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Applications of cascade multilevel inverters

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Abstract: Cascade multilevel inverters have been developed for electric utility applications. A cascade M-level inverter consists of (M-1)/2 H-bridges in which each bridge's dc voltage is supported by its own dc capacitor. The new inverter can: (1) generate almost sinusoidal waveform voltage while only switching one time per fundamental cycle; (2) dispense with multi-pulse inverters' transformers used in conventional utility interfaces and static var compensators; (3) enables direct parallel or series transformer-less connection to medium- and high-voltage power systems. In short, the cascade inverter is much more efficient and suitable for utility applications than traditional multi-pulse and pulse width modulation (PWM) inverters. The authors have experimentally demonstrated the superiority of the new inverter for power supply, (hybrid) electric vehicle (EV) motor drive, reactive power (var) and harmonic compensation. This paper summarizes the features, feasibility, and control schemes of the cascade inverter for utility applications including utility interface of renewable energy, voltage regulation, var compensation, and harmonic filtering in power systems. Analytical, simulated, and experimental results demonstrated the superiority of the new inverters.

Key words: Cascade inverter, Multilevel inverter, Utility application, Power supply
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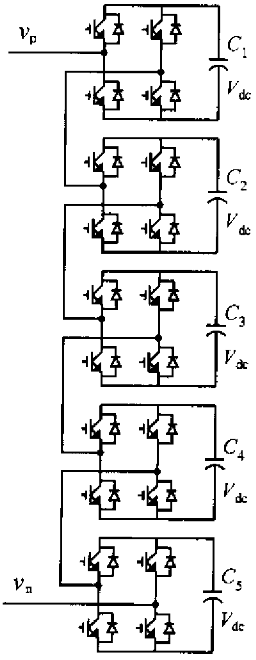
INTRODUCTION

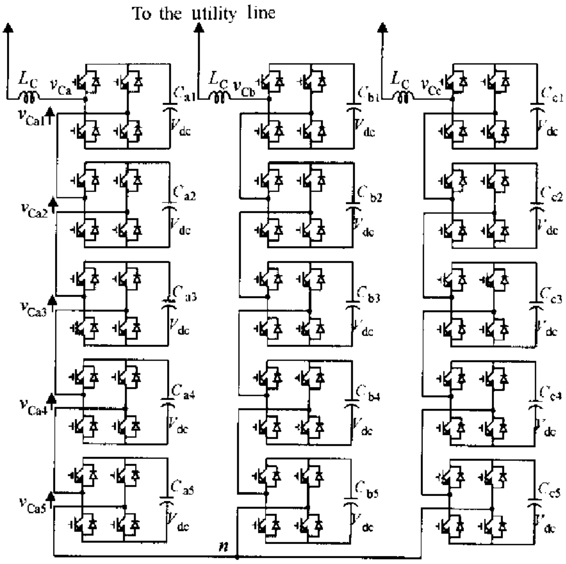
Recently, flexible alternating current transmission systems (FACTS), custom power, and power quality have been hot topics because of the increasing power demand, the widespread use of non-linear electronic equipment, and the higher power quality requirements of sensitive loads. To maximize power transmission capability and to provide high power quality at the point of common coupling (PCC) of a distribution system, power conditioning, including voltage regulation and reactive voltage-amperes (var)/harmonic compensation, is an indispensably necessary technology. Traditionally, a multi-pulse inverter consisting of several voltage-source inverters connected together through zigzag-arrangement transformers is used for renewable energy utility interfaces and var compensation (Schauder *et al*., 1994; Mori *et al*., 1992; Van Wyk *et al*., 1986; Walker, 1986; Fujita *et al*., 1995; Schauder, 1994; Seki and Uchino, 1994; Nakamori and Eguchi, 1994). These custom-built transformers are: (1) the most expensive equipment in the system; (2) produce about 50% of the total losses of the system; (3) occupy a large area of real estate, about 40% that of the total system; (4) cause difficulties in control due to dc magnetization and dc overvoltage of the inverters resulting from saturation of the transformers (Gyugyi and Strycula, 1976) and (5) prone to failure. Correspondingly, high switching frequency (about 10 kHz) PWM inverters have been used for harmonic compensation (Akagi *et al*., 1986; Peng *et al*., 1990; Peng and Lai, 1995, 1996a). However, the high initial and running costs have hindered its practical use in power distribution systems. The cascade multilevel inverters developed in (Peng and Lai, 1996b; Peng *et al*., 1997; Carpita and Teconi, 1991) had few components and were more suitable for utility applications than other multilevel inverters (Meynard and Foch, 1993; Hochgraf *et al*., 1994; Mohan and Kamath, 1995; Peng and Lai, 1997). The cascade M-level inverter consists of (M-1)/2 H-bridges, with each bridge's dc voltage being supported by its own dc capacitor. This multilevel inverter generates almost sinusoidal staircase voltage while switching only one time per line cycle, thus eliminating the required bulky transformers of the multipulse inverter based static var compensators (SVCs) and reducing the initial and running costs tremendously compared with the traditional PWM inverter. A prototype of a compensator (10 kVA) using an 11-level cascade inverter (21-level line-to-line voltage waveform) has been built for var and harmonic compensation. This paper summarizes the features, feasibility, and control schemes of the cascade inverter for voltage regulation, var compensation, and harmonic filtering in power systems. Analytical, simulated, and experimental results demonstrated the superiority of the new compensator.

