Research Report

2004-12

Investigation of the Dual Bridge Matrix Converter Operating Under Boost Mode

Wei, L., T.A. Lipo*

Rockwell Automation - Allen Bradley
Mequon, WI 53092
lwei@ra.rockwell.com

*University of Wisconsin - Madison
Madison, WI 53706
lipo@engr.wisc.edu

Wisconsin
Electric
Machines &
Power
Electronics
Consortium

University of Wisconsin-Madison
College of Engineering
Wisconsin Power Electronics Research Center
2559D Engineering Hall
1415 Engineering Drive
Madison WI 53706-1691

Investigation of the Dual Bridge Matrix Converter Operating Under Boost Mode

Lixiang Wei, Thomas A Lipo*

Rockwell Automation – Allen Bradley
Mequon, WI, 53092, USA
E-Mail: lwei@ra.rockwell.com

*The University of Wisconsin-Madison.
Madison, WI 53706 USA
Email: lipo@engr.wisc.edu

Abstract* – The dual bridge matrix converter can create high quality input/output waveforms as the normal double bridge converter with less switches, simpler clamp circuit and easier control. Moreover, it can also operate with a common bus-multiple inverter fed load condition. As a result, a more flexible and compact design can be made with this topology. This paper investigates the operation of a dual-bridge matrix converter (DBMC) under the boost mode. The converter operates at several hundred hertz fundamental frequency at both the input and two output sides. The high frequency operation at both sides further reduces the size and the weight of the system. Finally, theory analysis and simulation results are presented in the paper to verify its effectiveness.

I. INTRODUCTION.

The dual-bridge matrix converter (DBMC) is a newly developed concept [1][2][3]. Compared to the conventional matrix converter [4], it possesses the same high quality performance, including near sinusoidal input/output waveforms, adjustable input power factor, and a compact system design due to absence of large energy storage components. Moreover, it has a number other advantages over the conventional matrix converter, including safer commutation, reduced number of switches, simple clamp circuit, easier operation with multi-motor configurations [5], etc.

With all above advantages, the dual bridge matrix is suitable to be used for variable frequency AC/AC conversion applications, including distributed electrical power systems or many on-board electrical power generation systems. Some example systems include turbine and micro-turbine power units, electrically powered ships, aircraft, hybrid electrical buses and trains, etc[6]. The freedom of selecting both input and output frequencies can help operate the system at higher frequency to reduce the volume, weight and cost.

Generally in the past, the DBMC has been used for buck mode operation. The input of the converter is connected to the utility with constant voltage amplitude and frequency and the output is connected to the load with variable amplitude and frequency. With this configuration, the output/input voltage transfer ratio cannot exceed 0.866 without introducing distortion into the input current and output voltage waveforms. This paper investigates the feasibility of operating a DBMC instead under the boost mode as shown in Fig. 1(a). With this configuration, the converter allows the input frequency to be changed and voltage amplified freely without worrying about the resonance of an input filter.

One advantage of the DBMC operating in the boost mode is that it can support two kind of loads with only a very small energy storage component as shown in Fig. 1(b). In this figure, the input of converter has a power input that with a wide frequency range proportional to the shaft rotating speed of an alternator. In the output of this converter as a means of an example, one load is an inductive resistor load with fixed voltage and frequency and the other is an adjustable speed motor load.

This configuration has the following advantages.

1) Only minimum energy storage components are needed. Hence more compact design is possible for different kind of loads.
2) The filter design is much simplified due to the fixed frequency of the load. As a result, the input of the converter can operate over a wide range of input frequencies and voltages
3) Higher frequency power conversion capacity at 10 times higher than the utility frequency.
4) It has the capability of providing two type of loads with the least number of energy storage components. In this paper, one is the stiff voltage load with fixed amplitude and frequency; the other is a stiff current load with adjustable voltage and frequency. Moreover, it would also be possible to be applied as multi-motor-common DC bus applications [5].
5) Good control of the power factor of the input. A unity power factor can be achieved with the control method provided in this paper.
6) A pre-charge circuit is not needed. The capacitor at the load side can be charged up gradually by monitoring the input synchronization angle. As a result, the cost and size can be further minimized

The paper is organized through the following steps. After a brief description of the proposed topology, the switching scheme of the system is discussed in detail. An implementation of the input power factor control is then described. Finally, simulation results are presented to prove the feasibility of the proposed method.

