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Multilevel Converters for Power System Applications

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Abstract: Multilevel converters are emerging as a new breed of power converter options for power system applications. These converters are most suitable for high voltage high power applications because they connect devices in series without the need for component matching. One of the major limitations of the multilevel converters is the voltage unbalance between different levels. To avoid voltage unbalance between different levels, several techniques have been proposed for different applications. Excluding magnetic-coupled converters, this paper introduces three multilevel voltage source converters: (1) diode-clamp, (2) flying-capacitors, and (3) cascaded inverters with separate dc sources. The operation principle, features, constraints, and potential applications of these converters will be discussed.

1. Introduction

Recently the "multilevel converter" has drawn tremendous interest in the power industry [1~12]. The general structure of the multilevel converter is to synthesize a sinusoidal voltage by several levels of voltages, typically obtained from capacitor voltage sources. The so-called "multilevel" starts from three levels. A three-level converter consists of two capacitor voltages in series with the center tap as the neutral [13]. Each phase leg of the three-level converter has two pairs of switching devices in series. To avoid unbalanced voltage sharing, the center of each device pair is clamped to the neutral by diodes. The waveform obtained from a three-level converter is a quasi-square wave output.

The diode-clamp method can be applied to higher level converters [6]. As the number of levels increases, the synthesized output waveform adds more steps, producing a staircase wave which approaches the sinusoidal wave with a minimum of harmonic distortion [14]. Ultimately a zero harmonic distortion of the output wave can be obtained by an infinite number of levels. More levels also mean higher voltages can be spanned by series devices without device voltage sharing problems. Unfortunately, the number of the achievable voltage levels is quite limited due to voltage clamping requirement, circuit layout, and packaging constraints. Computer simulation has been reported for a 21-level inverter for static var generator (SVG) applications [7]. However, hardware implementation has only been reported up to six-level for a back-to-back intertie application [9].

The diode-clamp method is not the only way to balance voltage sharing in series device connections. The magnetic transformer coupled multi-pulse voltage source converter is a well-known method and has been implemented in 18- and 48-pulse converters for battery energy storage and static condenser (STATCON) applications, respectively [15,16]. Problems of the magnetic transformer coupling method are excessive size and weight and non-characterized harmonics due to non-rational transformer turns ratio. The capacitor voltage synthesis method is thus preferred to the magnetic coupling method. There are three reported capacitor voltage synthesis based multilevel converters: (1) diode-clamp, (2) flying capacitors, and (3) cascading inverters with separated dc sources.

This paper will describe operating principles of the above-mentioned capacitor voltage synthesis multilevel converters. Based on the features and constraints of these multilevel converters, the application areas will be addressed. Typically different circuit topologies have their niche applications. Some applications may function better with current source converters. Apparently there exist current source dual circuit topologies to the voltage source multilevel converters which may be called "multi-branch converters." Discussions of these current source converters will be excluded from this paper.

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duty requires a different device rating. When the inverter design is to use average duty for all devices, the outer switches may be oversized, and the inner switches may be undersized. If the design is to suit the worst case, then there will be (m−1)×(m−2)/2 devices oversized.

2.2.3 Capacitor Voltage Unbalance

It can be seen from Table 1 and Fig. 2 that the inner two switches, S_{a4} (1 for all voltage levels except $-V_{dc}/2$) and $S_{a'1}$ (1 all voltage levels except for $+V_{dc}/2$), need to be turned on for a longer period than the outer two switches, S_{a1} (1 for $+V_{dc}/2$ only), $S_{a'4}$ (1 for $-V_{dc}/2$ only). When operating at unity power factor, the inner two capacitors, C_{s2} and C_{s3}, will be charged (for rectifier operation) or discharged (for inverter operation) more than the outer two capacitors, C_{s1} and C_{s4}.

Fig. 3 indicates that voltage level V_4 is charged by a positive current but never discharged, V_3 is charged in the positive half cycle and discharged in the negative half cycle, and V_2 is discharged by a negative current but never charged. In steady-state, the voltage across capacitor C_{s2}, V_4, will be increased to $+V_{dc}/2$ for rectifier operation or decreased to 0 for inverter operation, and the voltage across C_{s3}, V_2, will be decreased to $-V_{dc}/2$ for rectifier operation or increased to 0 for inverter operation. On the other hand, the voltage across the outer level capacitors, C_{s1} and C_{s4}, will be converged to 0 for rectifier operation or diverged to $\pm V_{dc}/2$ for inverter operation.

