω_i is angular input frequency.

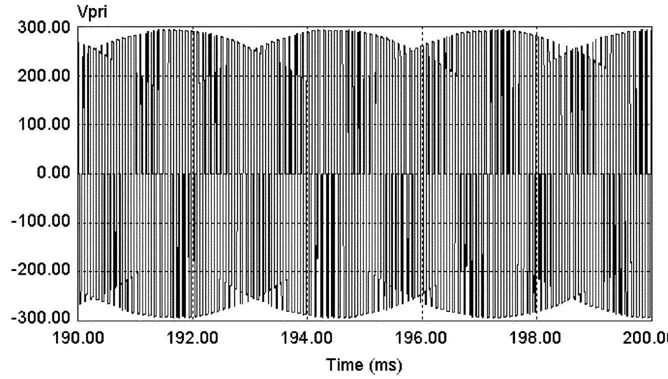

Fig. 9. High frequency output voltage V_{pri} of the matrix converter.

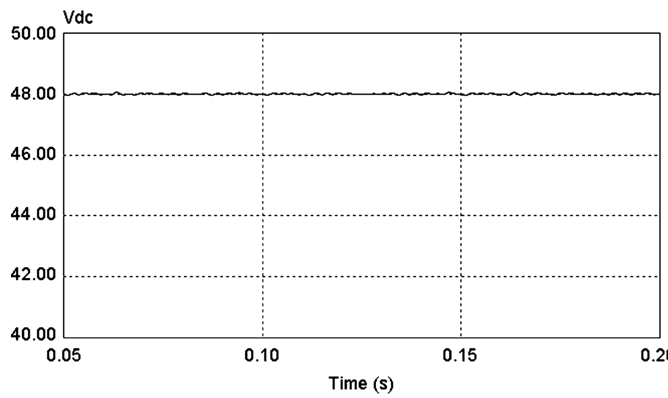

Fig. 10. Output dc voltage (48 V).

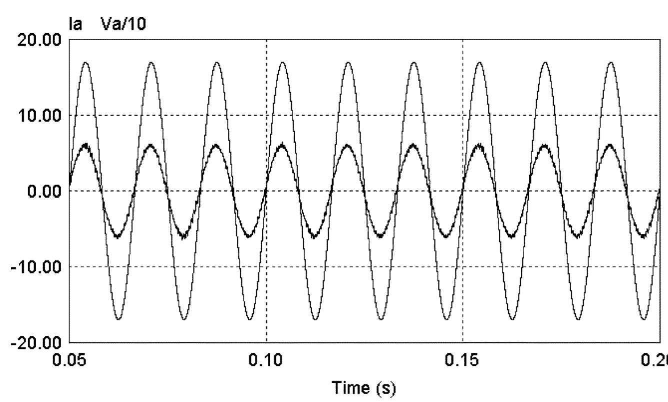

Fig. 11. Input line to neutral input voltage V_{an} and input current I_a.

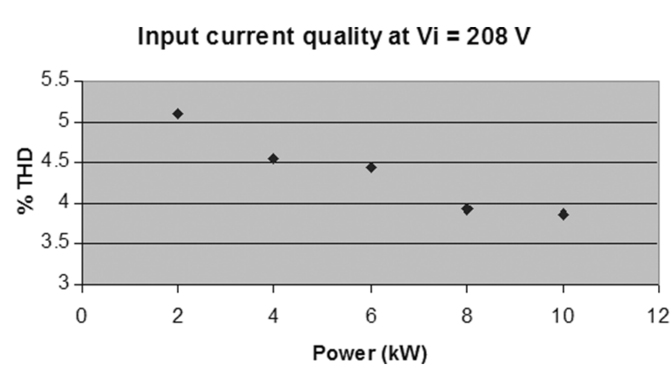

Fig. 12. THD percentage at different loads.

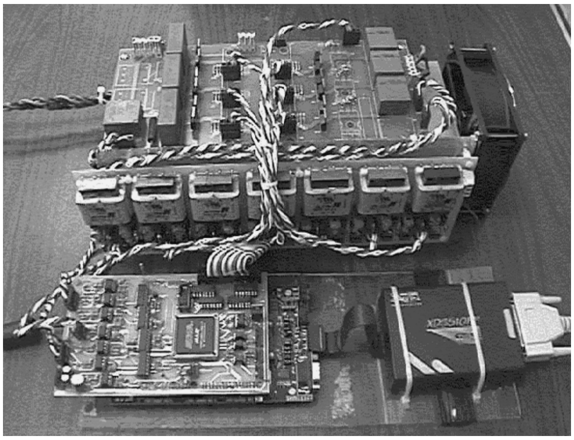

Fig. 13. Proposed matrix converter prototype.