II. INTRODUCTION.

Figure 1(a) shows a circuit diagram of the proposed topology. There are main three components shown in this figure.

1) The input to the converter is a variable frequency/variable voltage generator. The three phases of this generator is designated as V1, V2 and V3 respectively. It is assumed that the generator is a permanent magnet machine which operates at different speeds when driven by a prime mover such as a gas turbine. Generally, the speed and angle of this generator can be identified by the both the characteristics of the generator and its operating parameters.

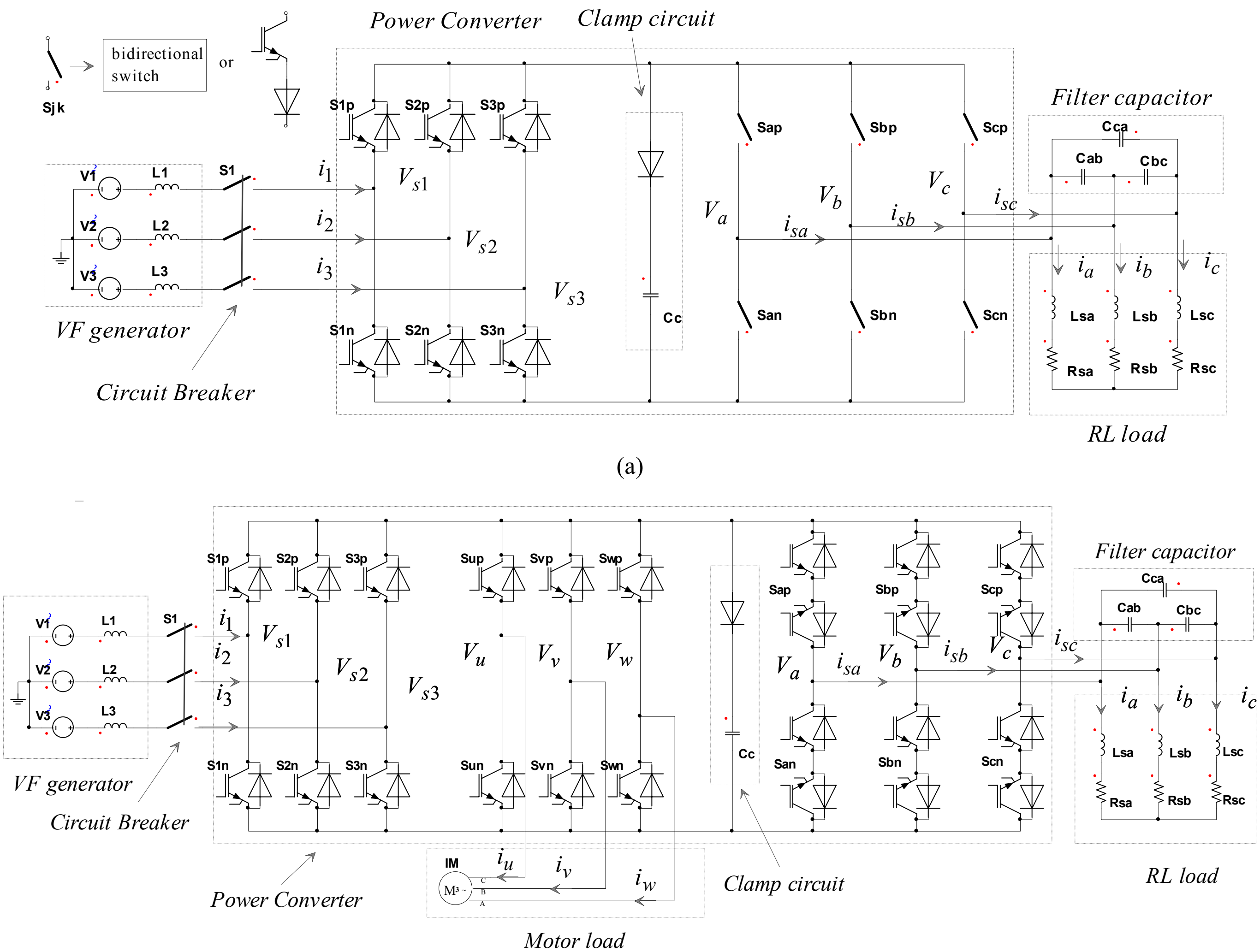


Fig. 1. Circuit configuration of DBMC operating under boost mode
(a): DBMC operating under the boost mode; (b): the proposed topology configuration of the example system