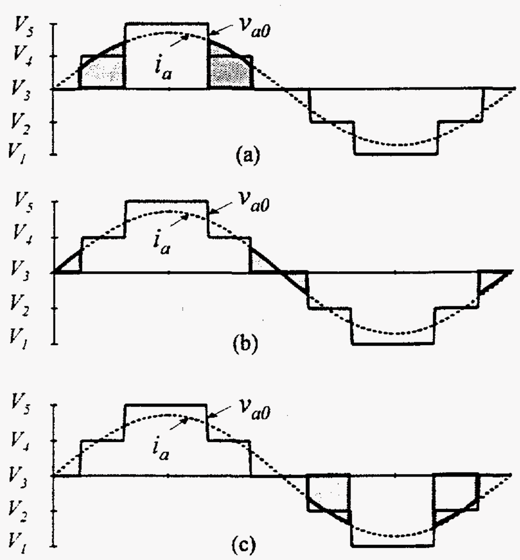


Fig. 3. Waveforms showing unbalanced capacitor charging profile (a) over-charging at V_4 level, (b) balanced charging and discharging of at V_{dc}, and (c) over-discharging at V_2.

The voltage unbalance problem in such a multilevel converter can be solved by a number of approaches such as replacing capacitors by a controlled constant dc voltage or by space vector modulation for balancing capacitor charging. The use of a controlled dc voltage will result in cost penalties and the complexity of the system. Using the space vector modulation or pulse-width modulation (PWM) method to control capacitor charging time is not favored because of excessive switching losses. With the high power nature in a power system, the converter switching frequency must be kept to a minimum to avoid switching losses and electromagnetic interference (EMI).

2.3 Applications

2.3.1 Reactive Power Compensation

When the converter draws pure reactive power, the phase voltage and current are 90° apart, and the charge and discharge of capacitors C_{s2} and C_{s3} will be balanced [2,4,5,8]. The converter, when serving for reactive power compensation, is called "SVG," one of the flexible ac transmission system (FACTS) devices.

The multilevel structure allows the converter to be directly connected to a high voltage distribution or transmission system without the need of a step-down transformer. Fig. 4 shows the circuit diagram of a multilevel converter directly connected to a power system for reactive power compensation.

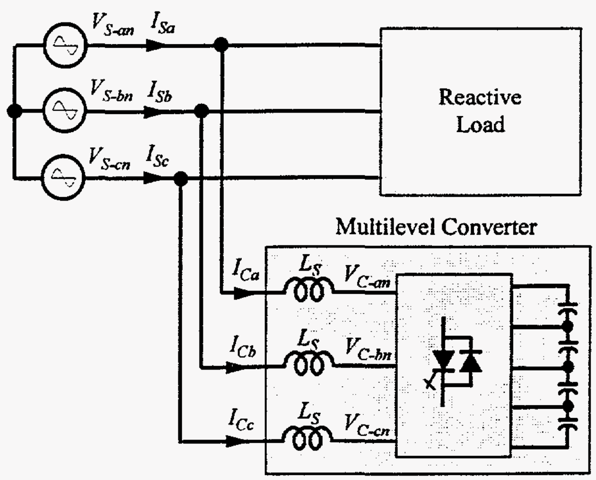


Fig. 4. Circuit diagram showing a multilevel converter is directly connected to a power system for reactive power compensation.

The relationship of the source voltage vector, V_S, and the converter voltage vector, V_C, is simply $V_S=V_C+jI_C X_S$, where I_C is the converter current vector, and X_S is the inductor impedance. Fig. 5 illustrates the phasor diagram of the source voltage, converter voltage, and the converter current. Fig. 5(a) indicates that the converter voltage is in phase with the source voltage with a leading reactive current, while Fig. 5(b) indicates a lagging reactive current. The polarity and the magnitude of the reactive current are controlled by the magnitude of the converter voltage V_C, which is a function of the dc bus voltage and the voltage modulation index.

(a) Leading current (b) Lagging current

Fig. 5. Phasor diagrams showing the relationship between the source voltage and the converter voltage when using the multilevel converter for reactive power compensation.

