A Hybrid Cascaded Multilevel Inverter Application for Renewable Energy Resources Including a Reconfiguration Technique

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***Abstract-* A hybrid cascaded multilevel inverter application for renewable energy resources including a reconfiguration technique is developed. The objective of this research is to propose an alternative topology of hybrid cascaded multilevel inverter applied to a low voltage dc microgrid in telecommunication buildings. The modified PWM technique is also developed to reduce switching losses. Also, the proposed topology can reduce the number of required power switches compared to a traditional cascaded multilevel inverter. A possible reconfiguration technique after faulty condition is also discussed. PSIM (PowerSim) and Simulink/MATLAB are used to simulate the circuit operation and control signal. A 3-kW prototype is developed. The switching losses of the proposed multilevel inverter are also investigated. By using the modified PWM technique and reconfiguration method, the proposed hybrid inverter can improve system efficiency and reliability. The proposed inverter efficiency is 97% under tested condition. The results show that proposed hybrid inverter topology is a promising method for a low voltage dc microgrid interfacing with renewable energy resources.**

I. INTRODUCTION

Renewable energy resources (RES) have had increasing penetration levels for grid connected distributed generation (DG) in recent years. Photovoltaic, micro-turbine, wind turbine and fuel cell put forward many promising applications with high efficiency and low emissions. Together with power electronics technologies, these have provided an important improvement for RES and DG applications; especially, a microgrid concept is introduced in [1] to provide more system capacity and control flexibility when several RESs with different electric behaviors are integrated in the same grid. The microgrid also offers extra degrees of freedom to optimize RESs connected to the utility grid; additionally, power quality requirements, system reliability and control flexibility would be achieved by using the microgrid concept as discussed in [2].

Data center or telecommunication buildings in Thailand normally consist of large nonlinear electronic loads; for instance, switching router units, personal computers (PC), monitors, lighting, and adjustable speed drives (ASD) for air conditioning system. The electrical system used in telecommunication equipment is a low voltage dc system with a dc voltage equal to –48 V. A single phase 220 V, 50 Hz electrical system is used for PCs, monitors, and lighting; whereas, three phase 220/380 V, 50 Hz is utilized for the air conditioning system. It is promising that a dc microgrid consisting of a photovoltaic panel as a RES, battery as an energy storage (ES), and a diesel generator set as a standby source is implemented so that net-zero energy for telecommunication building could be accomplished. The dc microgrid with superb quality distribution system for residential application have been proposed in [3], and the low voltage distribution system for commercial power systems with sensitive electronic loads have been investigated in [4]. For dc distribution in telecommunication buildings, a high power converter (about 100 kW) with high quality output voltage waveform, high efficiency, and single phase and three phase electrical system available is required.

Therefore, multilevel inverters are suitable for this application because a multilevel inverter can provide the high voltampere ratings; more specially, in renewable energy applications, a cascaded H-bridge multilevel inverter can be applied to interface a group of batteries, photovoltaic or fuel cells. As explained in [5], a cascaded multilevel inverter may have more potential than other multilevel topologies since input separated dc sources (SDCS) could be naturally interfaced to the multilevel inverter to provide higher output voltages with high quality waveforms. However, a cascaded multilevel inverter contains many power switches, and the number of power switches will depend upon the number of required output voltage levels. Consequently, higher switching losses will be traded off with output voltage

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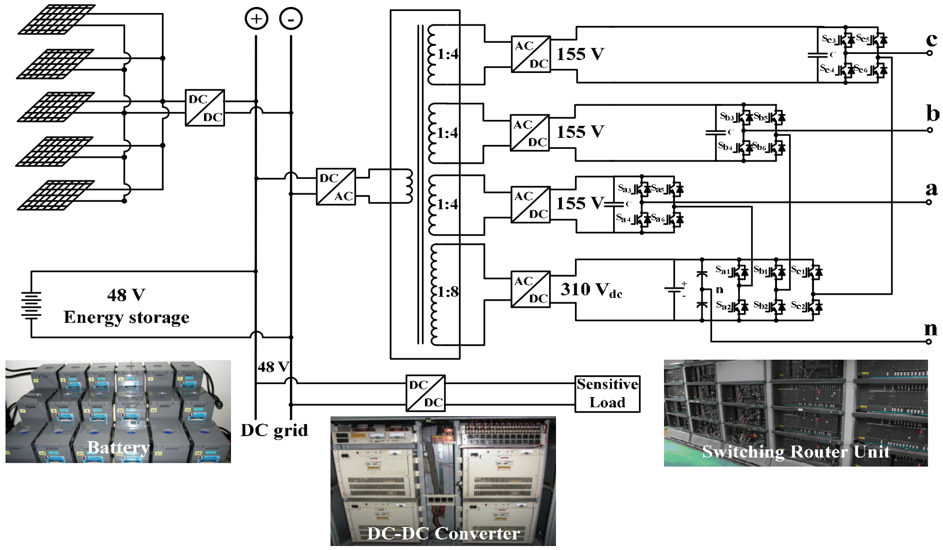