CASCADE MULTILEVEL INVERTERS

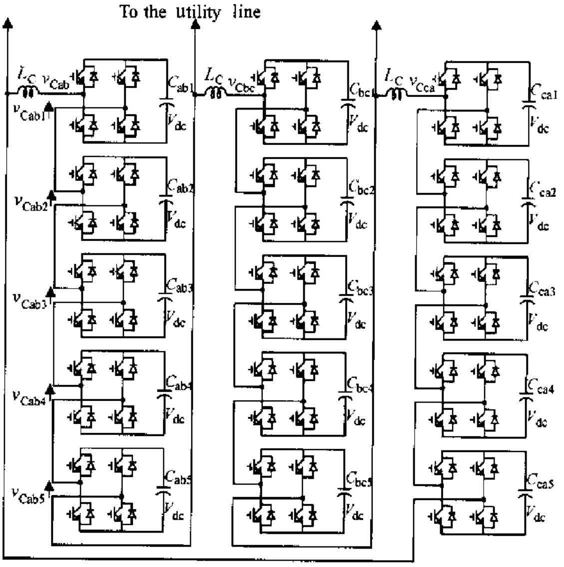
Fig. 1a shows the single phase 11-level cascade inverter. Figs. 1b and 1c show the Y-connected and △-connected 11-level cascade inverters respectively, where L_C serves as an interface inductor between the inverter and the utility line. As shown in the figures, the cascade inverter consists of a series of H-bridge inverter units for each phase. Fig. 2 shows waveforms of the Y-connected cascade inverter. Each H-bridge generates a quasi-square wave, P1 – P5, which sums up to the phase voltage, $v_{Ca\text{-}n}$, approaching its reference, $v^*_{Ca\text{-}n}$.



(a)



(b)



(c)