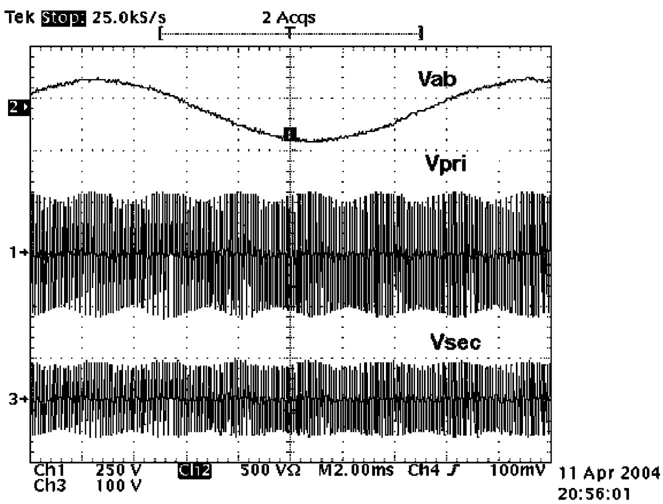

Fig. 14. Input voltage V_{ab}, matrix converter output voltage $V_{\rm pri}$, and transformer secondary voltage $V_{\rm sec}$. (1: $V_{\rm pri}$ [250 V/div], 2: V_{ab} [500 V/div], 3: $V_{\rm sec}$ [100 V/div]).

The value of filter inductor is chosen by

$$L_F = \frac{1}{(2\pi f_c)^2 * C_F} \tag{34}$$

where f_c is the cut-off frequency and is chosen to be lower than the switching frequency (10 kHz). With the parameter values given in this design example, and cut-off frequency is chosen to be 1.7 kHz:

filter capacitance $(C_{\rm F}) = 60\ \mu$F;
filter inductor $(L_{\rm F}) = 150\ \mu$H.

VI. Simulation Results

In this section, simulation results of the proposed approach are discussed. Fig. 9 shows the high frequency output voltage of the matrix converter. Fig. 10 shows the 48-V dc output voltage. Fig. 11 illustrates the performance of the proposed converter from utility perspective. It is clear for these results that input current is of high quality and is in phase with the input line to neutral voltage. Fig. 12 shows the variation of input current THD as a function of load.

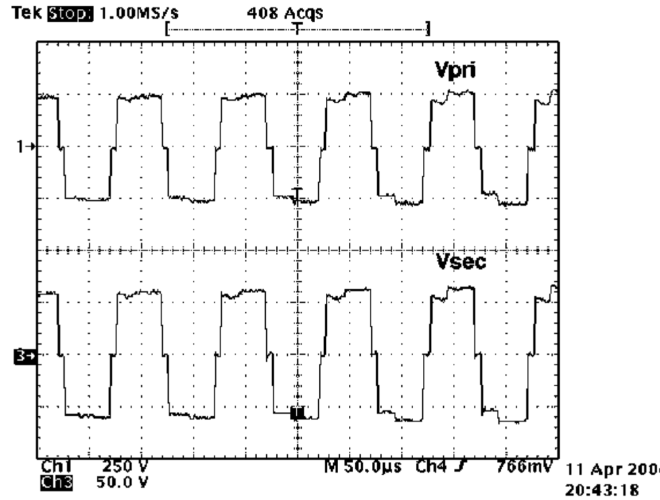

Fig. 15. Transformer primary $V_{\rm pri}$ and secondary voltages $V_{\rm sec}$. (1: $V_{\rm pri}$ [250 V/div], 3: $V_{\rm sec}$ [50 V/div]).

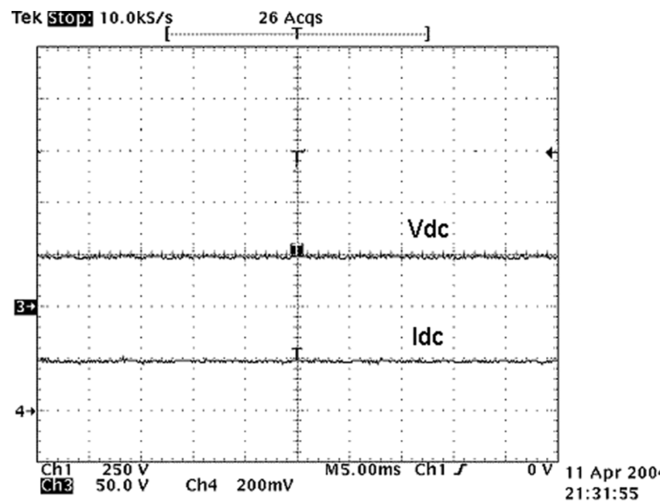

Fig. 16. Output dc voltage $V_{\rm dc}$ and load current $I_{\rm dc}$. (3: $V_{\rm dc}$ [50 V/div], 4: $I_{\rm dc}$ [10 A/div]).

