Investigation of Direct Matrix Converter Working as a Versatile Converter (AC/AC, AC/DC, DC/AC, DC/DC Conversion) with Predictive Control

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***Abstract*—The three-phase direct matrix converter has been researched exclusively as a direct AC/AC converter, being a competitive alternative to the conventional AC/DC/AC converter. Other possibilities of the matrix converter such as AC/DC, DC/AC and DC/DC conversion still remain unexplored. This paper firstly explores these possibilities and puts forward a concept of the versatile converter. With one matrix converter, different conversion purposes can be accomplished as required. The matrix converter based conversion has some advantages compared with other converters. Model predictive control (MPC) is applied in this work to control the matrix converter to perform the required conversion goals. A generalized model is obtained for all types of conversion in this work. With MPC, different objectives and constraints can be easily included in the control scheme. In addition, the observers are used to reduce the number of voltage and current sensors. Simulation results verify the effectiveness and feasibility of AC/DC, DC/AC and DC/DC conversion with the matrix converter.**

Keywords—Versatile Conversion; Matrix Converter; Model Predictive Control; AC/AC; AC/DC; DC/AC; DC/DC; Smart Grid

I. INTRODUCTION

Smart grids and eco-friendly distributed generation systems are growing in popularity [1]. Power electronic converters are becoming common components in the power industry and they are becoming more important especially in the context of modern smart grids involving various renewable energy sources and energy storage systems. They play a vital role in various areas such as renewable energy integration, grid synchronization, energy conversion and power control [2-4]. Power electronic converters can be generally classified into following four types: AC/AC, AC/DC, DC/AC and DC/DC converters. Almost all power electronic converters are employed for one unique purpose of conversion only, such as a rectifier for the AC/DC conversion, an inverter for the DC/AC conversion and a Buck-Boost converter for the DC/DC conversion. However, the modern power industry requires more flexibility in power conversion and control strategies [5][6]. Different converters are required in different situations. Therefore, it is beneficial if one converter can perform any conversion function when required. The concept of versatile conversion with the matrix converter was put forward in [7] where a three-phase direct matrix converter was proposed for the stand-alone operation of an AC microgrid to supply stable and sinusoidal voltages to local loads.

The direct three-phase matrix converter, shown in Fig. 1, has been considered as an alternative to the traditional AC/DC/AC converter. It is suitable for a wide range of applications including renewable energy and aerospace systems [8]. It has advantages such as compact volume, bidirectional power flow, controllable input power factor, sinusoidal waveform, direct conversion and longer life cycle [9]. Its derivatives have been proposed for many applications [10]. However, the matrix converter has only really been researched as an AC/AC converter. This paper investigates some interesting possibilities of the matrix converter for other types of conversion i.e. AC to DC, DC to AC and DC to DC conversion, which leads to a versatile converter. This illustrates some open research and potential application areas of the matrix converter, such as electric vehicles, AC and/or DC grid interface, renewable energy systems, UPS and aircraft systems. Some features of different types of conversion with a matrix converter are compared with their traditional counterparts. The different possibilities, except for AC/AC conversion which is already well known, are discussed here.

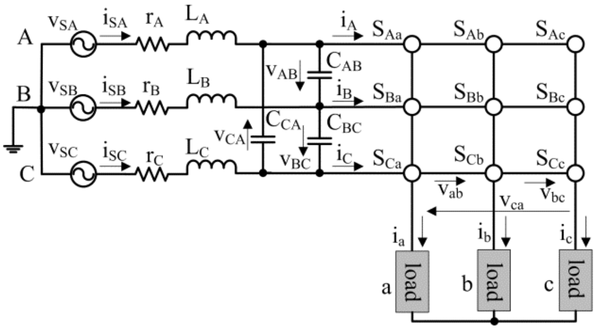

Fig. 1. A three-phase direct matrix converter system with input filters.