Fig. 1. Low voltage dc microgrid for telecommunication building.

quality. Multilevel inverter topologies for stand-alone PV systems have been discussed in [6]. The prototype in [6] shows that 96% efficiency at 3 kVA for a single phase inverter was achieved. It would be better if we could reduce the number of power switches in a multilevel inverter with the same functionality in order to reduce switching losses and improve inverter efficiency.

Thereupon, a hybrid multilevel inverter (HMI) is developed for a dc microgrid in telecommunication building as shown in Fig. 1. One can see that the proposed HMI can supply both single phase and three phase electrical system. As previously mentioned, three phase 220/380 V is supplied for an air conditioning unit and single phase 220 V is supplied for a lighting and PC load. The HMI consists of two types of inverter: a conventional three phase six switches inverter and a single phase four switches H-bridge inverter. HMI has been proposed with several applications as clearly explained in [7-10]; however, so far, the application for a telecommunication building with 48 V dc microgrid is limited. For this reason, a hybrid cascaded multilevel inverter application for dc microgrid in telecommunication building including a reconfiguration technique is developed to improve the system efficiency and reliability.

II. Proposed PWM Scheme

The *main inverter* refers to the six-switch three phase inverter, and the *auxiliary inverter* refers to the four-switch H-bridge inverter. Since low switching losses during PWM operation is required, the main inverter will operate in square wave mode, and the auxiliary inverter will operate in PWM mode as depicted in Fig. 2. In practice, if a single chip is used to generate the PWM signals, it normally has only one carrier signal with six PWM channels; nevertheless, the HMI requires 12 PWM channels for both the main and auxiliary inverter. Thereafter, the reference signal of sinusoidal PWM

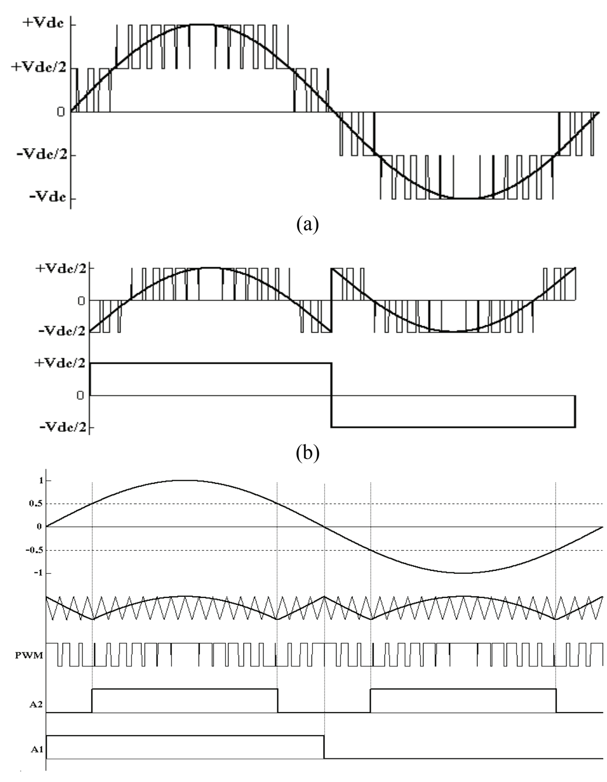


Fig. 2. Proposed PWM paradigm: (a) output phase voltage, (b) auxiliary and main inverter output voltages and (c) modulation signals of both main and auxiliary inverter.