2) The output of the converter has two types of loads. The first load is an induction motor connected with a six switch inverter. The names of its three terminals are Vu, Vv and Vw respectively. This induction motor can also operate at variable frequency by adjusting its voltage command. The speed control of the induction machine is similar to the other induction machine operating with a DC/AC inverter.
3) The second load consists of various consumer loads, such as lighting, heaters, fans, etc. To make the simulation simple, it is simplified as a simple RL load with phases referred as Va, Vb and Vc. It is connected to a converter via six idea switch rectifier. Between this load and the rectifier, are three line capacitors serving as a filter to smooth out the harmonics caused from the other two energy components.

The operation of this system can be illustrated as follows. First, the voltage of the VF generator is boosted up to the required higher voltage across the three filter capacitors at the RL load. Once the voltages of the filter capacitors have stabilized, the induction machine can be operated similarly as a second inverter portion of the DBMC.

The configuration of Fig. 1 has the following advantages.

1. Two kinds of loads can be directly applied which allows the least filter requirement without degrading the performance of the system;
2. Compared to using conventional matrix converter, it can be used to drive a multi-motor multiple speed drive system without any difficulty.
3. The system does not have any limitation of input/output frequencies. Thus, a higher frequency and more compact system can be built with this configuration.
4. Unlike the traditional AC/DC/AC converter, this configuration does not need a pre-charge circuit. As a result, the size and the price of this circuit can be further reduced.

III. CONTROL PRINCIPLE OF THE BOOST MATRIX CONVERTER

A. Modeling of the DBMC operating in the boost mode

With reference to Fig. 1(a), the large signal equations for the boost rectifier can be derived using duty-cycle averaging and expressed as follows:

$$\begin{aligned} V_k &= R_{sg} i_k + L_{sg} p i_k + V_{gk}, k = 1,2,3 \\ i_{sj} &= C_f p V_{cj} + i_j, j = a,b,c \\ V_{cj} &= L_l p i_j + R_l i_j \end{aligned} \tag{1}$$

In (1), V_k are the phase 'k' voltage of the generator. V_{gk} are the phase 'k' voltage of the matrix converter at the generator side. L_{sg} and R_{sg} are the phase inductance and resistance of the generator. i_{sj} are the phase 'j' current at the converter side of the load. i_j are the phase 'j' current of the load. C_j is the per phase capacitance of the load. V_{cj} are the phase 'j' voltage of the filter. L_s and R_s are equivalent phase inductance and resistance of load.

Using the space vector PWM control proposed in [1][2][3], it can be determined that the voltage transfer ratio is directly related to the power factor angle of the voltage V_{cj} and i_{sj}. In Fig. 1, this power factor angle can only be controlled by the per phase impedance angle of the load at steady state as shown in (2).

$$\begin{aligned} Z_l &= j\omega_l C_f \,//(R_l + j\omega_l L_l) \\ PF &= \mathrm{Re}(Z_l)/|Z_l| \end{aligned} \tag{2}$$

In (2), Z_l is the phase impedance of the load. PF is the power factor of the load. ω_l is the angle speed of the load.

The input and output quantities of the matrix converter can then be represented as (3)

$$\begin{aligned} V_{gm} &= k \cdot PF \cdot V_{lm} \\ I_{lm} &= k \cdot PF \cdot I_{gm} \\ 0 &< k < 0.866 \end{aligned} \tag{3}$$

In (3), V_{gm} and I_{gm} are the magnitude of matrix converter voltage phase voltage and current amplitude on the generator side repsectively. V_{lm} and I_{lm} are the magnitude of the matrix converter voltage phase voltage and current amplitude on the load side. k is the voltage transfer ratio of the matrix converter.

From (3), it can be determined that the maximum voltage transfer ratio is decided by the power factor angle. Since from (2), the power factor angle of the load side cannot be controlled, it is important to investigate the load characteristics and choose the filter capacitor carefully before designing the system. In this paper, it is assumed that it must be designed to meet nearly unity power factor, PF ≈ 1.