• AC to DC conversion: in the matrix converter based conversion, the capacitance required at the DC side is reduced markedly compared with common rectifiers [11], from hundreds to thousands of microfarads to dozens of microfarads. As there are three terminals at the output side, three levels of DC voltage can be obtained, which results in the increased flexibility. Interestingly, the matrix converter based AC/DC

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converter can be used as either the boost or buck type of converter to supply DC loads with a wide voltage range. The output DC voltages can cover a wide range (being able to reach zero), and the input power factor can be regulated to reach unity. This is advantageous considering more stringent requirements on the current total harmonic distortion (THD) and power factor. The unity input power factor can be maintained even under low DC output voltage operations. This conversion topology can handle the issues of unbalanced input AC supplies.

• DC to AC conversion: with the matrix converter, up to three independent DC voltages can be connected to the input side. This structure can handle the common mode voltage which is intractable with traditional DC/AC inverter drives [12]. In this structure, the large electrolytic capacitors are not required at the DC side. Other benefits of the traditional DC/AC inverter are retained with this structure.

• DC to DC conversion: it is worth noting that the DC to DC conversion is possible with the matrix converter although it is not very practical to do so because of the high number of switches. However, both input and output have three terminals which can enable the best use of switches and flexible use of DC sources. High power capacity can be achieved.

Model predictive control (MPC) is a simple yet powerful control for power electronic converters [13]. It is adopted in this work to achieve the desired control objectives. Various control objectives and system constraints can be easily included in this control strategy. It is very easy to understand and implement. A generalized MPC is employed in this work to control all types of conversion. The rest of this paper is organized as follows. In Section II, the prediction model for the matrix converter system is obtained, and then the observers are developed to reduce the required number of sensors. The model predictive controller is designed in Section III. Section IV details the implementation for the AC/AC, AC/DC, DC/AC and DC/DC conversion using the matrix converter and presents their simulation results. Section V concludes this paper.

II. System Modeling and Observers Design

A. System Modeling for the Matrix Converter

The general AC/AC conversion topology shown in Fig. 2 is used to obtain a generalized model for the prediction implementation. It is sufficient to consider a one-phase system for explanation. The matrix converter output filter of phase *a* can be modeled in a state-space model:

$$\begin{bmatrix} \dot{i}_{oa} \\ \dot{v}_a \end{bmatrix} = F \begin{bmatrix} i_{oa} \\ v_a \end{bmatrix} + G \begin{bmatrix} v_{oa} \\ i_{la} \end{bmatrix} \tag{1}$$

$$F = \begin{bmatrix} -R_{oa}/L_{oa} & -1/L_{oa} \\ 1/C_a & 0 \end{bmatrix} \tag{2}$$

$$G = \begin{bmatrix} 1/L_{oa} & 0 \\ 0 & -1/C_a \end{bmatrix} \tag{3}$$

where C_a is the capacitance of equivalent star-connected capacitors. The feature of the delta-connected capacitors is that the required capacitance is one-third ($C_{ab} = C_a/3$) while the voltage rating is $\sqrt{3}$ times ($V_{ab} = \sqrt{3}V_a$) of a star-connected network with equivalent ratings. The zero-order-hold based discretized model can be derived from

$$\begin{bmatrix} i_{oa}[k+1] \\ v_a[k+1] \end{bmatrix} = A \begin{bmatrix} i_{oa}[k] \\ v_a[k] \end{bmatrix} + B \begin{bmatrix} v_{oa}[k] \\ i_{la}[k] \end{bmatrix} \tag{4}$$

$$A = e^{F \cdot T_s} \tag{5}$$

$$B = \int_0^{T_s} e^{F\cdot\tau} d\tau \cdot G \tag{6}$$

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = \frac{1}{a-b} \begin{bmatrix} a\cdot e^{a\cdot T_s} - b\cdot e^{b\cdot T_s} & -(e^{a\cdot T_s} - e^{b\cdot T_s})/L_{oa} \\ (e^{a\cdot T_s} - e^{b\cdot T_s})/C_{ab} & (a\cdot e^{a\cdot T_s} - b\cdot e^{b\cdot T_s}) + R_{oa}\cdot(e^{a\cdot T_s} - e^{b\cdot T_s})/L_{oa} \end{bmatrix} \tag{7}$$