(SPWM) used for the auxiliary inverter is modified by using equation (1)-(4). The multiplexing signals from (3) and (4) are used to synthesize a PWM signal by using the logic diagram as shown in Table I and Fig. 3. In this particular application, PIC18F4431 single chip is used to generate the PWM signals incorporated with a CPLD XC9536XL to fabricate the PWM signals for the proposed HMI.

$$f(t) = m_a \cdot \sin(\omega t) \tag{1}$$

$$\frac{T_P}{T_C} = \begin{cases} 2\left(f(t) - \frac{1}{2}\right) ; \frac{1}{2} \le |f(t)| \le 1 \\ 2\left(\frac{1}{2} - f(t)\right) ; 0 \le |f(t)| \le \frac{1}{2} \end{cases} \tag{2}$$

$$A_1 = \begin{cases} 1 \ ; f(t) \ge 0 \\ 0 \ ; f(t) < 0 \end{cases} \tag{3}$$

$$A_2 = \begin{cases} 1 \ ; |f(t)| \ge \frac{1}{2} \\ 0 \ ; |f(t)| < \frac{1}{2} \end{cases} \tag{4}$$

where $f(t)$ is a reference signal,
m_a is modulation index (0.0/1.0-1.0/1.0),
A_1 is a multiplexing signal #1,
A_2 is a multiplexing signals #2,
$\frac{T_P}{T_C}$ is pulse width of PWM (0.0–1.0).

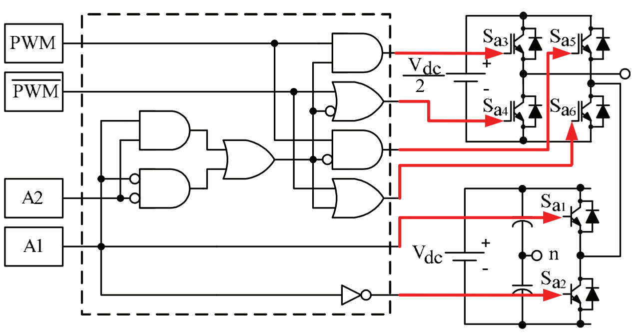


Fig. 3. Logic diagram for converter control signal.

TABLE I.
FABRICATED PWM SIGNAL FOR PROPOSED HYBRID MULTILEVEL INVERTER

S_n	Hybrid PWM mixing operator
S_{a1}	$A1$
S_{a2}	$\overline{A1}$
S_{a3}	$PWM \bullet ((A2 \bullet A1) + (\overline{A2} \bullet \overline{A1}))$
S_{a4}	$\overline{PWM} + \overline{((A2 \bullet A1) + (\overline{A2} \bullet \overline{A1}))}$
S_{a5}	$PWM \bullet \overline{((A2 \bullet A1) + (\overline{A2} \bullet \overline{A1}))}$
S_{a6}	$\overline{PWM} + ((A2 \bullet A1) + (\overline{A2} \bullet \overline{A1}))$

III. HYBRID CONVERTER SIMULATION

PSIM (Powersim) [11] and MATLAB/Simulink are utilized to create the simulation model. MATLAB/Simulink is used to simulate the control signals and PSIM acts as a hardware prototype. This simulation model could offer the simplicity of a changing control scheme and simple to transfer the control model from simulation to implementation in a single chip. Fundamental output voltages can be controlled by changing a modulation index (m_a) of the reference signal; also, the fundamental output frequency can be adjusted by changing the frequency of the reference signal.

The simulation results of the proposed hybrid multilevel

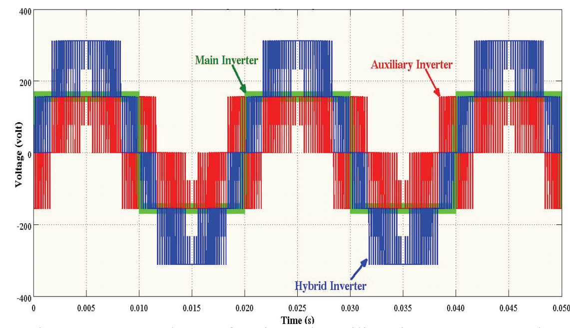


Fig. 4. Output voltage of main and auxiliary inverter operated at $m_a = 0.9/1.0$.

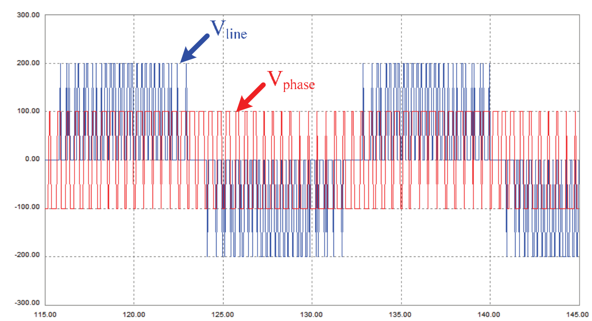


Fig. 5. Line to line and line to neutral output voltage of the hybrid inverter operated at $m_a = 0.48/1.0$.