B. Synchronous Reference Frame Transformation

The state-space equations (1) can be transformed to the synchronous reference frame with the q-axis aligned with the generator phase voltage of phase '1', resulting in the following equations, where $u_g = [e_{gq}^e \quad e_{gd}^e \quad v_{lm}]^T$ and $x_g = [i_{gq}^e \quad i_{gd}^e]^T$:

$$\begin{aligned} p x_g &= A_1 x_g + B_1 u_g \\ A_1 &= \begin{bmatrix} -R_g/L_g & -\omega_g \\ \omega_g & -R_g/L_g \end{bmatrix} \\ B_1 &= \begin{bmatrix} 1/L_g & 0 & -d_{gq}^e/L_g \\ 0 & 1/L_g & -d_{gd}^e/L_g \end{bmatrix}^T \end{aligned} \tag{4}$$

In (4), ω_g is the electric angle frequency of the generator. d_{gd}^e and d_{gd}^e are the d and q axis duty ratio of the DBMC.

Assuming unity power-factor at the input, the steady-state operating point of the rectifier can be obtained from (4) as

$$\begin{aligned} E_{gq}^e &= R_g I_q^e + \omega L_g I_d^e + D_{gq}^e V_{lm} \\ E_{gd}^e &= R_g I_d^e - \omega_e L_g I_q^e + D_{gd}^e V_{lm} \end{aligned} \tag{5}$$

If unity power factor is controlled in the steady state, then equation (5) can be further simplified as

$$\begin{aligned} E_{gq}^e &= R_g I_q^e + D_{gq}^e V_{lm} \\ 0 &= -\omega_e L_g I_q^e + D_{gd}^e V_{lm} \end{aligned} \tag{6}$$

C. Controller design of generator side of the boost DBMC

The operation of the DBMC under the boost mode is similar to that of a three phase boost rectifier. The structure of the controller chosen is shown in Fig. 2. The control is similar to that of a high-performance active front end rectifier controller [7]. The current and voltage loop of this controller are all traditional PI controllers.

The voltage loop controller regulates the load side voltage amplitude by providing an appropriate q-axis current command to the inner current loop. To improve the dynamic response of the system, a load power feedback control is applied into the system. The load power is estimated from the measured load side current and voltage command.

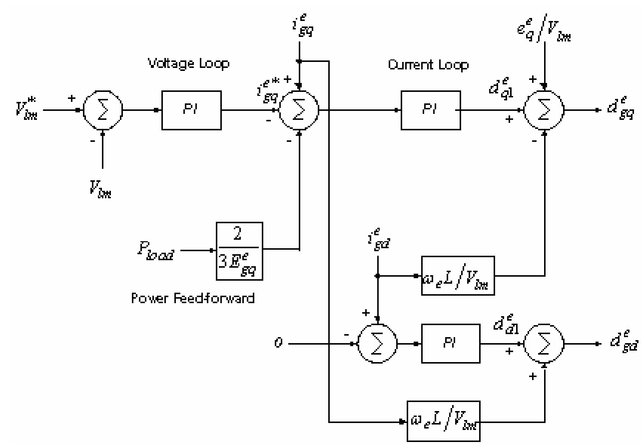


Fig. 2. Closed loop controller for the generator side

D. Operation of the DBMC under boost mode

The main objective of the control for the RL load side of the DBMC is to maintain a required constant voltage amplitude and frequency. Since the amplitude of this load can be regulated by the generator side automatically from the discussion above, it is only necessary to maintain a constant frequency in the RL load. Figure 3 shows the diagram of the space vector PWM of the DBMC under boost mode operation. The function of each block is illustrated as follows.

The voltage transformation block is used to transform the voltage command from the synchronous frame into stationary frame. The variables in this block is defined by (7)

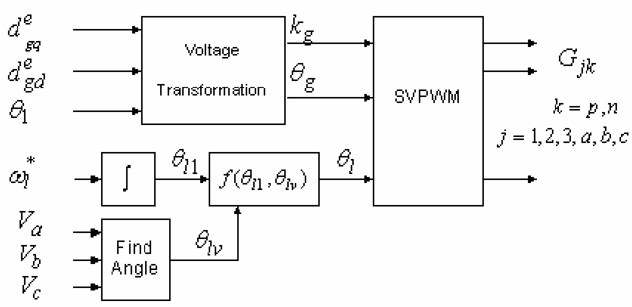


Fig. 3. Space vector PWM of DBMC under boost mode

$$
\begin{aligned}
k_g &= \sqrt{(d_{gq}^e)^2 + (d_{gd}^e)^2} \\
\theta_g &= \theta_1 + \arctan(\frac{d_{gd}^e}{d_{gq}^e})
\end{aligned}
\tag{7}
$$

In (7), k_g is the voltage transfer ratio of the DBMC. θ_g is the voltage reference angle of the DBMC at the generator side.