Fig.1 The 11-level cascade inverter for utility applications

(a) Single phase (b) Three-phase Y-structure (c) Three-phase △-structure

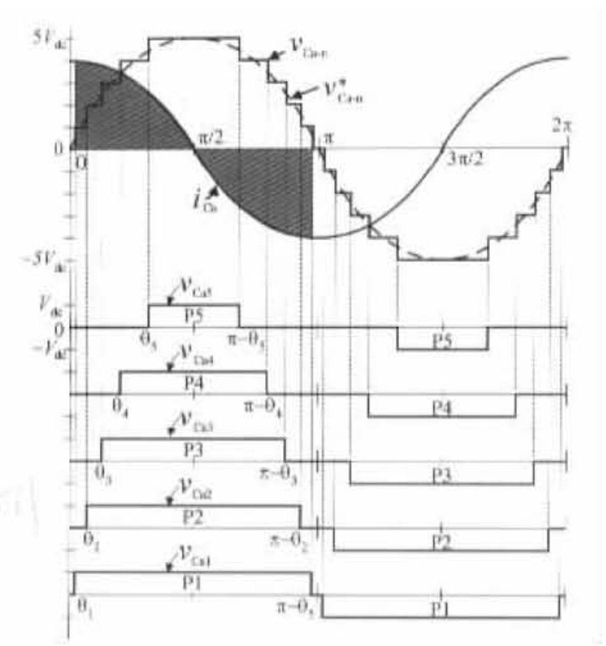


Fig.2 Waveforms of the 11-level Y-connected cascade inverter

CASCADE INVERTERS FOR POWER SUPPLY AND EV APPLICATIONS

1. EV traction motor drives

As can be seen from the structure, the cascade multilevel inverter is suited for EV traction motor drives. Fig.3 shows the system configuration of a 10 kW prototype and Fig.4 shows experimental results (Tolbert *et al.*, 1999). With fundamental frequency switching, the inverter produces an almost sinusoidal voltage with low EMI.

2. Premium (high quality) power supply

The cascade multilevel inverter provides the following features characterizing a high quality power supply:

1) Pure sinusoidal voltage possible with minimal LC filter requirements;

2) Extremely low voltage ripples and low EMI;

3) High speed response unlike the traditional

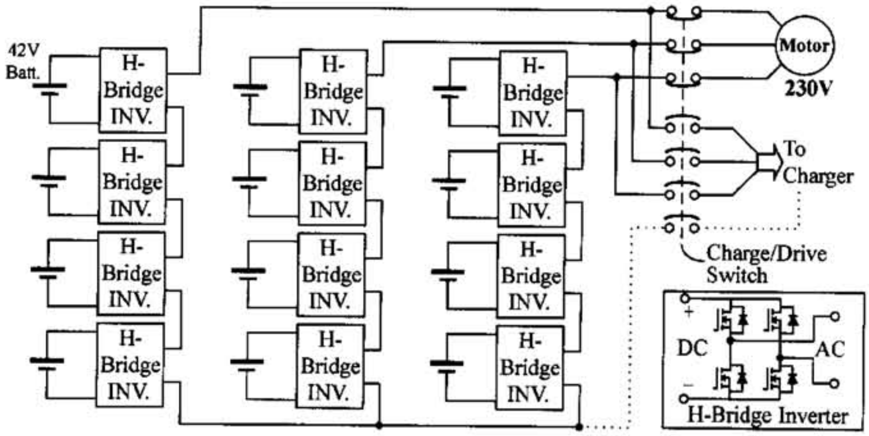
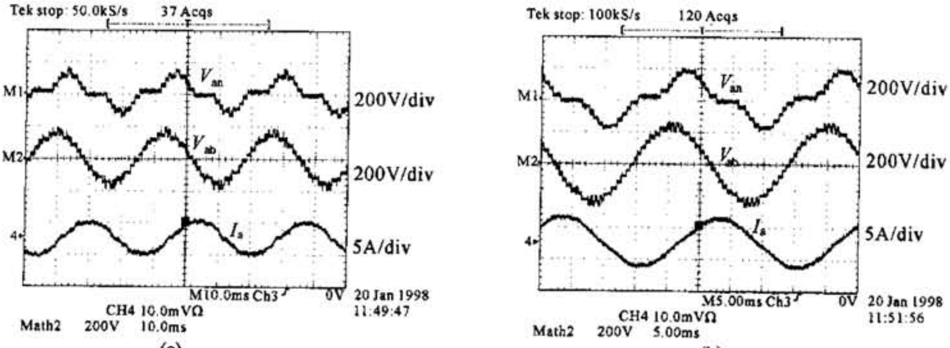


Fig.3 System configuration of an EV motor drive



(a) (b)

Fig.4 Experimental waveforms

(a) At 20% rated speed; (b) At 35% rated speed

PWM inverter with large LC filters that delay response and causes resonance;

4) High efficiency, compact size, and light weight.

