Control Strategy of Single Phase Back-to-back Converter for Medium Voltage Drive under Cell Fault Condition

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***Abstract*— Cascaded H-Bridge (CHB) inverter is the most widely used topology for Medium Voltage (MV) drive system due to the high degree of modularity, easier implementation of medium output voltage, and ability to continuous operation under the cell fault condition. Because each power cell of CHB should have isolated DC source, multi-winding input transformer and three phase Active Front-End (AFE) are generally used for regenerative applications. The whole system can be reduced by replacing the three phase AFE with single phase AFE. However, input power imbalance among three phases under the cell fault condition inevitably occurs, if control strategy of normal operation is employed in system. This paper proposes a control scheme for the cell fault condition of single phase AFE CHB. Not only DC-link voltages of each cell but also grid current are regulated well without imbalance by applying the proposed control scheme to the system, even in the cell fault condition. Simulation and experimental results are provided to verify the effectiveness of the proposed scheme.**

Keywords*— Medium Voltage Drive, Single phase AFE, Cascaded H-Bridge, Fault operation, Current control, DC link voltage control

I. INTRODUCTION

One of the most widely used multilevel inverter topologies for Medium Voltage (MV) drive is Cascaded H-Bridge (CHB) inverter [1]. CHB inverter has several advantages such as high degree of modularity, easier implementation of medium output voltage with relatively low voltage components, low current harmonic distortion, and higher availability [2]. In addition, one of the most notable features of CHB topology is that it could be continuously operated under the cell fault condition by bypassing the faulty cell with external switch [3]. There have been several studies about modulation strategy of CHB inverter to keep the balanced line-to-line output voltage in the fault condition [4], [5].

Meanwhile, regenerative capability is required to several loads such as downhill conveyors and mill drives [6]. Generally, regenerative CHB consists of multi-winding input transformer and three phase Active Front-End (AFE). To reduce complexity of system and production cost, single phase back-to-back converter topology for MV drive was introduced [7]. As the topology is employed in regenerative system, it can reduce the number of secondary windings of input transformer to one-third and the number of legs per one power cell to four-fifth, compared with three phase AFE CHB. Structure of the cell used in single phase back-to-back converter is shown in Fig. 1.

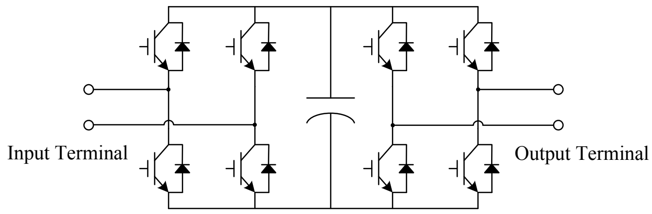

Fig. 1. Cell structure of single phase back-to-back converter

The DC link voltage control method of single phase back-to-back converter has been proposed [8]. With the method, under the cell fault condition, power imbalance among three phase input powers is inevitably invoked, because there should be lots of negative sequence current in grid, also malfunction of DC link voltage controller would occur. And, under cell fault condition, not only faulty cells but also healthy cells have to be shut down in order to make the number of cells per each phase the same. In this arrangement, the control method referred in [8] may be adopted at the severe cost penalty in the view point of cell usage. It means that, under the cell fault, output voltage range of single phase AFE CHB is severely reduced compared with three phase AFE CHB or three phase DFE CHB. To avoid this situation, a proper reconfiguration scheme after the cell fault should be devised. This paper proposes not only a novel reconfiguration scheme but also new DC link voltage control method for single phase back-to-back CHB converter system under the cell fault condition, extending its output voltage range as much as possible, simultaneously maintaining balanced DC link voltage of each cell, and keeping three phase grid current be balanced and sinusoidal.