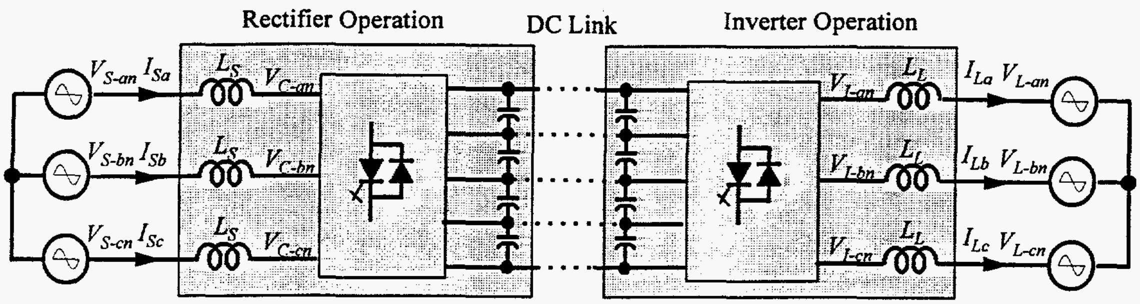


Fig. 6. General structure of the diode-clamped multilevel converter intertied with a corresponding multilevel inverter.

2.3.2 Back-to-Back Intertie

When interconnecting two diode-clamp multilevel converters together with a "dc capacitor link," as shown in Fig. 6, the left-hand side converter serves as the rectifier for the utility interface, and the right-hand side converter serves as the inverter for the ac load. Each switch remains switching once per fundamental cycle. The result is a well-balanced voltage across each capacitor while maintaining the staircase voltage wave because the unbalance capacitor voltages on both sides tend to compensate each other. Such a dc capacitor link is categorized as the "back-to-back intertie."

The back-to-back intertie is to connect two systems with two asynchronous systems. It can be treated as (1) a frequency changer, (2) a phase shifter, or (3) a power flow controller. The power flow between two systems can be controlled bidirectionally. Fig. 7 illustrates the phasor diagram for real power transmission from the source end to the load end. This diagram indicates that the source current is in phase with the source voltage, and the converter voltage is lagging behind the source voltage. If the source voltage is constant, then the magnitude of the converter voltage will be controlled by the current condition.

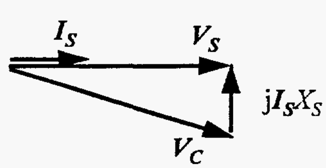


Fig. 7. Phasor diagram of the source voltage, converter voltage, and current showing real power transmission from the source end to the load end.

A 6-level "back-to-back" intertie hardware model has been constructed and tested as a phase-shifter and a power flow controller. This model employs the Insulated Gate Bipolar Transistor with a built-in diode as the switching device and a digital signal processor, TMS32031, as the controller for a fully digital control system. The 2 intertie systems contain a total of 60 switching devices, 60 built-in diodes, and 60 clamping diodes.

It should be noted that having a 6-level phase voltage is equivalent to having an 11-level line voltage. Fig. 8 shows experimental results of the input utility source line voltage, $V_{S\text{-}ab}$, converter terminal line voltage, $V_{C\text{-}ab}$, and the source current, I_{Sa}, operating at a unity power factor. From the oscillogram, it can be seen that the current, I_{Sa}, is 30° lagging behind the line voltage $V_{S\text{-}ab}$. This implies that phase a current is in phase with phase a voltage $V_{S\text{-}an}$.

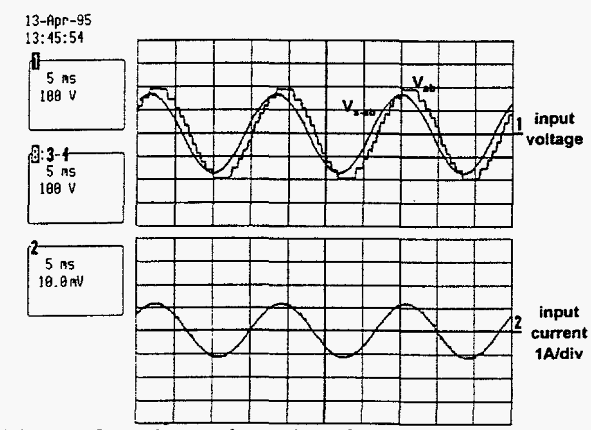


Fig. 8. Experimental results of 11-level line-to-line input voltage and current for a 6-level converter system with back-to-back intertie.

Results from a Fourier series analysis of the total harmonic distortions (THDs) for the above voltages and current are listed below.

Utility source voltage, $V_{S\text{-}ab}$:	THD=1.39%
Converter terminal voltage, $V_{C\text{-}ab}$:	THD=7.19%

Source current I_{Sa}: THD=0.95%

The above harmonic analysis results indicate that the THDs obtained from the multilevel converter are well within the requirements of IEEE Std 519-1992 [18].