CASCADE INVERTERS FOR UTILITY APPLICATIONS

1. Utility interface of renewable energy sources

As can be seen in the structure of cascade inverters, each H-bridge needs a separate or isolated dc source. This requirement makes the cascade inverter a perfect fit for utility interface of renewable energy sources such as photovoltaics or fuel cells where isolated dc sources naturally exist. Since the cascade inverter eliminates custom-designed transformers, a tremendous cost reduction can be expected.

2. Voltage regulation and phase shifting

Fig. 5 shows the system configuration of a cascade inverter for voltage regulation (restoration) and phase shifting. The cascade inverter is coupled in series with the power system and is controlled so that the output voltage, V_C, is shifted 90 degrees from the line current. In this way, the inverter can provide a stable sine-wave voltage to loads that are sensitive to voltage sags, swings and harmonics, or can provide phase shifting necessary for power flow control.

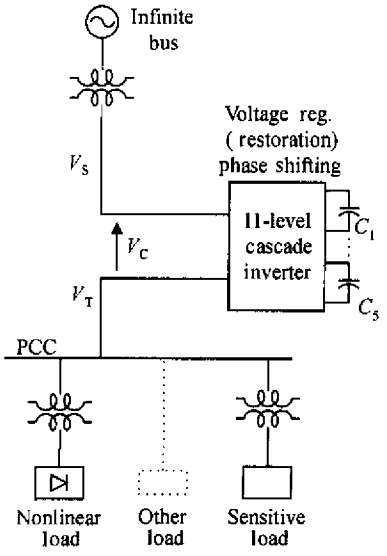


Fig.5 System configuration (series compensation) for voltage regulation (restoration), phase shifting, and harmonic isolation

3. Reactive power control and compensation

Fig.6 shows the system configuration for reactive power control and compensation. The cascade inverter is connected in parallel with the system and can be employed to (1) regulate the terminal voltage, V_T, and (2) compensate load reactive current through reactive power control.

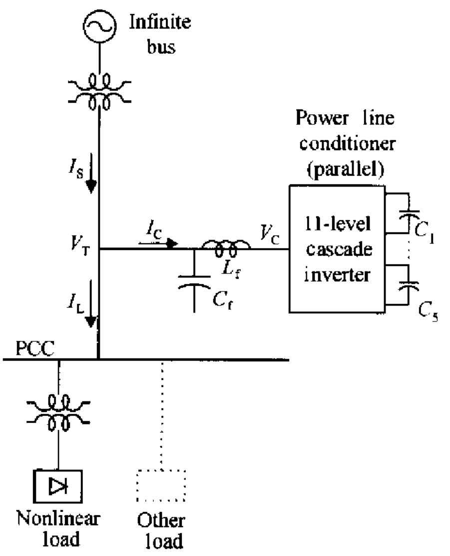


Fig.6 System configuration (parallel compensation) for var and harmonic compensation

4. Harmonic filtering

Both configurations shown in Figs. 5 and 6 can be used for harmonic compensation depending on harmonic source types and compensation objectives (Peng and Lai, 1995). Fig.5 is the series compensation structure for voltage-source nonlinear loads, voltage regulation, and can be used for harmonic isolation between the source and the load or between the upstream and the downstream. Correspondingly, Fig.6 is the parallel compensation structure for current-source nonlinear loads. Fig. 7 shows a combination of Figs.5 and 6 for series and parallel compensation.