II. RELATION BETWEEN CONVERTER CURRENT AND GRID CURRENT IN FAULT CONDITION

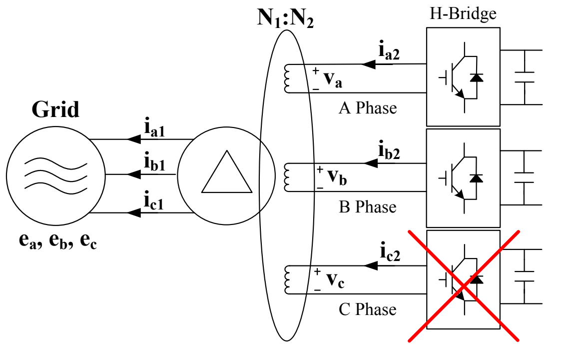

Fig. 2. Input transformer and grid side circuit of single phase AFE CHB

To simplify the analysis about the relation between converter current and grid current under the cell fault condition, it is assumed that there is just one cell per phase and the cell of C phase is faulty cell as depicted in Fig. 2.

N_1 and N_2 are the numbers of turns in the primary winding and secondary winding, respectively. In normal condition, relationship between grid current and converter current can be derived as (1), because primary winding consists of delta winding.

$$\begin{aligned} i_{a1} &= \frac{N_2}{N_1} i_{a2} - \frac{N_2}{N_1} i_{c2} \\ i_{b1} &= \frac{N_2}{N_1} i_{b2} - \frac{N_2}{N_1} i_{a2} \\ i_{c1} &= \frac{N_2}{N_1} i_{c2} - \frac{N_2}{N_1} i_{b2} \end{aligned} \quad . \tag{1}$$

As shown in Fig. 2, as input terminal of the faulty cell is disconnected from the grid source, there is no current path for i_{c2}. Equation (1) can be rewritten as (2), because cell input current of C phase becomes zero.

$$\begin{aligned} i_{a1} &= \frac{N_2}{N_1} i_{a2} \\ i_{b1} &= \frac{N_2}{N_1} i_{b2} - \frac{N_2}{N_1} i_{a2} \\ i_{c1} &= -\frac{N_2}{N_1} i_{b2} \end{aligned} \quad . \tag{2}$$

It is assumed that i_{a2} and i_{b2} are regulated as the same magnitude of sinusoidal waveform with phase delay of 60° between these two currents like (3).

$$\begin{aligned} i_{a2} &= I_m \cos(\omega t + \phi) \\ i_{b2} &= I_m \cos(\omega t - 60^\circ + \phi) \end{aligned} \quad . \tag{3}$$

Then, the grid currents i_{a1}, i_{b1} and i_{c1} can be represented as (4).

$$\begin{aligned} i_{a1} &= \frac{N_2}{N_1} I_m \cos(\omega t + \phi) \\ i_{b1} &= \frac{N_2}{N_1} I_m (\cos(\omega t - 60^\circ + \phi) - \cos(\omega t + \phi)) = \frac{N_2}{N_1} I_m \cos(\omega t - 120^\circ + \phi) \\ i_{c1} &= -\frac{N_2}{N_1} I_m \cos(\omega t - 60^\circ + \phi) = \frac{N_2}{N_1} I_m \cos(\omega t + 120^\circ + \phi) \end{aligned} \quad . \tag{4}$$

According to this equation, three phase currents of grid are regulated well as balanced three phase currents even in the cell fault condition, by controlling currents of remaining two phase cells as (3).

However, if only one power cell is left, such case as one more cell is out from Fig. 2, there is no way to make balanced three phase grid current. Therefore, in some cases of cell fault conditions, it could happen to turn off healthy cells. In that reason, to make use of maximum capacity of healthy power cells, reconfiguration of those cells is necessary. For example, in the case of CHB with 5 cells in series in a phase, if one faulty cell is in B phase and 2 faulty cells are in C phase as shown in Fig. 3.(a), then it can be denoted as 5-4-3 fault condition. Before the reconfiguration of healthy cells, normal operation pairs (A3, B3, C3), (A4, B4, C4), (A5, B5, C5) are ordinarily making three phase balanced voltage. The normal operation means the operation based on the control scheme proposed in [8]. A faulty pair (A2, B2) could make three phase balanced currents in grid by regulating current according to (3). Then, only one healthy cell, A1, should be shut down. Otherwise, it would result unbalanced grid current.