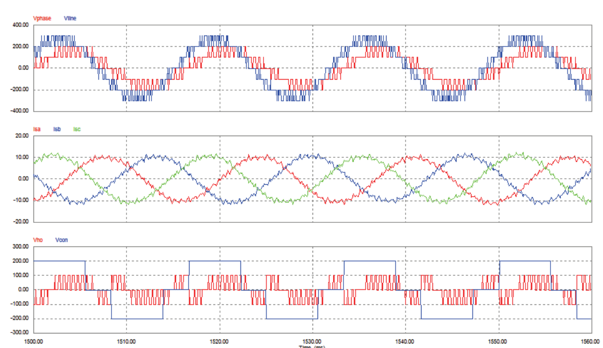


Fig. 6. Line to line and line to neutral output voltage and output current of the hybrid inverter operated at $m_a = 0.9/1.0$.

inverter are illustrated in Figs. 4-6. As can be seen, the simulation model can operate at different modulation indices. The simulation results for switching losses have been performed in [12] to compare between the conventional cascaded multilevel inverter and the proposed hybrid multilevel inverter. The simulation study in [12] shows that switching losses of the proposed HMI are less than the conventional cascaded multilevel inverter by about 26 % for a 3 kW load. This result illustrates that the system efficiency could improve by using the proposed HMI.

IV. Reconfiguration Technique

The neutral shift (NS) technique proposed in [13] can also be applied in HMI during a fault condition. The essence of NS technique is the adjustment angle of neutral point of three phase wye-connection system as shown in Fig. 7. Obviously, the line to neutral voltages (V_{an},V_{bn},V_{cn}) are not out of phase with each other by 120° as usual; however, the line to line voltages (V_{ab},V_{bc},V_{ca}) are balanced even though the auxiliary power cell on phase *b* is malfunctioning. The angles of reference signals to shift the neutral point under a fault condition at an auxiliary inverter in each phase can be calculated as follows:

A. Faulty auxiliary cell at phase a:

$$\theta_a = 60^\circ + \cos^{-1}\left(\frac{V_{an} \bullet \sin(30^\circ)}{V_{bn}}\right); \tag{5}$$

$$\theta_c = \theta_a; \tag{6}$$

$$\theta_b = 360^\circ - \theta_a - \theta_c. \tag{7}$$

B. Faulty auxiliary cell at phase b:

$$\theta_b = 60^\circ + \cos^{-1}\left(\frac{V_{bn} \bullet \sin(30^\circ)}{V_{cn}}\right); \tag{8}$$

$$\theta_a = \theta_b; \tag{9}$$

$$\theta_c = 360^\circ - \theta_a - \theta_b. \tag{10}$$

C. Faulty auxiliary cell at phase c:

$$\theta_c = 60^\circ + \cos^{-1}\left(\frac{V_{cn} \bullet \sin(30^\circ)}{V_{an}}\right); \tag{11}$$

$$\theta_b = \theta_c; \tag{12}$$

$$\theta_a = 360^\circ - \theta_b - \theta_c. \tag{13}$$

A calculated example of faulty auxiliary inverter at phase *b* is elucidated as follows:

$$\theta_b = 60^\circ + \cos^{-1}\left(\frac{120 \bullet \sin(30^\circ)}{150}\right);$$

$$\theta_b = 136.66^\circ;$$

$$\begin{aligned} &\theta_a = \theta_b = 136.33^\circ; \\ &\theta_c = 360^\circ - 136.66^\circ - 136.66^\circ; \\ &\theta_c = 87.34^\circ. \end{aligned} \tag{14}$$

One can see that the computational process is simple so that this reconfiguration method would be implemented in a single chip. It should be noted that this proposed reconfiguration can be only performed under a fault in the auxiliary inverter. If the fault occurs at the main inverter, all auxiliary inverters are bypassed; then, the conventional six switches fault tolerance technique could be used as discussed in [14]. Of course, the high quality output voltage waveform and full rated power operation can not be possible; however, the amount of reduction of the rated power and waveform quality that can be tolerated depends upon the HIM applications; nevertheless, in most cases a reduction of the rated power is more preferable than a complete shutdown. In this particular application, the HMI is used to supply the air conditioning system; therefore, the reduced power operation and waveform quality would be acceptable.

V. Experimental Setup and Results

The 3-kW prototype was developed by using IGBT (FAIRCHILD G20N60B30 40 A 600 V) in both the main inverter and in the auxiliary inverter. The multiple winding transformer with bidirectional ac-dc converter were used as SDCS for supplying dc voltages to the HMI. A 1-hp induction motor and R-L elements were used as a load to emulate an air conditioning compressor. A Yokogawa oscilloscope incorporated with a PC was used to perform a measurement unit. The experimental setup is shown in Fig. 8.