In Fig. 3, the current angle θ_l of the DBMC at RL load side is determined by the open loop current angle θ_l derived by expected load side frequency and voltage angle of the load side filter θ_{lv}, where

$$
\begin{aligned}
\theta_{l1} &= \int \omega_l^* dt \\
\theta_{lv} &= \angle(V_a + V_b e^{j\frac{2\pi}{3}} + V_b e^{-j\frac{2\pi}{3}})
\end{aligned}
\tag{8}
$$

To speed up the dynamic response and simplify the commutations of the DBMC, the power factor angle of the load side is determined to be less than $\pi/6$. Thus

$$
\theta_l = f(\theta_{l1}, \theta_{lv}) = \begin{cases} \theta_{l1}, & |\theta_{l1} - \theta_{lv}| < \pi/6 \\ \theta_{lv} + \pi/6, & \theta_{l1} - \theta_{lv} > \pi/6 \\ \theta_{lv} - \pi/6, & \theta_{l1} - \theta_{lv} < -\pi/6 \end{cases} \tag{9}
$$

In Fig. 3, the SVPWM block is to calculate the duty ratios and generate the gating signals for each switch in Fig. 1 (a). The similar PWM control of [1][2][3] can be used in this block.

E. Operation of induction motor load

The operation of the induction motor load is similar to the control of a DBMC under buck mode[1][2][3]. Where the input of the DBMC is the three phase filter voltage at the RL load side, the output of the DBMC is the three phase motor of the induction motor. The maximum voltage the induction motor load is determined by

$$
\begin{aligned}
V_{im} &= k \cdot PF \cdot V_{lm} \\
0 &< k < 0.866
\end{aligned}
\tag{10}
$$

From (10), the maximum voltage amplitude of the induction motor is 0.866·PF.

IV. SIMULATION RESULTS

The proposed topology of Fig. 1 (b) has been extensively investigated by a detailed simulation utilizing Simplorer©. In the simulation, all switches are represented as a ideal switches.

The voltage and current waveforms of the generator, DC link, RL load and induction motor side are obtained to test the feasibility of the proposed control method. The switching frequency of the converter was selected as 15kHz.

On the generator side, the PM generator was simplified as an ideal voltage source behind stator leakage inductance. Its parameters are

Maximum Line RMS Voltage: 184V
Rated power: 37.5KVA
Frequency: 400Hz
Leakage inductance: 0.2 per unit;

The parameters of the RL load side are

Filter capacitance: 15uF/45uF - Δ/Y
Resistance: 2.82Ω; Inductance: 75uH
Frequency: 600Hz; Rated Power: 19KVA
Line voltage command: 230V

The induction motor was also assumed to operate at the steady state and it is simplified as another RL load. Its parameters are

Resistance: 2.82Ω; Inductance: 100uH
Frequency: 450Hz; Rated Power: 19KVA

The waveforms of all three sets of terminals are shown from Fig. 4 to Fig. 11.

Figure 4 shows the line to line voltage waveform of the generator. Fig. 5 (a) shows the generator side voltage V_1 and current i_1 waveforms under steady state. Fig. 5 (b) shows the harmonic components and the total THD of the phase current. In Fig. 5 (a), it can be verified that the unity power factor on the generator side can be achieved. It can also be found from Fig. 5 (b) that the input THD is only 8% as a result of the high input frequency. The effectiveness operating DBMC under boost mode and the proposed control method can clearly be verified.

Figure 6 shows the expected and the calculated voltage amplitude of the RL load. From this figure, it can be found that the voltage amplitude of the RL load side voltage can be controlled effectively with the proposed control scheme.

Figure 7 shows the DC link voltage of the converter, it can be seen clearly that the DC link voltage remains positive in steady state. However, it was shown in the simulation that it can become negative and short the diode of generator side inverter in transient state. To solve this problem, future work will be required to address this issue.