2.3.3 Utility Compatible Adjustable Speed Drives

A utility compatible system requires unity power factor, negligible harmonics, no EMI, and high efficiency. By extending the application of the back-to-back intertie, the multilevel converter can be used for a utility compatible adjustable speed drive (ASD) with the input from the utility constant frequency ac source and output to the variable frequency ac load. The major differences, when using the same structure converter for ASD and for back-to-back intertie, are the control design and the size of the capacitor. Because the ASD needs to operate at different frequencies, the dc link capacitor needs to be sized to avoid a large voltage swing under dynamic conditions. A large voltage swing can cause device over-voltage, induce uncharacterized harmonics, and worsen current ripples.

2.4 Summarized Features of the Diode-Clamp Multilevel Converter

In summary, pros and cons of a diode-clamp multilevel voltage source converter are listed below.

Pros:

- When the number of levels is high enough, harmonic contents will be low enough to avoid the use of filters.
- Reactive power flow can be controlled.
- Efficiency is high because all devices are switched at the fundamental frequency.
- The control method is simple for a back-to-back intertie system.

Cons:

- Excessive clamping diodes are required when the number of levels is high.
- It is difficult to do real power flow control for the individual converter.

3. Multilevel Converter Using Flying Capacitors

3.1 Basic Principle

Instead of using diodes to clamp voltages in a multilevel converter, an alternative voltage balancing technique is to synthesize the output voltage with discrete capacitors at several voltage levels. A structure, known as "flying-capacitor multilevel inverter" [5, 6] is shown in Fig. 9. This figure illustrates the fundamental building block of a three-phase flying-capacitor based 5-level converter. Each phase has an identical structure. Assuming that each capacitor has the same voltage rating, the series connection of capacitors in Fig. 9 is to indicate the voltage level between the connected points. Three inner loop balancing capacitors for phase a, C_{a1}, C_{a2}, and C_{a3}, are independent from those for phases b and c. All three phases share the same dc link capacitors, C_1~C_4.

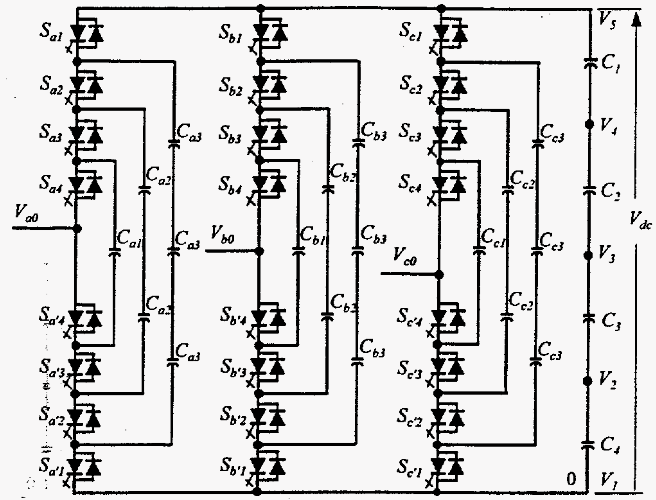


Fig. 9. Circuit diagram of a flying capacitor based 5-level voltage source converter.

The voltage level defined in the flying-capacitor inverter is similar to that of the diode-clamp type inverter, shown in Fig. 1. Assuming that each capacitor has the same voltage rating as the switching device, the dc link needs $(m-1)$ capacitors for an m-level converter. The phase voltage of an m-level converter has m levels including the reference level, and the line voltage has $(2m-1)$ levels.

The voltage synthesis in a flying-capacitor inverter has more flexibility than a diode-clamp inverter. Using Fig. 9 as the example, the 5-level phase a voltage with respect to the negative dc rail, V_{a0}, can be synthesized by the following switch combinations:

(1) For voltage level $V_{a0}=+V_{dc}$, turn on all upper switches S_{a1} through S_{a4}.

(2) For voltage level $V_{a0}=+3V_{dc}/4$, there are three combinations:

(a) S_{a1}, S_{a2}, S_{a3}, $S_{a'4}$ ($V_{a0}=V_{dc}-V_{dc}/4$),

(b) S_{a2}, S_{a3}, S_{a4}, $S_{a'1}$ ($V_{a0}=3V_{dc}/4$), and

(c) S_{a1}, S_{a3}, S_{a4}, $S_{a'2}$ ($V_{a0}=V_{dc}-3V_{dc}/4+V_{dc}/2$).