Experimental results illustrated in Fig. 9(a) shows the output line to neutral voltage and line output current of the proposed HMI operating at unity modulation index. As can be seen, the HMI can operate in PWM mode with an output current. The output voltages of main and auxiliary inverter

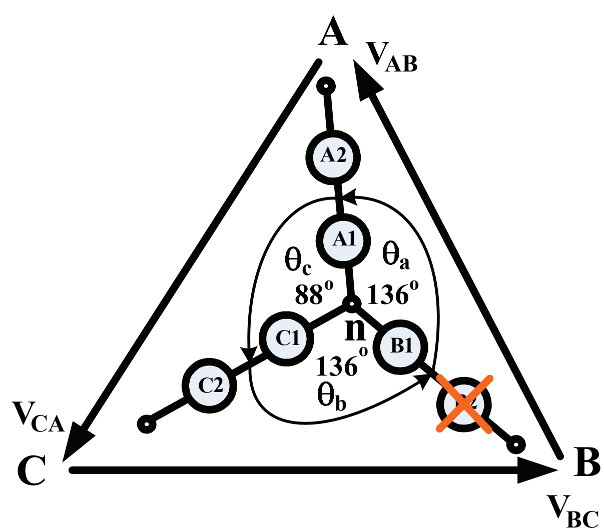
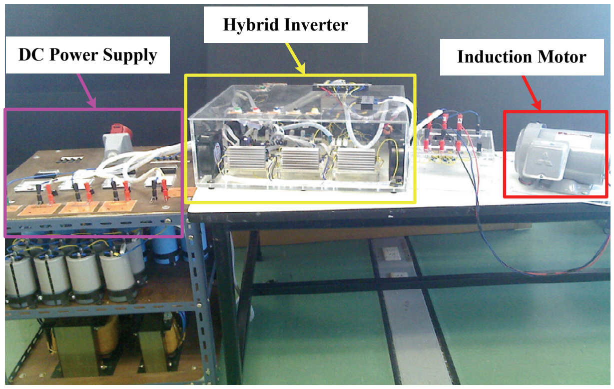
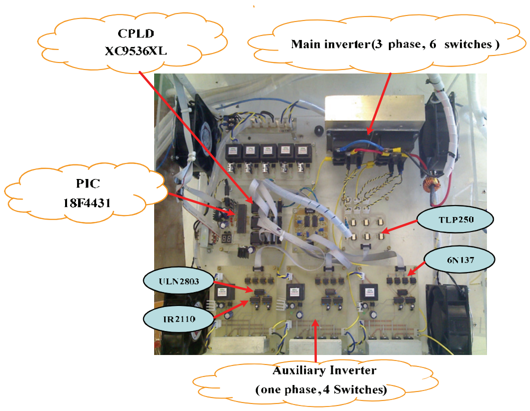


Fig. 7. The "neutral shift method [7]" for a reconfiguration technique.



(a)



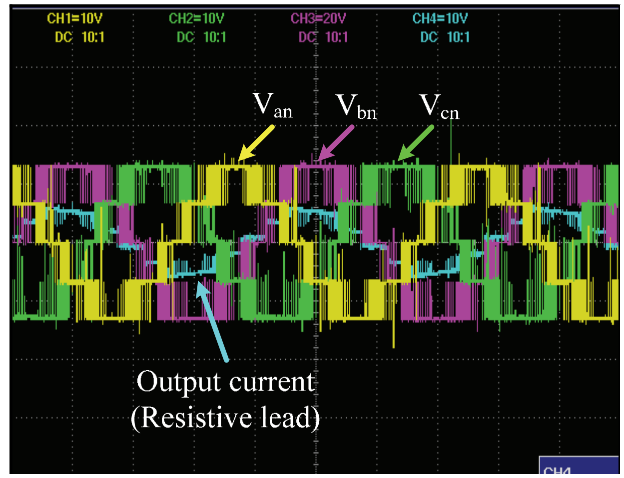
(b)

Fig. 8. Experimental setup: (a) connected with load and measurement unit, and (b) proposed hybrid multilevel inverter.