$$B = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} = \frac{1}{a-b} \begin{bmatrix} (e^{a\cdot T_s} - e^{b\cdot T_s})/L_{oa} & \dfrac{[a\cdot(e^{b\cdot T_s}-1) - b\cdot(e^{a\cdot T_s}-1)]}{(L_{oa}\cdot C_{oa}\cdot a\cdot b)} \\ \dfrac{[-a\cdot(e^{b\cdot T_s}-1) - b\cdot(e^{a\cdot T_s}-1)]}{(L_{oa}\cdot C_{oa}\cdot a\cdot b)} & -e^{a\cdot T_s} + e^{b\cdot T_s} + \dfrac{R_{oa}\cdot[a-b-a\cdot e^{b\cdot T_s} + b\cdot e^{a\cdot T_s}]}{(L_{oa}\cdot C_{oa}\cdot a\cdot b)} \end{bmatrix} \tag{8}$$

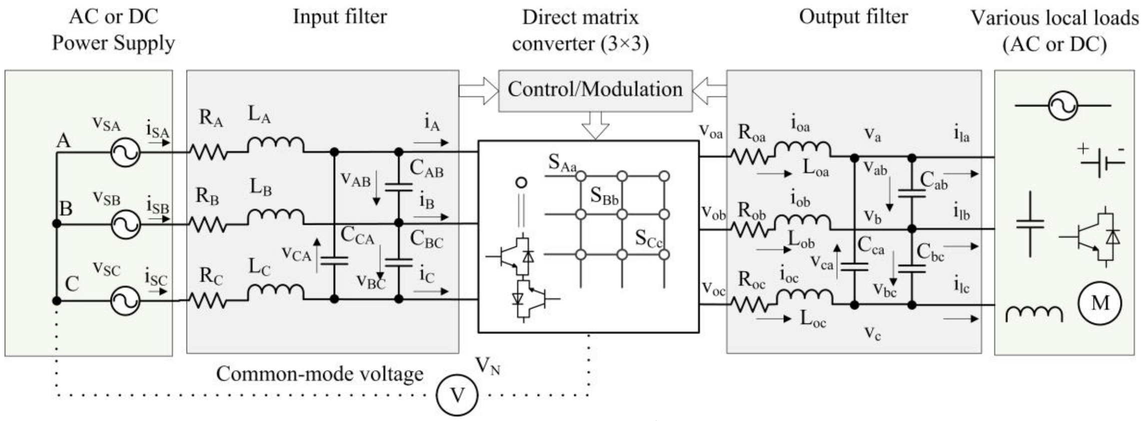


Fig. 2. Matrix converter system diagram for model development.

where T_s is the sampling time and the matrices A and B can be obtained from (7) and (8) so that

$$a,b = \frac{-R_{oa}/L_{oa} \pm \sqrt{(R_{oa}/L_{oa})^2 - 4/C_{oa}/L_{oa}}}{2} \tag{9}$$

Therefore, the future behavior of the output voltage can be predicted by

$$\begin{aligned} v_a[k+1] &= A_{21} \cdot i_{oa}[k] + A_{22} \cdot v_a[k] \\ &+ B_{21} \cdot v_{oa}[k] + B_{22} \cdot i_{la}[k] \end{aligned} \tag{10}$$

using the discretized model (4). Similarly, the input current prediction

$$\begin{aligned} i_{sA}[k+1] &= M_{11} \cdot i_{sA}[k] + M_{12} \cdot v_A[k] \\ &+ N_{11} \cdot v_{sA}[k] + N_{12} \cdot i_A[k] \end{aligned} \tag{11}$$

can be derived using the input filter model to predict the input current future behavior, where the matrices M_{11}, M_{12}, N_{11} and N_{12} are derived in a similar manner.