(3) For voltage level $V_{a0}=+V_{dc}/2$, there are six combinations:

(a) S_{a1}, S_{a2}, $S_{a'3}$, $S_{a'4}$, ($V_{a0}=V_{dc}-V_{dc}/2$),

(b) S_{a3}, S_{a4}, $S_{a'1}$, $S_{a'2}$, ($V_{a0}=V_{dc}/2$),

(c) S_{a1}, S_{a3}, $S_{a'2}$, $S_{a'4}$, ($V_{a0}=V_{dc}-3V_{dc}/4+V_{dc}/2-V_{dc}/4$),

(d) S_{a1}, S_{a4}, $S_{a'2}$, $S_{a'3}$, ($V_{a0}=V_{dc}-3V_{dc}/4+V_{dc}/4$),

(e) S_{a2}, S_{a4}, $S_{a'1}$, $S_{a'3}$, ($V_{a0}=3V_{dc}/4-V_{dc}/2+V_{dc}/4$), and

(f) S_{a2}, S_{a3}, $S_{a'1}$, $S_{a'4}$. ($V_{a0}=3V_{dc}/4-V_{dc}/4$).

(4) For voltage level V_{a0}=+V_{dc}/4, there are three combinations:

(a) S_{a1}, $S_{a'2}$, $S_{a'3}$, $S_{a'4}$ (V_{a0}=V_{dc}−3V_{dc}/4),

(b) S_{a4}, $S_{a'1}$, $S_{a'2}$, $S_{a'3}$ (V_{a0}=V_{dc}/4), and

(c) S_{a3}, $S_{a'1}$, $S_{a'2}$, $S_{a'4}$ (V_{a0}=V_{dc}/2−V_{dc}/4).

(5) For voltage level V_{a0}=0, turn on all lower switches $S_{a'1}$ through $S_{a'4}$.

Table 2 lists one possible combination of the voltage levels and their corresponding switch states. In order to balance the capacitor charge and discharge, one may employ two switch combinations for middle voltage levels (i.e., 3V_{dc}/4, V_{dc}/2, and V_{dc}/4) in one or several fundamental cycles. Thus, by proper selection of switch combinations, the flying-capacitor multilevel converter may be used in real power conversions. However, when it involves both real and reactive power conversions, the selection of a switch combination becomes very complicated.

Table 2: A possible switch combination for the flying capacitor based 5-level converter.

Output V_{a0}	Switch State							
	S_{a1}	S_{a2}	S_{a3}	S_{a4}	$S_{a'4}$	$S_{a'3}$	$S_{a'2}$	$S_{a'1}$
$V_5 = V_{dc}$	1	1	1	1	0	0	0	0
$V_4 = 3V_{dc}/4$	1	1	1	0	1	0	0	0
$V_3 = V_{dc}/2$	1	1	0	0	1	1	0	0
$V_2 = V_{dc}/4$	1	0	0	0	1	1	1	0
$V_1 = 0$	0	0	0	0	1	1	1	1

3.2 Fundamental Problems

Besides the difficulty of balancing voltage in real power conversion, the major problem in this inverter is the requirement of a large number of storage capacitors. Provided that the voltage rating of each capacitor used is the same as that of the main power switches, an m-level converter requires a total of (m−1) main dc bus capacitors plus (m−1)×(m−2)×3/2 auxiliary capacitors. With the assumption that all capacitors have the same voltage rating, an m-level diode clamping inverter only requires (m−1) capacitors.

According to Table 2, the flying-capacitor multilevel inverter also has unequal device duty problem. For reactive power compensation, each device may be switched only once per cycle. The bottom device of the upper leg (S_{a4}) conducts only when V_{a0}=V_{dc}, and the bottom device of the lower leg ($S_{a'1}$) conducts only when V_{a0}=0.

3.3 Applications

3.3.1 Reactive Power Compensation

As with the diode-clamp converter, the-flying capacitor based multilevel converter can be used in reactive power compensation without much effort in balancing capacitor voltages. Fig. 10 shows a single-phase full-bridge, 5-level converter connecting to a power system for reactive power compensation. As described in Section 2.3.1, by controlling the phase angle of the converter voltage, V_C, to be in-phase with the source voltage, V_S, and varying the modulation index for different voltage magnitudes, the converter can supply reactive power back to the power grid. Fig. 11 shows the simulation results of the 5-level single-phase converter using the switch combination stated in Table 2. Different level capacitor voltages are well balanced without the need to vary the switch combination for middle voltage levels.