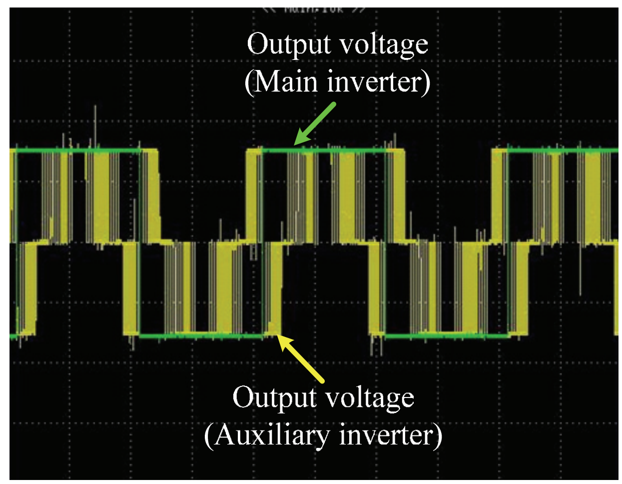
are depicted in Fig. 9(b). Clearly, the main inverter operates in square wave mode, but the auxiliary inverter operates in PWM mode. The output waveform quality in PWM mode is shown in Fig 9(c). The output voltages of the HMI with different m_a operation are shown in Fig. 10. One can see that the fundamental output voltage can be controlled by adjusting m_a; this implies that the HMI can also be applied in drive applications requiring *V/f* control mode.

The proposed HMI efficiency is evaluated as illustrated in Fig. 11 and Fig. 12. The voltage, current, and power waveform on the dc side are shown in Fig. 11, whereas the voltage, current, and power waveforms on the ac side are depicted in Fig. 12. The power consumption operating at unity modulation index on dc and ac side is summarized in Table II. The results show that the proposed HMI efficiency is about 97.33% in this particular load condition. As can be seen, the proposed HMI can be applied with renewable energy resources; more specially, when multiple separate dc sources is available. For instance, a battery or fuel cell can interface with main inverter and ultra capacitor or photovoltaic cell can also connect to auxiliary inverter.

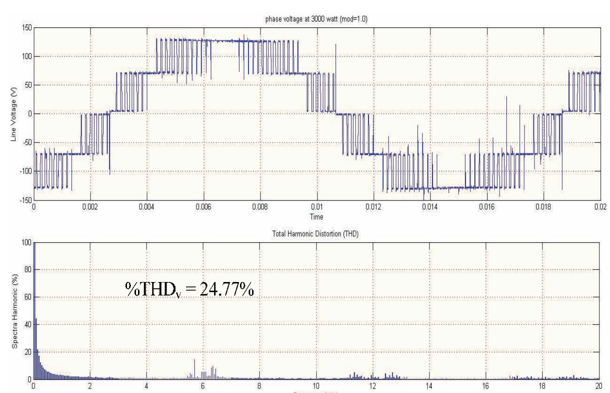
Fig. 13 shows the experimental results of the proposed HMI operating under faulty condition of auxiliary inverter at phase *b*. As can be seen, the waveform quality of output line



(a)



(b)



(c)

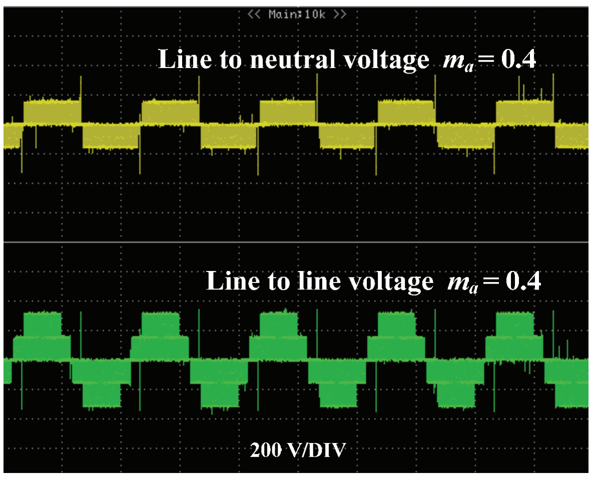
Fig. 9. Experimental results operating at m_a=1.0/1.0: (a) output line to neutral voltages and line current (b) output voltages of main and auxiliary inverter, (c) waveform quality of output voltage.

to neutral voltages and line to line voltages is distorted and unbalanced as depicted in Fig. 13(a) and (b). The deteriorated waveform quality and unbalanced line to line voltages due to auxiliary inverter at phase *b* failure are solved by using the reconfiguration technique as previously explained in section IV.