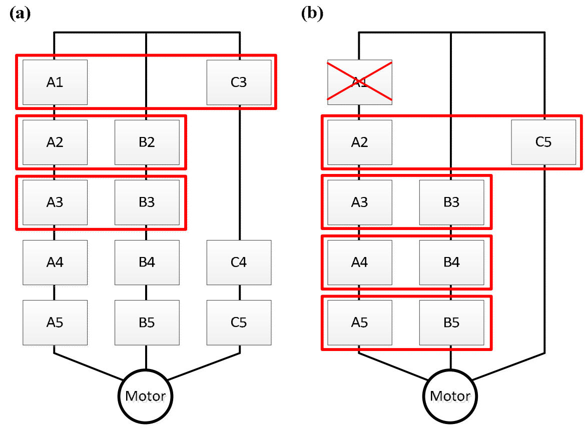

Fig. 3. Cell pairing example under (a) 5-4-3, (b) 5-3-1 fault condition

However, A1 cell could be matched to C3 cell and both cells work as a pair. Similarly, A2 and B2 work as a pair, and A3 and B3, as a pair. After reconfiguration such as shown in Fig. 3.(a), all healthy cells could be used. Because there is no electrical connection among the operation pairs such as (A3, B3, C3), cells could be easily reconfigured from original pairs to another pairs just by adjusting the magnitude and phase of their reference voltages.

In the case of 5-3-1 fault condition illustrated in Fig. 3.(b), there exists a cell, A1, which cannot make operation pair even after reconfiguration. In this case, healthy cell, A1, should be dropped out unavoidably.

III. Proposed Method

In single phase back-to-back converter, power consumptions of remained cells under fault condition are not the same according to the load condition. In case of the Fig. 2, cell power consumptions of A phase and B phase are different. In the worst case, one cell generates power and the other consumes power, simultaneously. Therefore, without proper DC link balancing control, DC link voltage difference between A and B phase should be getting larger and DC link over-voltage or under-voltage faults would happen. Accordingly, under cell fault condition, a DC link voltage control method should be devised, simultaneously keeping well-balanced three phase grid currents.

A. Definition of Active Current and Reactive Current

As described in section II, balanced three phase currents in grid side are guaranteed by regulating converter side current as

(3). Besides, that converter side current can be divided into two components as (5), similar with conventional d, q-axis currents [9].

$$\begin{aligned} i_{a2} &= I_{Pm}\cos(\omega t) + I_{Qm}\cos(\omega t - 90°) \\ i_{b2} &= I_{Pm}\cos(\omega t - 60°) + I_{Qm}\cos(\omega t - 150°) \end{aligned} \quad . \tag{5}$$

By the ratio of I_{Pm} and I_{Qm}, the phase angle of (3), ϕ, is determined.

As the first step of the definition, phase angles of grid phase voltage e_a, e_b, e_c are assumed to be fixed as 0°, -120° and 120°, respectively.

$$\begin{aligned} i_{Aa2} &= I_{Pm}\cos(\omega t°) \\ i_{Ab2} &= I_{Pm}\cos(\omega t - 60°) \end{aligned} \quad . \tag{6}$$

Then, active current is defined as (6). I_{Pm} is defined as the magnitude of active current. When it is changed into grid side, there would be balanced three phase currents which are in-phase with the grid phase voltage that can generate active power.

$$\begin{aligned} i_{Ra2} &= I_{Qm}\cos(\omega t - 90°) \\ i_{Rb2} &= I_{Qm}\cos(\omega t - 150°) \end{aligned} \quad . \tag{7}$$

Reactive current is defined as (7) which is quadrature to active current. And, I_{Qm} is defined as the magnitude of reactive current. When this current is changed into primary side, there would be balanced three phase currents which are quadrature to grid phase voltage that can generate reactive power.

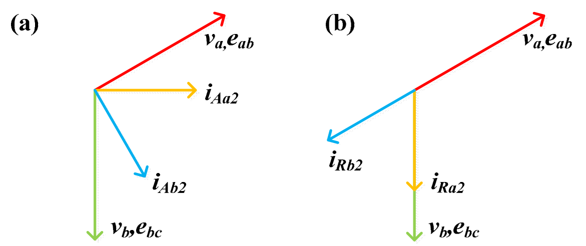

Fig. 4. Phasor diagram of (a) Active current (b) Reactive current

Finally, phasor diagram of active current and phase voltage is shown in Fig. 4.(a). e_{ab}, e_{bc} are grid line to line voltage and v_a, v_b are secondary side voltage as depicted in Fig. 2.