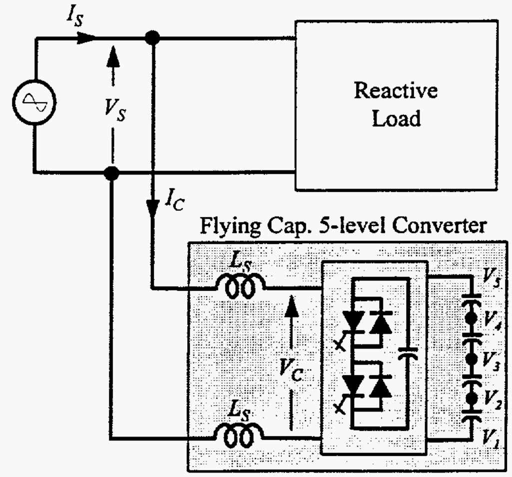


Fig. 10. A flying capacitor based 5-level single-phase converter as a reactive power compensator.

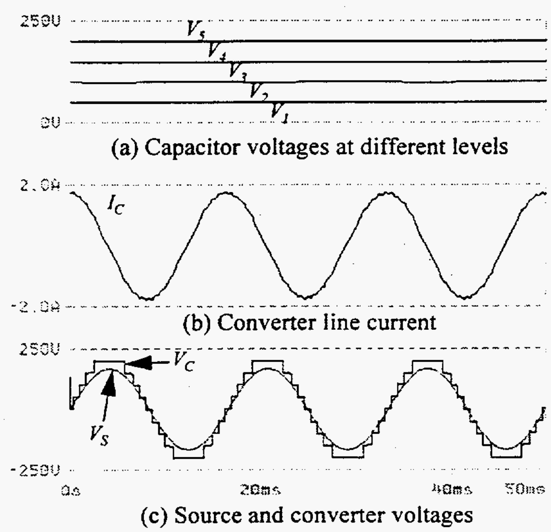


Fig. 11. Simulated results of the flying capacitor based 5-level converter for reactive power compensation.

3.3.2 Power System Intertie

Similar to interconnecting two diode-clamp multilevel converters, the flying-capacitor multilevel converter can also be used in a power system intertie. The differences are:

(1) The flying capacitors between inner layers cannot be tied between two systems.
(2) Because only the dc link capacitor is tied to the other system, it is possible to use the flying capacitor based converters for high voltage dc (HVDC) transmission.

The problem of using a flying-capacitor inverter for a back-to-back intertie is the difficulty of balancing inner layer capacitor voltages. By properly selecting the switch combinations, it may be possible to balance the voltage sharing, but the devices may need to switch more than twice per fundamental cycle. Varying the switch combination also introduces additional complexity in the inverter control.

3.3.3 Adjustable Speed Drives

The flying-capacitor multilevel converter can be used as a dc- or ac-powered adjustable speed drive. The ac-powered system is similar to that described in Section 2.3.3 that can be used for a utility friendly ASD. Both dc-powered or ac-powered ASDs will have the same difficulty of balancing inner layer flying capacitors.

3.4 Summarized Features of the Flying-Capacitor Multilevel Converter

In summary, pros and cons of a flying-capacitor multilevel voltage source converter are listed below.

Pros:

- When the number of levels is high enough, harmonic contents will be low enough to avoid the use of filters.
- Both real and reactive power flows can be controlled, making a possible voltage source converter candidate for HVDC transmission.
- Provides switch combination redundancy for balancing different voltage levels.
- Large amount of storage capacitors provide extra ride through capabilities during power outage.

Cons:

- An excessive number of storage capacitors are required when the number of converter levels is high. System could be more expensive with the required bulky capacitors.
- The inverter control can be very complicated and the switching loss could be high for real power flow transmission.

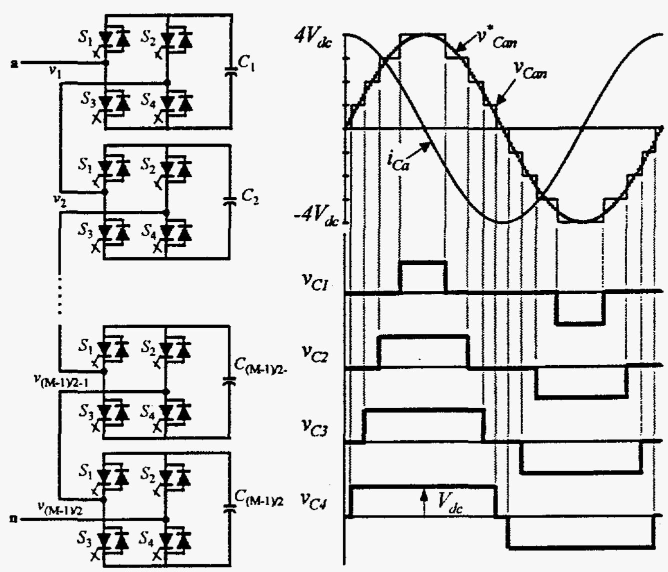
4. Multilevel Converter Using Cascaded Inverters With Separate DC Sources