In (10) and (11), i_{oa}, v_{a}, v_{A}, and i_{SA} are obtained directly from current and voltage sensors. v_{oa} and i_{A} are obtained using the switch matrix:

$$S = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix}, \ (S_{Ax} + S_{Bx} + S_{Cx} = 1, x = a,b,c) \tag{12}.$$

The elements represent switches in the matrix converter and they have two values, i.e., 1 for the "on" state and 0 for the "off" state. The conditions of (12) are to avoid short circuits of the voltage supplies and open circuits of the inductive loads. This leads to 27 allowable matrix converter states. i_{la} and v_{sA} and can be obtained using sensors or observers. Observers are designed to reduce the number of sensors, and thus cost. These rules apply to other phases to get the corresponding values.

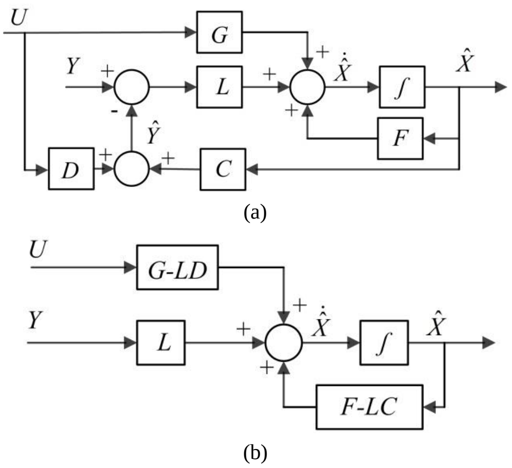


Fig. 3. (a) Luenberger observer design and (b) its simplified diagram.

Based on the prediction models (10) and (11), MPC evaluates each switch state (27 in total as shown in Fig. 4) and selects the optimum one which minimizes the prescribed cost function to be applied at the next sampling instant. The design of the cost function will be explained in the next section.

B. Observers Design

This part designs the Luenberger observers to estimate some variables in (10) and (11). A system can be described in the state-space form:

$$\dot{X} = FX + GU \tag{13}$$

$$Y = CX + DU \tag{14}.$$

The Luenberger state observer can be designed (Fig. 3):

$$\begin{aligned} \dot{\hat{X}} &= F\hat{X} + GU + LY - LC\hat{X} - LDU \\ &= (F - LC)\hat{X} + (G - LD)U + LY \end{aligned} \tag{15}$$

$$\hat{Y} = C\hat{X} + DU \tag{16}$$

where L is the gain matrix. System states X can be estimated using this observer. Depending on the specific observed state, the state space system should be modified and some assumptions are necessary. In order to observe the load current i_{la} for example, the assumption ($\mathrm{d}i_{la}/\mathrm{d}t = 0$) is made and added to the model to make either a 2-D or 3-D observer. This assumption is based on the fact that the algorithm sampling time is sufficiently small so that i_{la} is treated as a constant during one sampling interval. The gain matrix L should be designed properly so that the eigenvalues of F-LC are strictly on the left-hand side of the complex plane. Under this condition, the estimation error equation is asymptotically stable, which means the estimation error will decay to zero with time. In this work, load currents $i_{la,\ lb,\ lc}$ and source voltages $v_{sA,\ sB,\ sC}$ are estimated using the observers.

III. MPC Controller Design

The switch matrix of a matrix converter is arranged so that any output can be connected to any input. The switches are controlled by MPC to form any one of the 27 combinations. In MPC, the cost function design reflects the control objectives and efforts. In this work, the control objectives are sinusoidal output voltages, unity input power factor, elimination of the common-mode voltage, and low switching frequency. A cost function can contain any combination depending on the converter type and application. Therefore, a general cost function for selecting the optimum switch state is described by