If the magnitude of grid phase voltage is E_m, magnitude of secondary side voltage is determined as $\sqrt{3}\frac{N_2}{N_1}E_m$. Referring the phasor diagram shown in Fig. 4, average power consumed by active and reactive current at each cell can be derived as (8) and (9), respectively.

$$\begin{aligned} P_{Aa} &= \frac{\sqrt{3}}{2}\frac{N_2}{N_1}E_m I_{Pm}\cos(30°) = \frac{3}{4}\frac{N_2}{N_1}E_m I_{Pm} \\ P_{Ab} &= \frac{\sqrt{3}}{2}\frac{N_2}{N_1}E_m I_{Pm}\cos(-30°) = \frac{3}{4}\frac{N_2}{N_1}E_m I_{Pm} \end{aligned} \quad . \tag{8}$$

$$\begin{aligned} P_{Ra} &= \frac{\sqrt{3}}{2}\frac{N_2}{N_1}E_m I_{Qm}\cos(120°) = -\frac{\sqrt{3}}{4}\frac{N_2}{N_1}E_m I_{Qm} \\ P_{Rb} &= \frac{\sqrt{3}}{2}\frac{N_2}{N_1}E_m I_{Qm}\cos(60°) = \frac{\sqrt{3}}{4}\frac{N_2}{N_1}E_m I_{Qm} \end{aligned} \quad . \tag{9}$$

As shown in (8), average power consumed by active current at phase A and B are the same. Therefore, the active current can be used to control the average DC link voltage of phase A and B. As shown in (9), the sum of two average power is zero, because their magnitudes are the same and signs are different. It means the reactive current cannot affect the average DC link voltage of phase A and B, but it can have influence on DC link voltage of each phase.

As the result, by adjusting active current and reactive current defined as (6) and (7), DC link voltages of each cell can be controlled to arbitrary value, still keeping three phase well-balanced current in grid side.

B. DC Link Voltage Controller

As a result of (8), (9), average DC link voltage of phase A and B can be controlled by regulating active current, and difference between DC link voltages of phase A and B can be suppressed by regulating reactive current.

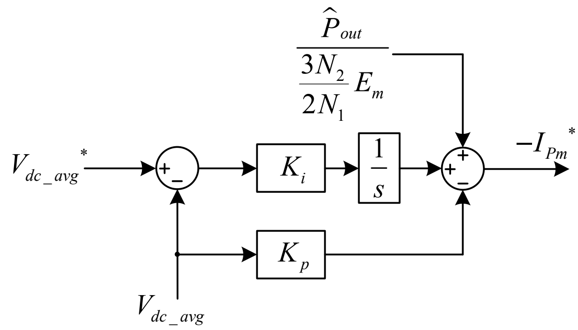

Fig. 5. Average of DC link Voltage controller

Average DC link voltage controller can be implemented by using IP (Integral-Proportional) controller to prevent overshoot of average DC link voltage as shown in Fig. 5. This controller can be presented as (10).

$$-I_{Pm}^{*} = -K_p V_{dc\_avg} + K_i \int (V_{dc\_avg}^{*} - V_{dc\_avg})dt + \hat{P}_{out} / \frac{3N_2}{2N_1}E_m \quad . \tag{10}$$

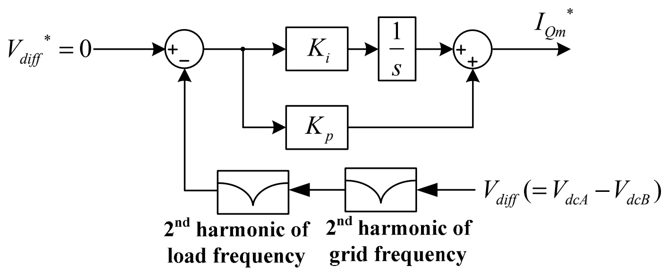

Fig. 6. DC link voltage balancing controller

DC link voltage balancing controller can be implemented by PI controller as shown in Fig. 6. This controller's purpose is to make $V_{dcA} - V_{dcB}$ be zero. However, the DC link voltages include second order harmonic components of the grid and load frequency, which cannot be regulated by the controller