5. Unified power flow control

Fig. 8 shows a configuration for unified power flow control by combining series cascade inverter and parallel cascade inverters (Peng and Wang, 2003). The series inverter produces the desired voltage for power flow control and the parallel inverters supply reactive current so that the resultant current flowing into the series inverter is reactive. As a result, only reactive current flows into the series and parallel inverter. Therefore, no additional power supply will be needed for either inverter.

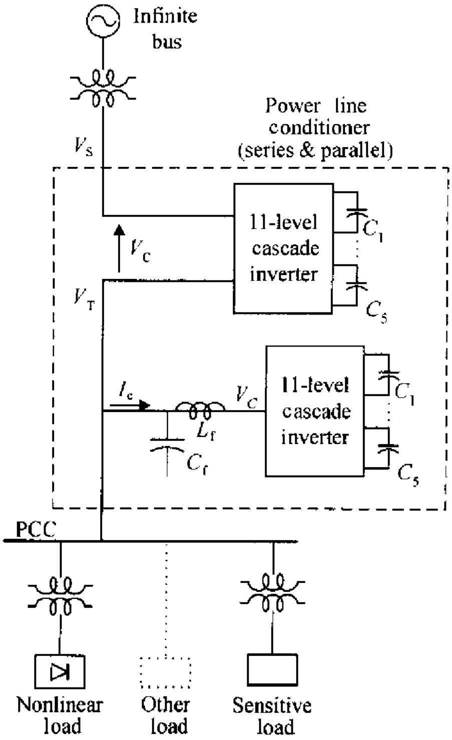


Fig.7 Combined system configuration for series and parallel compensation

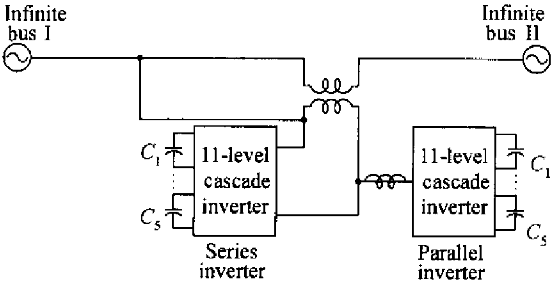


Fig.8 Combined system configuration of series and parallel connection for unified power flow control

CONTROL SCHEMES

Fig. 2 shows the waveforms of the Y-connected 11-level cascade inverter for var compensation. The output phase voltage v_{Ca-n} is the sum of the five H-bridge inverter units' outputs. The phase voltage magnitude is controlled by each inverter's duty cycle. For var compensation, the phase current, i_{Ca}, always leads or lags the phase voltage v_{Ca-n} by 90 degrees. The average charge to each dc capacitor is equal to zero over every half-line cycle for all pulses P1 to P5. In other words, the voltage of each dc capacitor is always balanced (Peng and Lai, 1996b; Peng *et al.*, 1997). Fig.9 shows the control block diagram for var compensation only. In the figure, a dc voltage control loop with inner loop is included to supplement power losses of the inverter so as to maintain a constant voltage for each dc level. However, there is voltage-balancing difficulty when the cascade inverter is applied to harmonic filtering. Fig. 10 shows the waveforms, where, for instance, a 5th-harmonic current needs to be absorbed by the inverter. In this case, as shown in the Fig. 10, an H-bridge inverter unit will be overcharged if it repeats pulse P5 and overdischarged if it repeats pulse P4. In order to overcome this problem, swapping pulses every half cycle as shown in Fig. 10 is proposed. Fig.9 shows the control block diagram. As a result, all dc capacitors will be equally charged and balanced. This pulse rotation provides several advantages to the inverter: (1) current ratings will be equalized among the H-bridges and (2) only one dc voltage needs to be monitored and fed-back, thus making control very simple.