$$\begin{aligned} g &= \lambda_1 \cdot \left\{ \left| v_a^* - v_a^p \right| + \left| v_b^* - v_b^p \right| + \left| v_c^* - v_c^p \right| \right\} \\ &+ \lambda_2 \cdot \left| Q^* - Q^p \right| + \lambda_3 \cdot \left| v_N \right| + \lambda_4 \cdot \sum_{i=1}^{9} \left| S_i^k - S_i^p \right| \end{aligned} \tag{17}$$

where $\lambda_{1,\ 2,\ 3,\ 4}$ are weighting factors for each term. Higher values mean higher control priority. Designing these factors is usually empirical [14] and the trade-off between each control objective needs to be considered when designing these factors. $v^*_{a,\ b,\ c}$, and $Q^*$are reference three-phase voltages and input reactive power and their counterparts are the predicted values. v_N is the common-mode voltage. S_i^k represents the switch state at the time instant of k, and S_i^p stands for the predicted switch states. A unity power factor is achieved via making the reactive power of supply to zero.

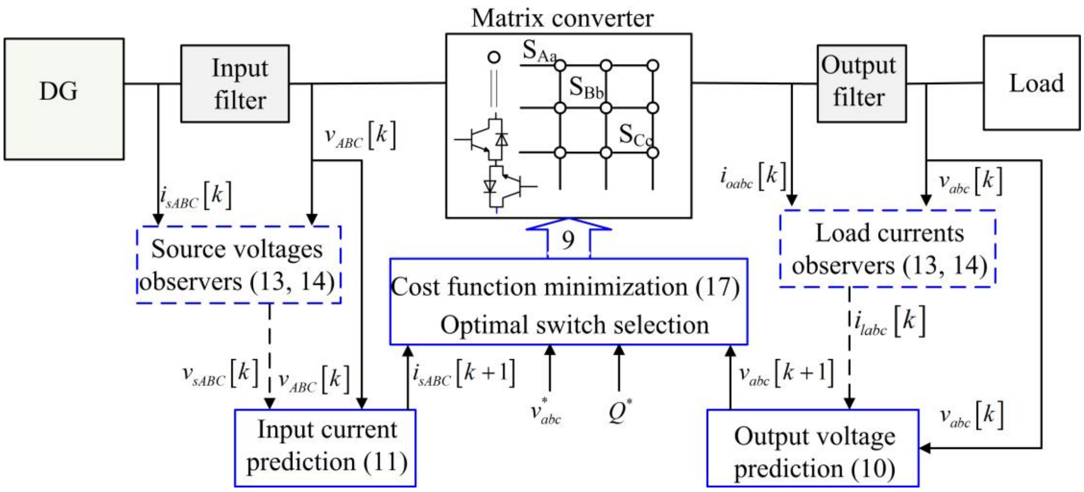


Fig. 4. MPC controller scheme involving observers for the matrix converter system.

TABLE I. SIMULATION SYSTEM PARAMETERS

V_s (V)	R_A (Ω)	L_A (mH)	C_{AB} (μF)	R_{oa} (Ω)	L_{oa} (mH)	C_{ab} (μF)	R_L (Ω)	L_L (mH)	C_L (μF)
220	0.5	3.2	2	0.5	4.8	10	50	10	20

The cost function form is not limited to (17); other terms such as integral, square and so on can be integrated into it for specific applications. Based on the above analysis, the predictive controller for the matrix converter is shown in Fig. 4 where measured variable flows are denoted by the solid arrow lines while the dashed arrow lines represent the observed variable flows.

IV. VERSATILE CONVERSION AND SIMULATION RESULTS

Simulation results are presented in this section for AC/AC, AC/DC, DC/AC and DC/DC conversions. The system parameters are shown in Table I. The sampling time T_s is set to 1×10^{-5} s. Weighting factors vary from case to case depending on the control objectives. The power sources and filter parameters should be appropriately adjusted according to the requirement of each type of conversion. Loads for AC/AC and DC/AC conversion are inductive loads while loads for AC/DC and DC/DC conversion are capacitive loads.