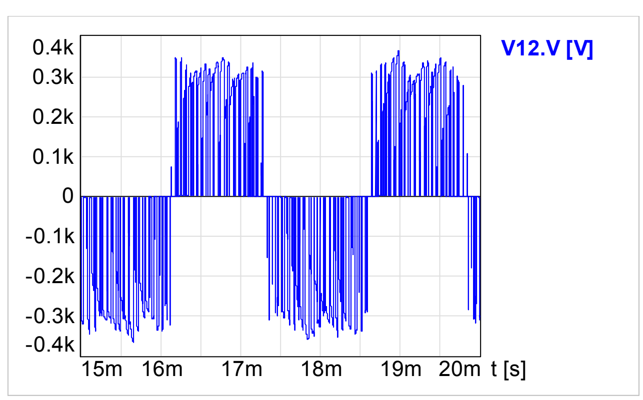
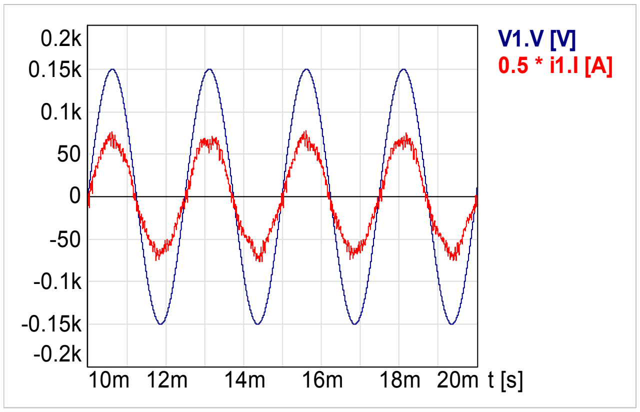
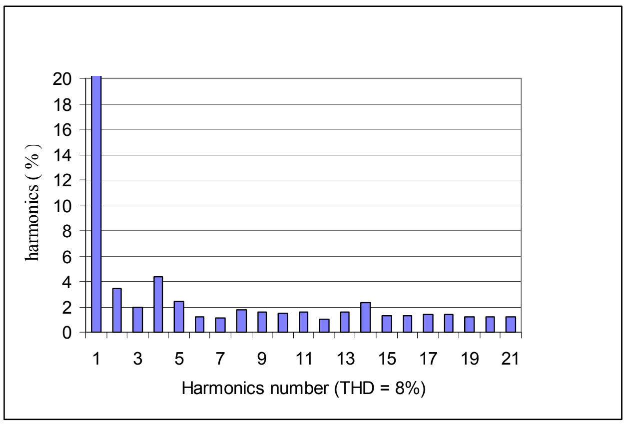


Fig. 4. Line voltage waveform of the generator



(a)



(b)

Fig. 5. Generator side voltage and current waveform (a) phase 1 current and voltage; (b) Harmonics component of the phase 1 current i_1