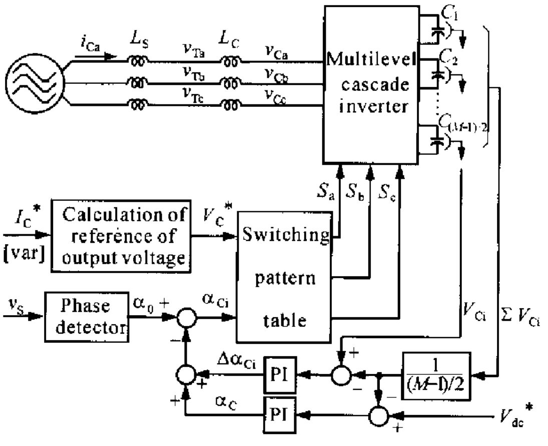


Fig.9 Control block diagram of the cascade inverter for var compensation

As shown in Figs.9 and 11, a voltage reference V_C^*, is needed to control the cascade inverter. Fig. 12 shows a control block diagram for generating V_C^* of a cascade inverter-based com-

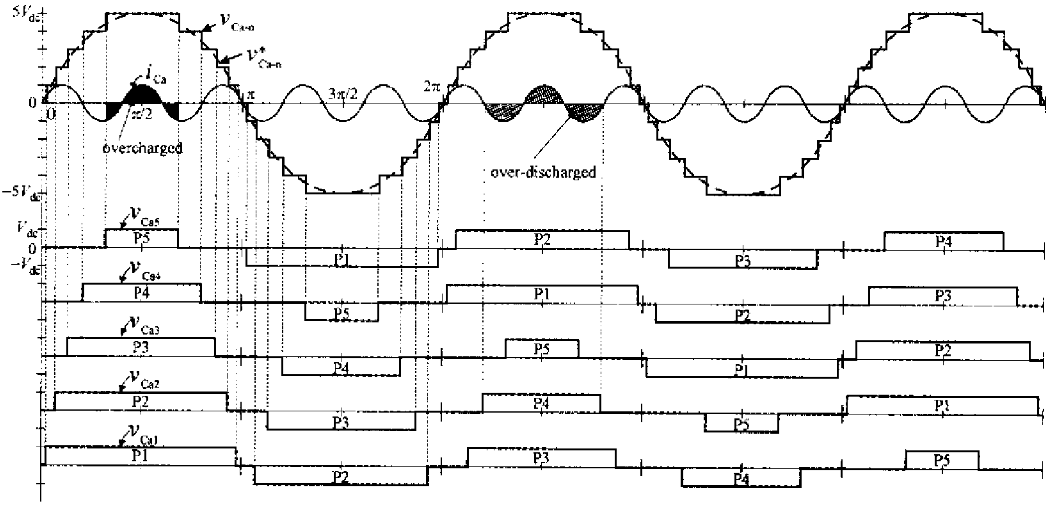


Fig.10 Waveforms of the cascade inverter for harmonic filtering

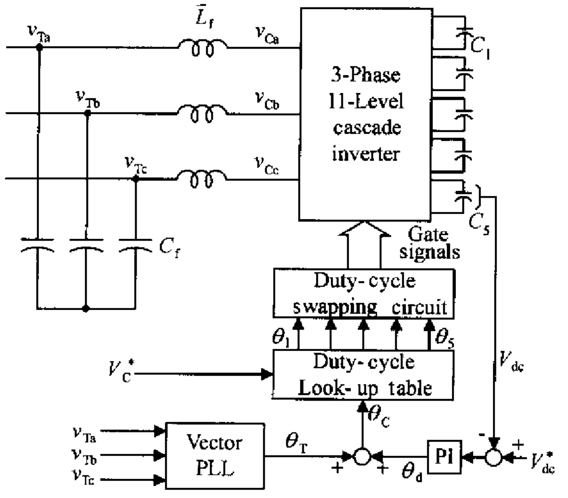


Fig.11 Control block diagram of the cascade inverter for harmonic and/or var compensation