A. AC-AC Conversion

AC to AC conversion of the matrix converter (shown in Fig. 5) has been researched widely, mainly focusing on the output current control. However, the output voltage control of matrix converter is rarely investigated. The stand-alone operation of a matrix converter based AC microgrid has already been proposed in [15] to supply stable and sinusoidal voltages to the loads. In [15], the input power factor, common-mode voltage and switching frequency are considered in the model predictive control; therefore they are not presented here.

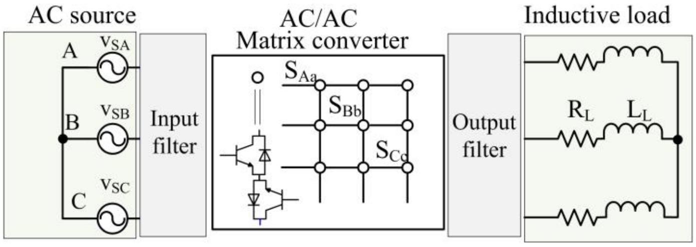


Fig. 5. Diagram for AC/AC conversion using matrix converter.

B. AC-DC Conversion

Regarding AC to DC conversion shown in Fig. 6, the output voltage and input power factor are regulated. Reference voltages for three DC output terminals are [100 -33.33 -66.67] V before 0.05 s and [100 -33.33 -66.67]×1.5 V after 0.05 s. The output DC voltages can be obtained either from each terminal (level) or from two terminals to get the difference between two levels. Simulation results are shown in Fig. 7. From Fig. 7(b), it is evident that the dynamic response is fast and zero steady state error is maintained. The voltage and current of phase *A* input are shown in Fig. 7(c) and they are in phase (unity power factor operation).

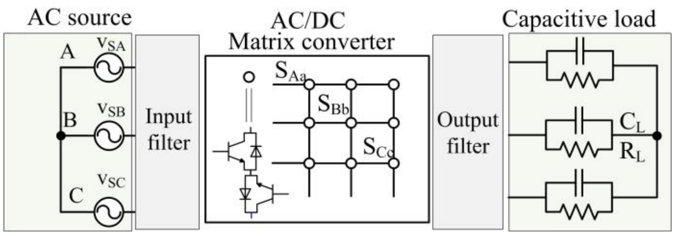


Fig. 6. Diagram for AC/DC conversion using matrix converter.

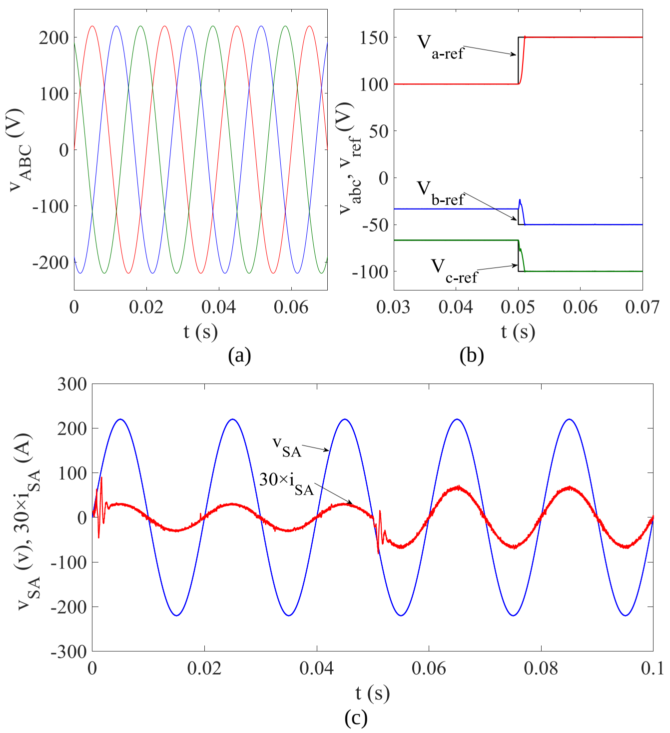


Fig. 7. AC/DC conversion (a) input voltages, (b) output voltages and (c) unity input power factor operation for the input phase *A*.