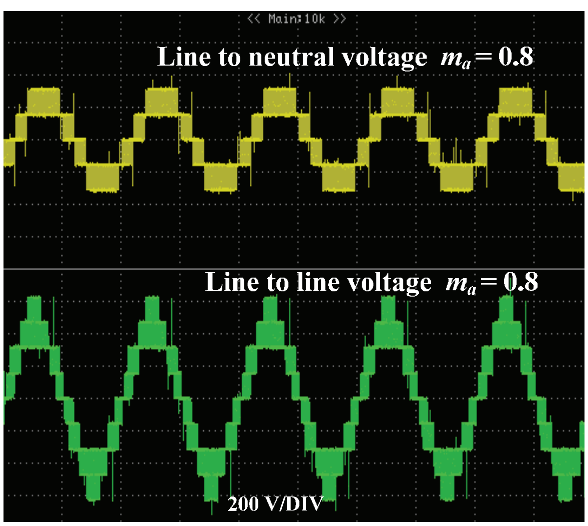
By utilizing the proposed HMI, a high quality output voltage waveform with high inverter efficiency and reliability can be achieved. In most cases, the HMI in renewable energy applications may not require a wide range of modulation indices; however, a wide range modulation index is needed for drive applications. Also, this HMI does require a half of dc input voltage of the main inverter supplying to the auxiliary inverter in order to achieve balanced output voltages.

TABLE II.
EFFICIENCY EVALUATION OF PROPOSED HYBRID MULTILEVEL INVERTER

Description	dc side		ac side	
	Main inverter	Auxiliary inverter	Main inverter	Auxiliary inverter
Voltage (V)	306.7	153.3	153.3	113.8
Current (A)	0.187	0.452	0.322	0.322
Power (W)	265.2		258.1	
Total losses (W)	7.1			
% losses	2.67 %			

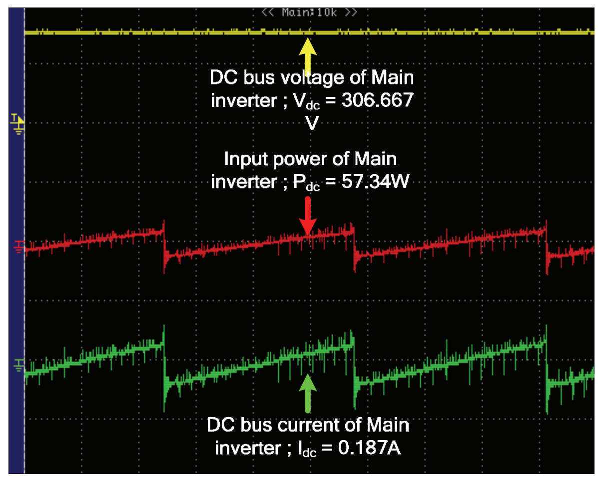


(a)

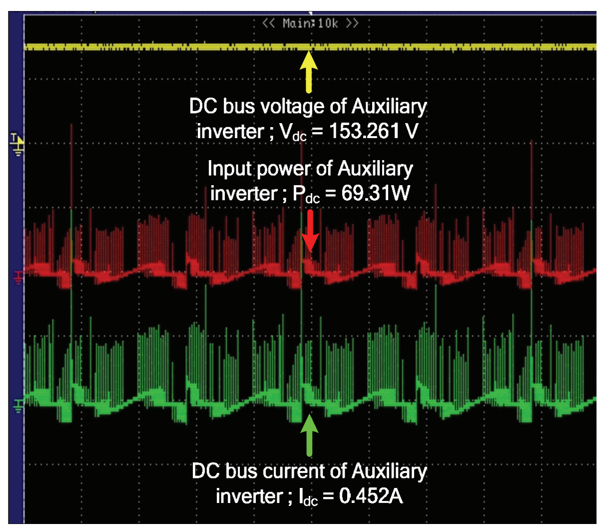


(b)

Fig. 10. Line to neutral and line to line voltage: (a) operating at $m_a = 0.4$, (b) operating at $m_a = 0.8$.

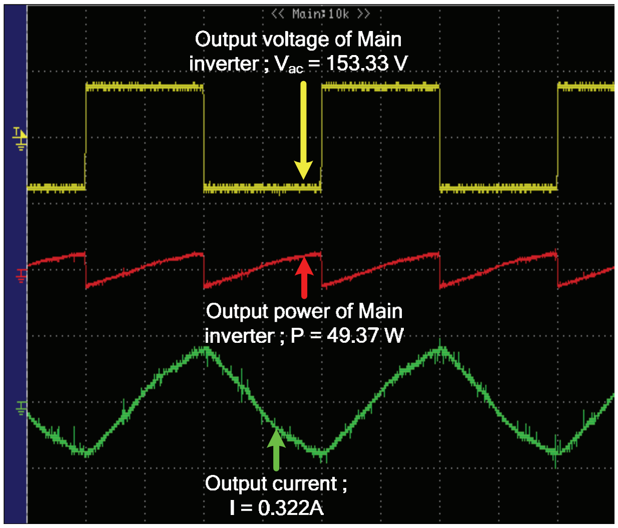


(a)