[8]. Therefore, notch filters should be employed to eliminate second order harmonic components of the grid and load frequency. Besides, the controller can be presented as (11).

$$I_{Qm}^* = K_p(V_{diff}^* - V_{diff}) + K_i \int (V_{diff}^* - V_{diff}) dt \quad . \qquad (11)$$

C. Currernt Controller

Outputs of DC link voltage controller $-I_{Pm}^*$ and I_{Qm}^* are input of the current controller. Control block diagram of current controller is depicted in Fig. 7. Converter current i_{a2} and i_{b2} are transformed into I_{Pm} and I_{Qm}. And, the currents are regulated by a PI regulator. Contrary to the conventional three phase current controller, the feed-forward terms for compensating back EMF, v_a and v_b in Fig. 7, should be added after the re-coordinate transformation. The reason is, v_a and v_b have 120° phase angle difference, so they cannot be expressed on the coordinate system that A phase and B phase have 60° phase angle difference.

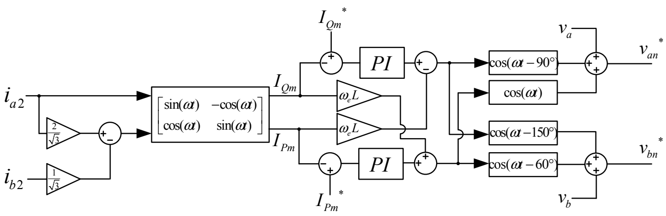

Fig. 7. Control block diagam of current controller

IV. Effect of Load Power Factor on Grid Current

By the definition of current and voltage symbols in Fig. 8 in case of 2-2-1 fault condition, phasor diagram of phase current and phase voltage through the load power factor can be drawn as Fig. 9.

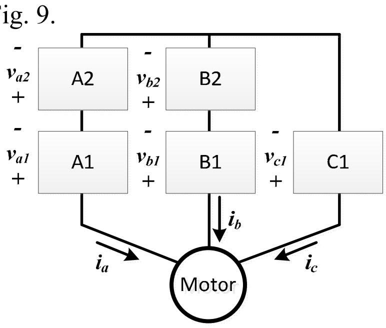

Fig. 8. Load operation under 2-2-1 fault condition

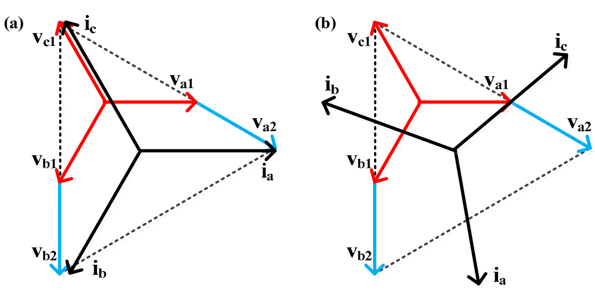

Fig. 9. Phasor diagrams of current and voltage by load power factor angle (a) 0°, (b) 80°

Red colored arrows are phase voltages to load made by A1, B1, C1 cells. They have 120° angle difference to each other. Therefore, regardless of load power factor, each cell always has the same power factor. That can be expressed with load power factor angle θ_L as (12).

$$\cos(\theta_{va1} - \theta_{ia}) = \cos(\theta_{vb1} - \theta_{ib}) = \cos(\theta_{vc1} - \theta_{ic}) = \cos(\theta_L) \ . \quad (12)$$

However, in fault operation, power factors of A2, B2, are different according to load power factor angle as (13).

$$\begin{aligned} pf_{A2} &= \cos(\theta_L - 30°) \\ pf_{B2} &= \cos(\theta_L + 30°) \end{aligned} \qquad (13)$$

When the load power factor angle is 0° or 180°, then A2 and B2 have the same power factor, but in other case they do not. Even load power factor goes to zero, difference between pf_{A2} and pf_{B2} is quite large. In case of $\theta_L = 80°$, as shown in Fig. 10.(b), $pf_{A2} = 0.643$ and $pf_{B2} = -0.342$ that cell A2 is supplying power to the load, but B2 is receiving power from that. In this condition, on the converter side of cells associated with load side, A2 and B2, there would be large reactive current for balancing DC link voltage of two cells and it would change d-axis current of grid. In other words, fault operation would affect power factor of the grid side too.