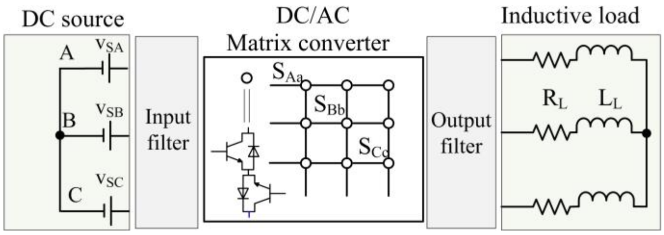


Fig. 8. Diagram for DC/AC conversion using matrix converter.

C. DC-AC Conversion

One of the main applications of DC/AC converters is AC motor drives where a rectifier is usually needed to generate a DC voltage supply. In this case, the AC/AC conversion of the matrix converter can be applied eliminating the DC link in the traditional AC/DC/AC drive structure [16]. Another main application of DC/AC converters is the integration of DC energy sources into an AC grid. This is the main interest of this work. Although up to 3 independent DC supplies can be utilized at the input as shown in Fig. 8, only one DC source is considered here to make it fairly comparable with traditional DC/AC converters. Therefore, the DC voltage supplies v_{SB} and v_{SC} are short circuited to the negative pole of v_{SA} (not just removed). Reference output AC voltages are [50sin(100πt) 50sin(100πt-2π/3) 50sin(100πt+2π/3)] V before 0.05 s and [90sin(100πt) 90sin(100πt-2π/3) 90sin(100πt+2π/3)] V after 0.05 s. The output voltage is shown in Fig. 9. It is evident that the voltage tracking performance is good and dynamic response is fast. With only one DC source, the common-mode voltage cannot be handled effectively. The common-mode voltage reduction for the case of two DC sources is shown in Fig. 10. The common-mode voltage is suppressed significantly.

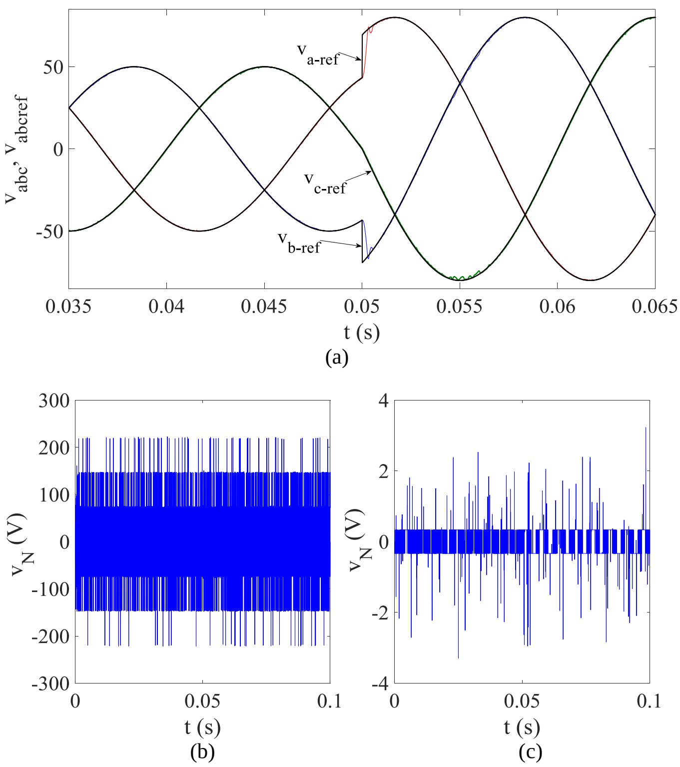


Fig. 9. DC/AC conversion (a) output voltages, (b) unregulated common-mode voltage and (c) regulated common-mode voltage.