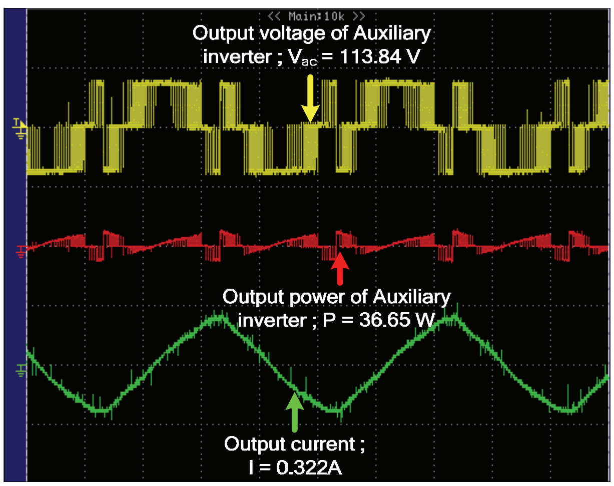


(b)

Fig. 11. Voltage, current and power waveform. operating at $m_a = 1.0/1.0$ on dc side: (a) main inverter, (b) auxiliary inverter.



(a)

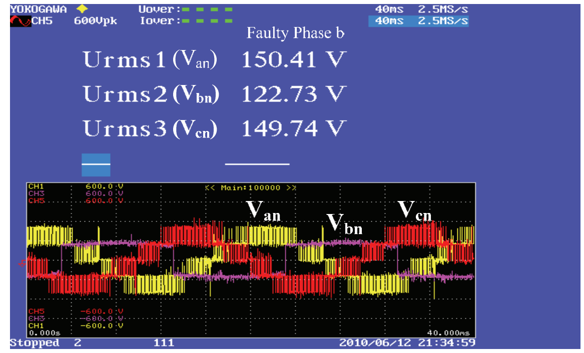


(b)

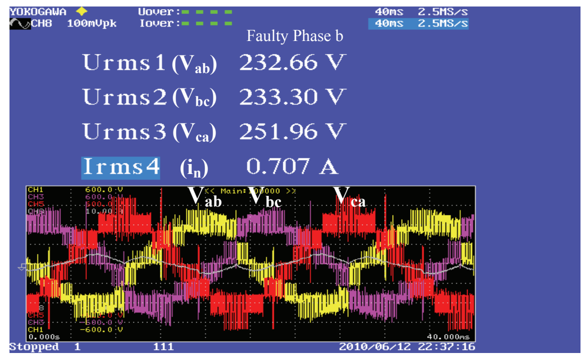
Fig. 12. Voltage, current and power waveform operating at m_a = 1.0/1.0 on ac side : (a) main inverter, (b) auxiliary inverter.

VI. Conclusion

The hybrid cascaded multilevel inverter application for renewable energy resources including a reconfiguration technique has been proposed. The modified PWM technique has also been developed to reduce switching losses. Also, the proposed topology can reduce the number of required power switches compared to a traditional cascaded multilevel inverter. Simulation and experimental results have been validated including efficiency evaluation. The switching losses of the HMI are less than the conventional multilevel inverter; consequently, the system efficiency would be improved by utilizing the HMI. In addition, 97.33% inverter efficiency has been achieved based on this particular load condition. A possible reconfiguration technique after a fault condition has also been developed to improve the system reliability. The results show that proposed hybrid inverter topology is a promising method for a low voltage dc microgrid interfacing with renewable energy resources in a telecommunication building.



(a)



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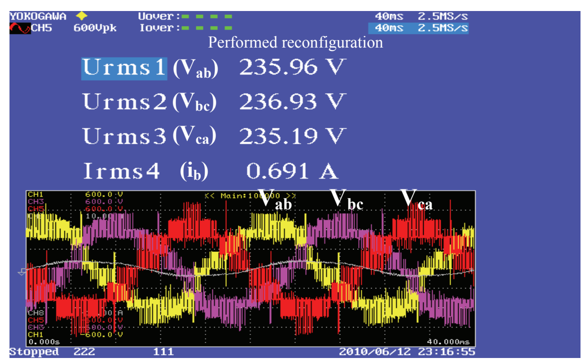

(c)

Fig. 13. Voltage and current waveforms showing: (a) Line to neutral voltages during fault at phase *b* condition, (b) Line to line voltages and neutral current during fault at phase *b* condition, (c) Line to line voltages and a line current after reconfiguration.

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