4.1 Basic Principle

A relatively new converter structure, cascaded inverters with separate dc sources (SDCs) is introduced here. This new inverter can avoid extra clamping diodes or voltage balancing capacitors. Fig. 12(a) shows the basic structure of the cascaded inverter with SDCs, shown in the single-phase configuration. Each SDC is associated with a single-phase full-bridge inverter with the ac terminal voltages connected in series.

Fig. 12(b) shows the synthesized phase voltage waveform of a 9-level cascaded inverter with four SDCs. The phase output voltage is synthesized by the sum of four inverter outputs, i.e., $v_{an} = v_1 + v_2 + v_3 + v_4$. Each single-phase full bridge inverter can generate three level outputs, $+V_{dc}$, 0, and $-V_{dc}$. This is made possible by connecting the dc-source sequentially to the ac side via the four gate-turn-off devices. Each level of the full-bridge converter consists of four switches, S_1, S_2, S_3, and S_4. Using the top level as the example, turning on S_1 and S_4 yields v_1=$+V_{dc}$. Turing on S_2 and S_3 yields v_1=$-V_{dc}$. Turning off all switches yields v_1=0. Similarly, the ac output voltage at each level can be obtained in the same manner. Minimum harmonic distortion can be obtained by controlling the conducting angle at different levels.

With the phase current, i_a , leading or lagging the phase voltage v_{an} by 90 degrees, the average charge to each dc capacitor is equal to zero over one line cycle, shown in Fig. 12(b). Therefore, all SDC capacitor voltages can be balanced.



(a) Circuit diagram (b) Waveform showing a 9-level converter phase voltage

Fig. 12. Circuit diagram and the phase voltage waveform of a cascaded inverter with separate dc sources.

To comply with the definition of the previously mentioned diode-clamp and flying-capacitor multilevel converters, the voltage level in a cascaded inverter is defined by m=2s+1, where m is the output phase voltage level, and s is the number of dc sources. For example, a 9-

level cascaded inverter will have four SDCs and four full bridges.

For a three-phase system, the output voltages of the three cascaded inverters can be connected in either Y- or Δ- configuration [7].

4.2 Fundamental Problems

Just like the general problems encountered in a typical multilevel converter, the cascaded inverter also has the difficulty of controlling real power flow. It may be possible to balance the capacitor voltage with sophisticated PWM control technique which is not favored because of additional switching losses.

Connecting separated dc sources between two converters in a back-to-back fashion is not possible because a short circuit will be introduced when two back-to-back converters are not switching synchronously.

4.3 Applications

Possible power system applications of the cascaded inverter based multilevel converter are reactive power compensation, power line conditioning, series compensation, phase shifting, etc. Figs. 4 and 5 illustrate how a multilevel converter can be used in the reactive power compensation. The same structure and principle in those two figures are also applicable to the cascaded inverter system.

Fig. 13 shows simulated converter phase voltage, source voltage, and line current waveforms of a cascaded-inverter based 21-level converter with 10 separated dc sources for reactive power compensation. Fig. 14 shows the simulated voltages at the SDC capacitors. Because each level of the converter has exactly the same structure, this converter can span much higher voltage levels without circuit layout and packaging problems that are very severe in the previously mentioned two multilevel converters.

A typical high power Gate-Turn-Off Thyristor (GTO) requires a substantial passive snubber circuit to prevent device failure from switchings. The cascaded inverter allows the use of an auxiliary resonant snubber circuit for soft-switching [17] that is more reliable than the conventional passive snubbers. This advantage has not been observed in other types of multilevel converters.

4.4 Summarized Features of the Cascaded-Inverter Multilevel Converter

In summary, pros and cons of the cascaded-inverter based multilevel voltage source converter are listed below.

Pros:

- Requires the least number of components among all multilevel converters to achieve the same number of voltage levels.
- Modularized circuit layout and packaging is possible because each level has the same structure, and there are no extra clamping diodes or voltage balancing capacitors.
- Soft-switching can be applied in this structure to avoid bulky and lossy resistor-capacitor-diode snubbers.