D. DC-DC Conversion

The DC/DC conversion using matrix converter requires too many semiconductor devices compared to traditional DC/DC converters [15][17]. However, both input and output have three terminals enabling the input and output to be connected to three DC sources and three loads respectively as shown in Fig. 10. The power capacity can be improved with this structure. In this type of conversion, some of the 9 switches will be underutilized and this depends on the input and output arrangements. Simulation results are shown for single DC input and three DC output. Output voltage references are [60 0 -60] V before 0.05 s and [100 0 -100] V after 0.05 s. Output voltages are shown in Fig. 11(a) and their performance is acceptable. Large electrolytic capacitors are not required in this topology. The average switching frequency of 9 switches in the matrix converter is shown in Fig. 11(b). As seen from this figure, some of the switches are underutilized and this is related to the input and output connections.

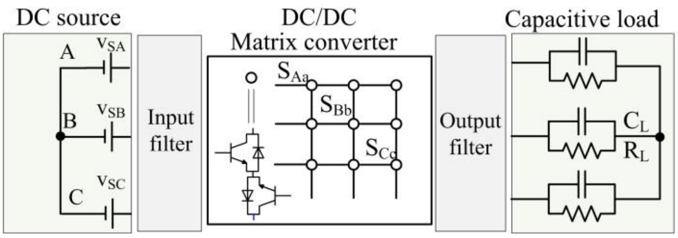
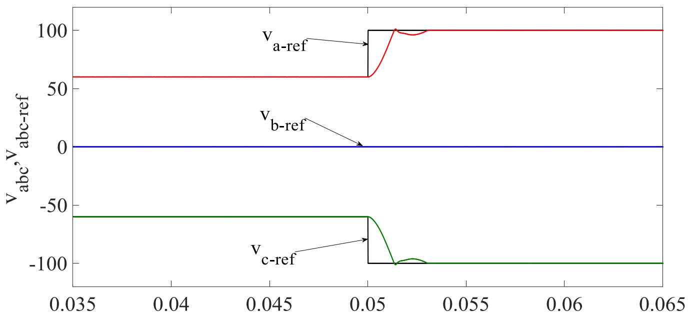
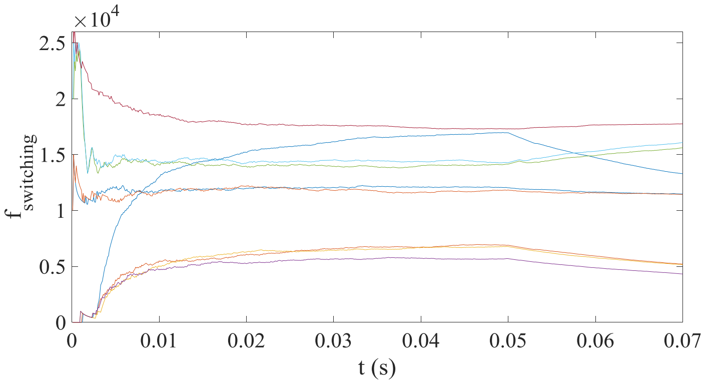


Fig. 10. Diagram for DC/DC conversion using matrix converter.



(a)



(b)

Fig. 11. DC/DC conversion (a) output voltages and (b) average switching frequencies of 9 switches in the matrix converter.

V. Conclusions

This paper puts forward an interesting concept for a versatile converter based on a direct three-phase matrix converter. Different types of conversion, i.e. AC/AC, AC/DC, DC/AC and DC/DC can be performed as required. MPC is adopted to control the matrix converter based on a generalized model. Various control objectives and system constraints can be considered in the MPC controller. Power can flow bidirectionally in the matrix converter. Simulation results verify the feasibility of the proposed scheme and demonstrate features for each type of conversion. Other aspects regarding this topic such as PWM techniques and control methods development, switching losses investigation and application exploration are yet open to be researched. Further work needs to be done to fully investigate the working mechanism of each type of conversion with the matrix converter. The operation of different scenarios under various input and load conditions needs to be further investigated too. To conclude, matrix converter cannot only be used as an AC/AC converter, but can also be used as AC/DC, DC/AC and DC/DC converters.

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