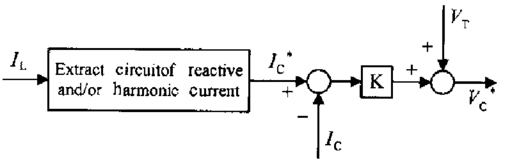


Fig.12 Control block diagram of cascade inverter-based compensator

pensator. To compensate for reactive and/or harmonic current, the load current I_L is sensed, and its reactive and/or harmonic components are extracted. The current reference, I_C^*, of the compensator can be the load reactive current component, harmonic component, or both depending upon compensation objectives. The cascade inverter has to generate a voltage V_C^* so that the compensator current I_C tracks the current reference I_C^*. V_T is the line voltage, and K is a gain. In a distribution system, the purpose of a power line conditioner is to provide a constant sine voltage to loads, where a constant sine wave is assigned to the voltage reference V_C. Because of limitation on pages, detailed theoretical analysis of the control strategies will be presented in another paper.

EXPERIMENTAL RESULTS

Figs. 13 and 14 show some experimental waveforms of the 11-level cascade inverter for var generation/compensation. In this case of Fig.6, only an interface inductor is connected between the terminal and the inverter. The line-to-line output voltage of the inverter is a 21-level staircase approaching the desired sine-wave. The line current is pure sinusoidal. The inverter can generate leading or lagging reactive power as commanded. Fig. 15 shows the dynamic response of the var compensator. The actual reactive power q_C follows the step-change command q_C^* within 2 ms, rapidly enough to cope with the fastest load change in a power system. Figs. 16 and 17 show waveforms before and after compensation

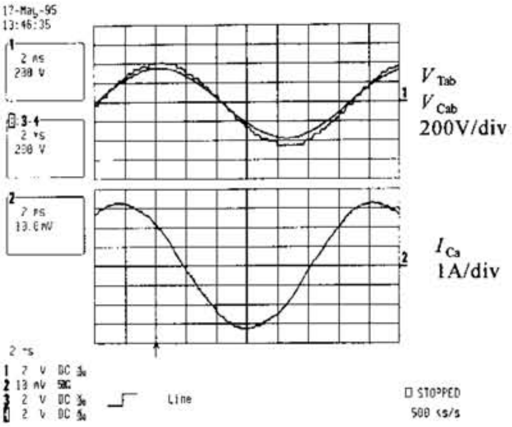


Fig. 13　Experimental results showing line-to-line voltages of the terminal and inverter，V_{Tab} and V_{Cab}，and line current，I_{Ca}，at leading 1 kvar output

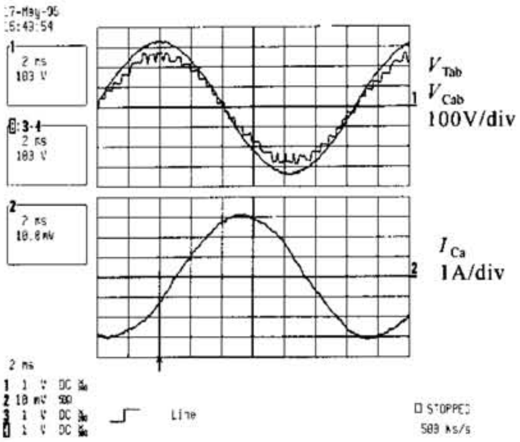


Fig. 14　Experimental results showing line-to-line voltages of the terminal and inverter，V_{Tab} and V_{Cab}，and line current，I_{Ca}，at lagging 1kvar output