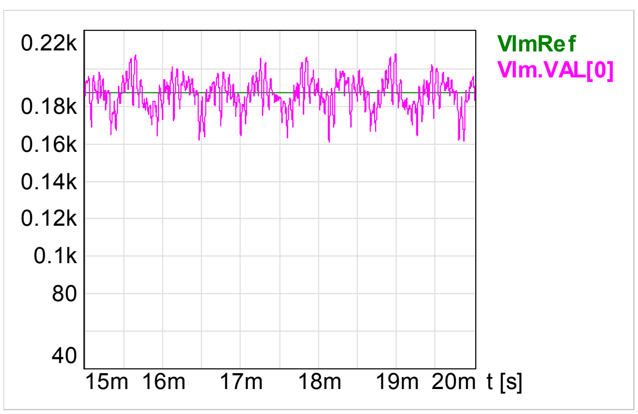


Fig. 6. RL load voltage command and the simulated voltage amplitude

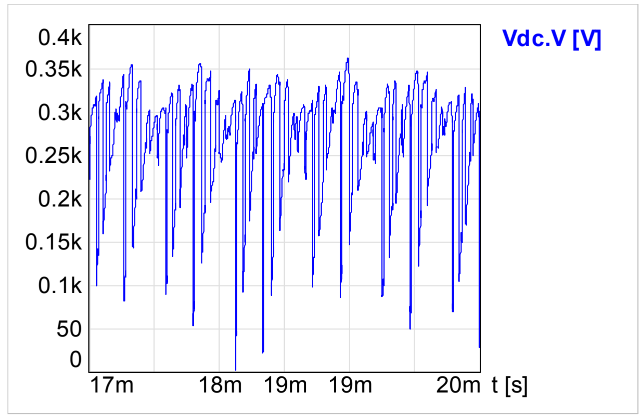


Fig. 7. DC bus voltage of the DBMC

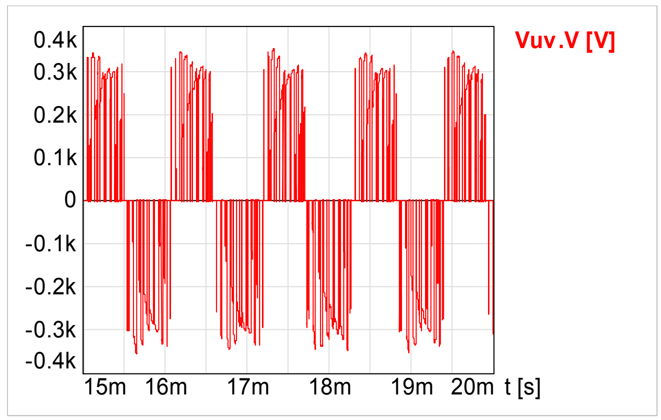


Fig. 8. Induction motor side line to line voltage

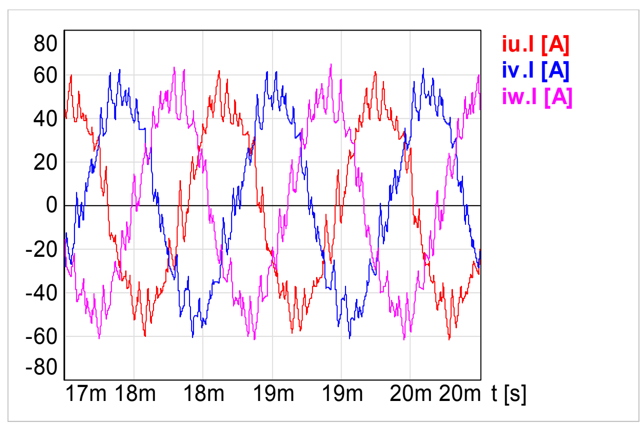


Fig. 9. Phase current of the induction motor

Figure 8 and Fig. 9 demonstrate the voltage and current waveforms of the induction motor. In Fig. 8, the line to line voltage of phase U and V are illustrated. In Fig. 9, the three-phase current is demonstrated. These two figures show that the induction motor load can be effective controlled with the proposed system configuration.

Finally, the waveforms of the RL load are shown in Fig.10 and Fig.11. Among them, Fig.10 shows the line to line voltage waveform of the RL load. Fig.11 (a) shows three phase current waveforms and Fig. 11(b) shows the THD of the phase A current. Because the existence of the capacitor in this side, it can be seen clearly from Fig.10 that the voltage waveform of the RL load is smooth with only small amount of voltage notches. This waveform is particularly suitable to support the loads that demand higher power supply quality. It can also be found from Fig. 5 (b) that the current THD of the RL load current is only 5.9% as a result of the high output frequency. As a result, the advantage of operating the DBMC under boost can be clearly verified.