For an example, if an induction machine is driven with no load and it results in low load power factor, then the single phase back-to-back CHB system under fault operation, would have some reactive current in converter side and d-axis current in the grid. If there is current margin in normal operation pairs, because they have degree of freedom in d-axis current, normal operation pairs could compensate d-axis current which is made by fault operation pairs.

V. Simulation Results

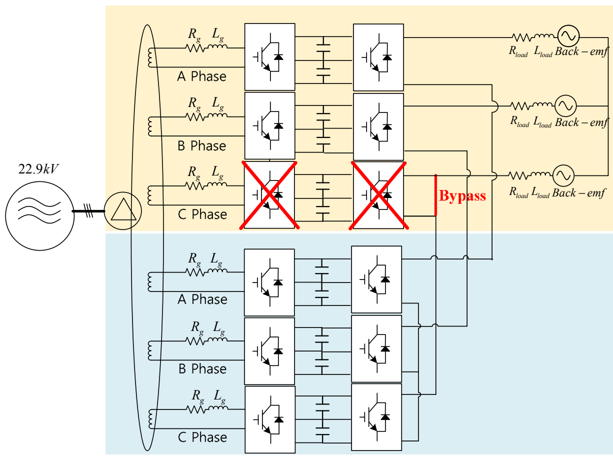

Fig. 10. Full structure of system

As shown in Fig. 10, simulation model is designed as 2-2-1 fault condition. It is assumed that upper C phase cell is out of the system due to fault. Experimental set also has the same structure, but parameters are different. On the other hand, this structure has one difference compared with Fig. 1. There are four legs in each cell combining input and output H-bridges. The legs are 2-level legs in case of Fig. 1, but in simulation and real experimental set, each leg is 3-level neutral point clamped leg. In this reason, there are two series connected capacitors as DC link of each cell. Therefore, input and output voltage of a cell is 5-level. At last, the model of the load is an induction motor drive system with V/f control.

TABLE I. GRID PARAMETERS

Capacity	*Line to Line Voltage*	*Frequency*	*Resistance*	*Inductance*
1.066MVA	22900V	60Hz	0.01p.u.	0.06p.u.

TABLE II. RATED LOAD CONDITION

Capacity	*Line to Line Voltage*	*Frequency*	*Pole number*	*Motor type*
0.833MW	4400V	60Hz	8 pole.	B type.

Structure is divided into one fault operation pair and one normal operation pair. Following the operation scheme in [3], maximum line to line voltage is 78.8% of rated line to line voltage. And, the induction motor is driven at 75% of rated speed, 45Hz. Switching frequency of each leg is 1620Hz. DC link capacitance is 900μF in total, and the reference of DC link voltage is set as 1900V.

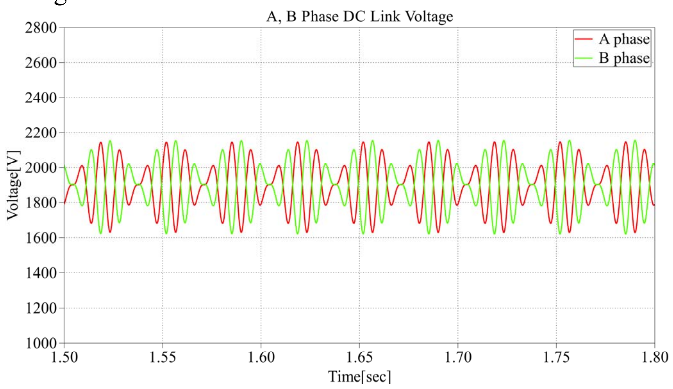

Fig. 11. DC link voltage of fault operation pair

In Fig. 11, it is revealed that the average DC link voltage is well kept as 1900V and ripples of DC link voltage are composed of 90Hz and 120 Hz frequency components which are two times of load and grid frequency. These ripples are not able to be handled by voltage controller because cell input and output structures are single phase.