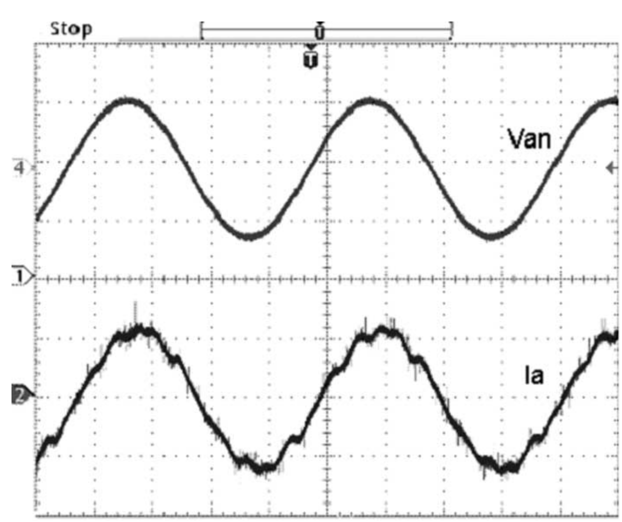

Fig. 17. Input line to neutral voltage V_{an} and the input line current I_a at 1.5 kW of output power. (2: I_a [5 A/div], 4: V_{an} [125 V/div]).

TABLE I
DESIGN SPECIFICATIONS OF THE PROPOSED APPROACH

Design specifications	Values
Input line voltage (V_i)	208 V
Input frequency (f_i)	60 Hz
Switching frequency (f_{sw})	10 kHz
Output DC voltage (V_{dc})	48 V
Load power (P_o)	1.5 kW
Matrix converter module 1200V	12 IGBTs

VII. EXPERIMENTAL RESULTS

A laboratory prototype of the proposed digitally controlled switch mode power supply was constructed to meet the specifications detailed in Section V. A commercially available matrix converter module: FM35R12KE3 from EUPEC [6] was employed. A digital signal processor (TMS320LF2407) was used for generating PWM gating signals and performing closed loop functions. Fig. 13 shows the prototype matrix converter unit. The unit is connected to bridge rectifier, which consists of four fast-recovery diodes (60EPU02), and an output filter to produce power supply voltage of 48 V dc.

Fig. 14 shows the input voltage V_{ab}, matrix converter output voltage (high frequency) V_{pri} (connected to the transformer primary winding) and the transformer secondary voltage V_{sec}. Fig. 15 shows the transformer primary and secondary voltages with expanded time scale. Fig. 16 shows the output dc voltage (48 V) and the load current. Fig. 17 shows the line to neutral voltage V_{an} and the line current I_a at 1.5-kW output power. It is clear that the input current is of high quality and unity power factor (see Table I) [8], [9].

VIII. CONCLUSION

In this paper, a digitally controlled switch mode power supply based on matrix converter for telecommunication applications has been shown. The proposed space vector PWM method has been shown to yield high quality input current for varying load conditions. Experimental results on a 1.5-kW prototype have demonstrated the feasibility of a direct ac to ac matrix converter in telecommunication power supplies.

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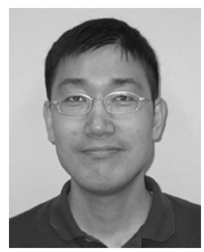

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Dr. Enjeti received the IEEE-IAS Second and Third Best Paper Award in 1993, 1998, 1999, 2001, and 1996, respectively; the Second Best IEEE-IA TRANSACTIONS paper published in mid-year 1994 to mid-year 1995, the IEEE-IAS Magazine Prize Article Award in 1996, the Class of 2001 Texas A&M University Faculty Fellow Award for demonstrated achievement of excellence in research, scholarship and leadership in the field, and he directed a team of students to design and build a low cost fuel cell inverter for residential applications, which won the 2001 future energy challenge award, grand prize, from the Department of Energy (DOE). He is a Registered Professional Engineer in the state of Texas.