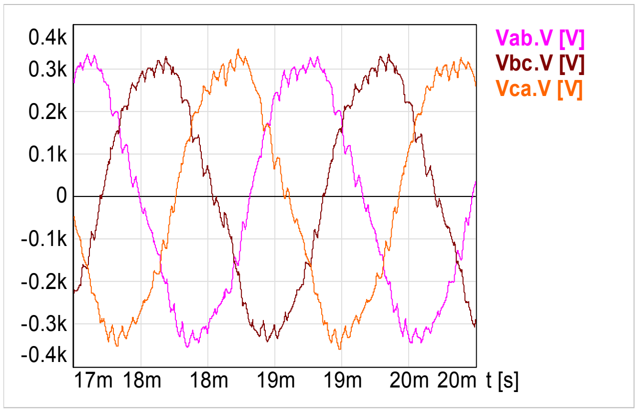
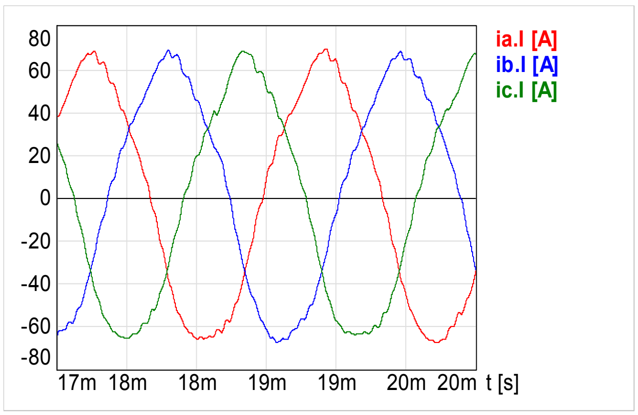
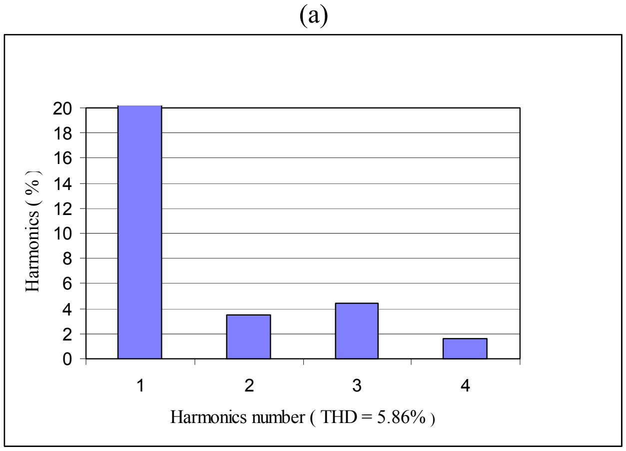


Fig. 10. Line to line voltage of the RL load



(a)



(b)

Fig. 11. Current waveforms of the RL load. (a) Three phase current; (b) harmonics components of phase a current

V. CONCLUSION

This paper investigates the possibility of operating the DBMC converter under boost mode. System analysis and simulation results show that this configuration has several advantages for a more compact system design.

1) The filter design is much simplified due to the fixed frequency of the load.

2) The input of the converter can operate over a wide range of input frequencies and voltages.

3) Higher frequency power conversion capacity with 10 times as high as current utility frequency.

4) It has the capability of providing two type of load with least number of energy storage components. One is the stiff voltage load with fixed amplitude and frequency; the other is a stiff current load with adjustable voltage and frequency. Moreover, it is also possible to be applied as multi-motor common DC bus applications [5].

5) Unity power factor can be achieved.

6) A bulky pre-charge circuit is not needed.

In the future, more detailed work on the DBMC under boost mode should be focused on the following,

1) Generating a robust commutation scheme for dynamic operation of the DBMC under boost mode.

2) A more elaborate controller design to improve both dynamic response and the RL load current THD of the system.

ACKNOWLEDGMENT

The authors like to express their special thanks to Richard A Lukaszewski from Rockwell Automation – Allen Bradley for his kind help with preparing this paper. The authors also wish to thank the Ansoft Co. for providing the Simplorer© software used to obtain the simulation results.

REFERENCES

[1] L. Wei and T.A. Lipo, "A novel matrix converter with simple commutation", *In Proceedings of 36th IEEE Industry Applications Society Conference. (IAS'2001), vol.3, pp. 1749-1754, Chicago, IL, USA, 2001.*

[3] J.W. Kolar, M. Baumann, et. al., "Novel three-phase AC-DC-AC sparse matrix converter", *In Proceedings of 17th IEEE Applied Power Electronics Conference and Exposition, APEC 2002, Vol. 2, pp. 777-791.*

[2] Lixiang. Wei and T. A. Lipo, "Matrix converter with reduced number of switches", *In Conf. Record of the IEEE PESC'2003, June, 2002.*

[4] M. Venturini , "A new sine wave in, sine wave out, conversion technique eliminates reactive component", in *Proc. POWERCON 7, 1980, pp. E3-1-E3-15.*

[5] Christian Klumpner and Frede Blaabjerg, "A new cost effective multi-drive solution based on a two stage direct power electronics conversion topology ," in *Proceedings of the IEEE IAS'2002 conference.* .

[6] Jie Chang, Anhua Wang, and Tom Sun, "VF-input and high frequency matrix converter – recent development and evaluation," in *Proceedings of IEEE IECON'2003 conference*.

[7] S. Hiti and D. Boroyevich, "Control of front-end three-phase boost rectifier," in *Proceedings of the Applied Power Electronics Conference*, pp. 927-933 1994.