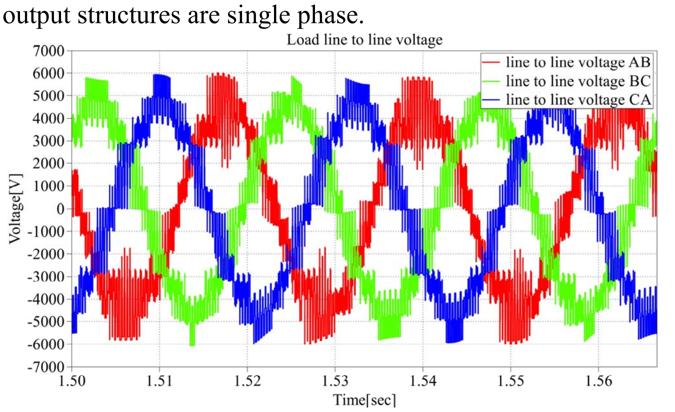

Fig. 12. Output line to line voltage of inverter

The line to line voltage to the motor is shown in Fig. 12. The voltages are well balanced and have 17 levels for AB phase, 13 levels for BC and CA phase. By Fourier transform, it is confirmed that the magnitude of fundamental frequency of Fig. 12 is 3292Vrms, almost 75% of rated voltage as expected.

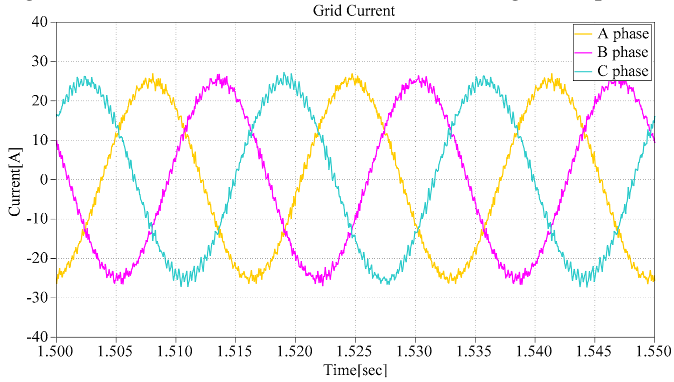

Fig. 13. Three phase well balanced grid current

In Fig. 13, it is shown that the grid current is well balanced sinusoidal waveform even under cell fault condition.

VI. EXPERIMENTAL RESULTS

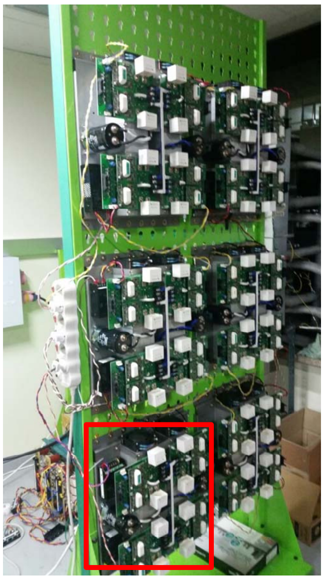

TABLE III. CONVERTER PARAMETERS

Parameters	*Value*
Number of Cell	6
Source Voltage	$127V_{rms}$
Cell input voltage	$110V_{rms}$
DC link Capacitance	1650μF
Rated Output Voltage	$440V_{rms}$
Rated frequency	60Hz
Switching frequency for one leg	2.5kHz
Rated Cell power	27kVA
Rated Converter power	162kVA

Fig. 14. Single phase back-to-back converter for induction machine drive

Experimental set is shown in Fig. 14 and the faulty cell is in the red box, so its input terminal is disconnected from grid and output terminal is bypassed. With remaining cells, left two cells are driven under fault operation and right three cells are driven with normal operation. Source voltage $127V_{rms}$ is changed into $110V_{rms}$ by transformer and there is no additional filter to reduce harmonics of grid current. Output of converter is connected to 11kW 4 pole induction motor. Load torque is produced by 20kW DC generator. M-G set under test is shown in Fig. 15.