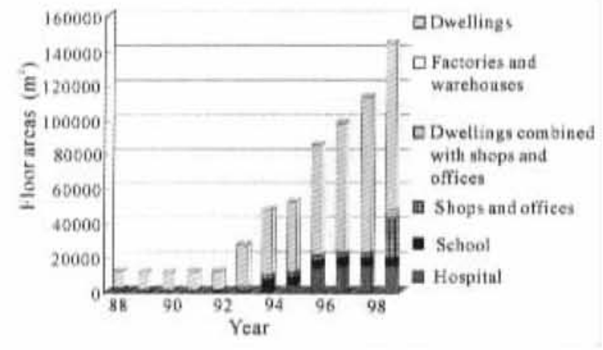


Fig. 15　Experimental waveforms of decoupling feedback control with a step change reference of the reactive current（or reactive power）

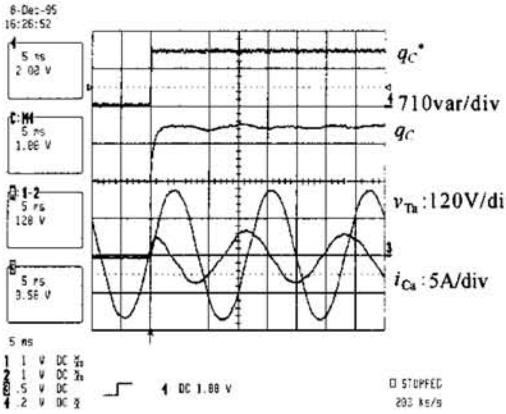


Fig. 16　Experimental waveforms of var and harmonic compensation（before the compensator was started）

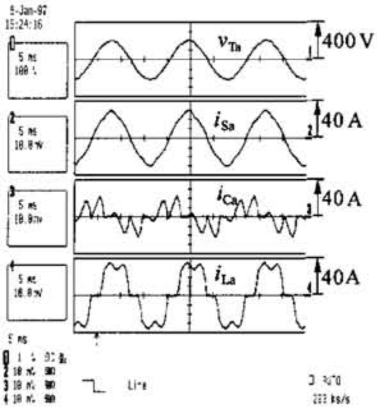


Fig. 17　Experimental waveforms of var and harmonic compensation（after the compensator was started）

respectively for both var and harmonic compensation at PCC. Before the compensator was started，both the terminal voltage，v_{Ta}，at PCC and source current i_{Sa} were distorted due to the nonlinear load. However，both the terminal voltage and source current became sinusoidal and in phase after the compensator was started.

CONCLUSIONS

A new multilevel voltage-source cascade inverter developed in Oak Ridge National Laboratory（Peng and Lai，1997）is presented for utility applications. The new inverter's desirable features are minimal components count and easy modularization and packaging，which solve the major problems of the conventional multi-pulse inverter, the diode-clamped multi-level inverter, and the flying capacitor multi-level inverter. The cascade inverter is especially suitable for EV motor drives, high quality power supplies, renewable energy interface, and FACTS applications including var/harmonic compensation, series compensation, phase shifting, and voltage balancing because each dc capacitor voltage can be self-maintained and independently controlled without additional dc sources. The superiority and validity for designing this novel multilevel voltoge source cascade inverter have been demonstrated through experimental and simulation results. This cascade inverter topology can be easily adapted to other applications, such as fuel cell and photovoltaic utility interfaces where the sources are naturally isolated dc sources. For these niched applications, the cascade inverter is very promising.

In summary, the new cascade multilevel inverter, (1) can eliminate the bulky transformers of a multi-pulse inverter, (2) can generate almost sinusoidal waveform voltage and current with only a single switching per fundamental cycle, and (3) has fast dynamic response. In addition, because of its modular and simple structure, the cascade inverter can be stacked up to a practically unlimited number of levels. These features make it the best candidate for medium-to high-voltage power system applications. This paper has summarized its main utility applications and controls. This cascade inverter had been shown to be suitable for many utility applications. The inverter costs less, has higher performance, less EMI, and higher efficiency than the traditional PWM inverter for power line conditioning applications. Simple control schemes are presented for reactive and harmonic compensation, which ensure dc voltage balance. Future use of Ultra-Capacitors makes the cascade inverter more attractive for wider utility applications.

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