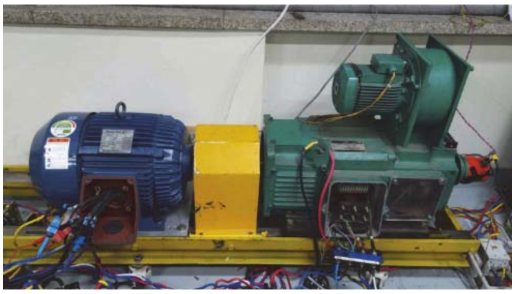

Fig. 15. Motor(left)-Generator(right) set for load test

DC link voltage of each cell is controlled as 200V and that of fault operation pair is shown in Fig. 16. As expected, there are some oscillations in the second order harmonics of 60Hz and 45Hz, which are grid and load frequency, respectively.

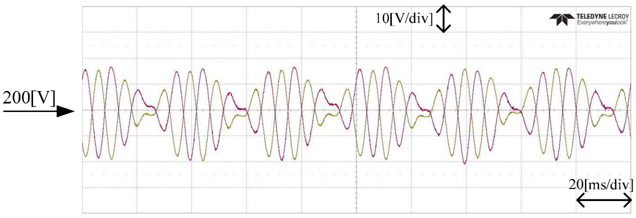

Fig. 16. DC link voltage of fault operation pair

Induction motor is driven with 45Hz, so the input line to line voltage is modulated as three-fourth of rated voltage as $330V_{rms}$. The voltage is depicted as Fig. 17. The well balanced multi-level line to line voltages are applied to the motor. Besides, load torque is 90% of rated value, so the power supplied from converter is totally 67.5% of rated power, which is about 7.5kW.

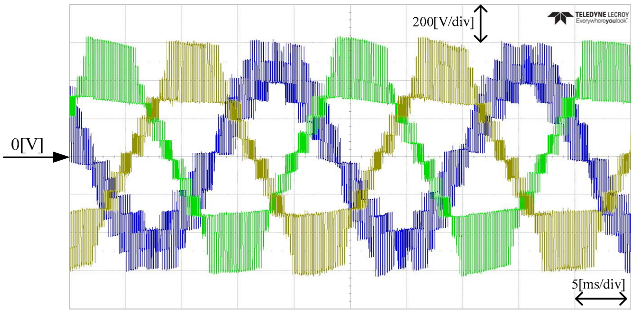

Fig. 17. Induction motor input line to line voltage

Finally, by the current controller, under the cell fault condition, three phase balanced current flows in the grid as shown in Fig. 18. There are some low order harmonics on the waveform because of impedance unbalance of input multi-winding transformer, however the harmonics are small enough to satisfy the grid code.

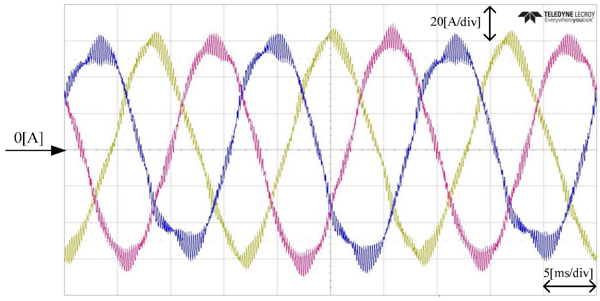

Fig. 18. Three phase grid current

VII. Conclusion

This paper has proposed a reconfiguration scheme for a single phase back-to-back CHB converter system driving a medium voltage induction motor under the cell fault condition. In fault condition, the power capability of the system would be smaller due to the reduced number of cells. However, by the virtue of the proposed reconfiguration scheme, the power capability can be extended as much as possible without turning off the healthy cells to make the number of operating cells in each phase the same. Accepting different number of cell in each phase, a balancing controller for DC link of each cell of each phase has been devised. Furthermore, a control scheme is proposed to make the grid current be balance and harmonic free. All control schemes are verified through full scale computer simulation and reduced size experimental tests. The results show well balanced DC link voltage of each cell and reasonably sinusoidal balanced grid current under cell fault.

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