Cons:

- Complicated control is required if used in power system intertie or real power flow control.

5. Conclusions

Multilevel converters are emerging as a new breed of power converters. This paper has presented three transformerless multilevel voltage source converters that synthesize the converter voltage by equally divided capacitor voltages. All these converters have been completely analyzed and simulated. One hardware model has been built and tested to verify the concept. Both simulation and experimental results prove that this new breed of power converters are very promising for power system applications.

These multilevel converters can immediately replace the existing systems that use six-, twelve-, or multi-step converters without the need for transformers or connecting devices in series. The static var compensators would be an excellent target for commercialization of these multilevel converters in high-voltage high-power systems. All three converters introduced in this paper can be used as the reactive power compensator. The second target could be the back-to-back intertie system for a unified power flow controller. The structure that is most suitable for the back-to-back intertie is the diode-clamp type. The flying-capacitor type is also suitable for the back-to-back intertie, but it requires more switchings per cycle and more sophisticated control to balance the voltage. Although the flying-capacitor multilevel converters, through proper controls, may be applied to HVDC transmissions for real power flow control, the power industry may prefer the current source type converters for safe operation during short circuit failures.

The application that may have the most impact is the adjustable speed drive. The industry recently reported numerous ASD bearing failures and winding insulation breakdowns due to high frequency switching PWM inverters. Using multilevel converters not just solves harmonics and EMI problems, but also avoids high frequency switching dv/dt induced motor failures.

Future research may be directed to current source type multilevel converters for various power system applications.

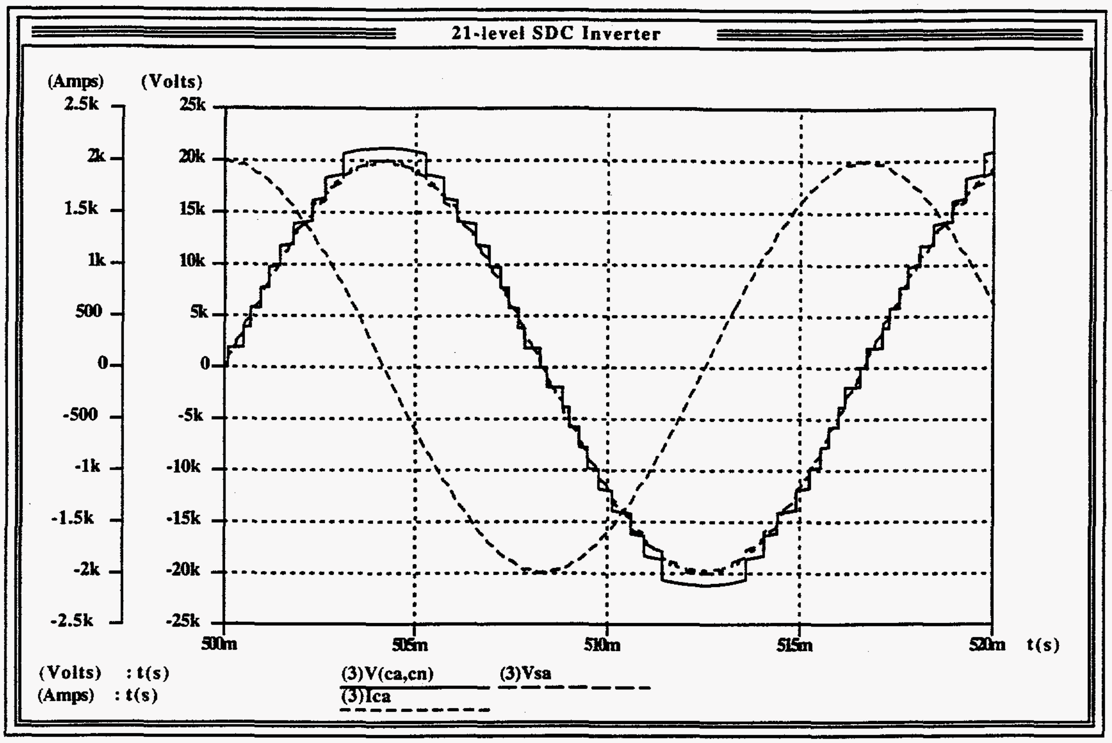


Fig. 13. Simulated voltage and current of a 21-level cascaded inverter for reactive power compensation applications.

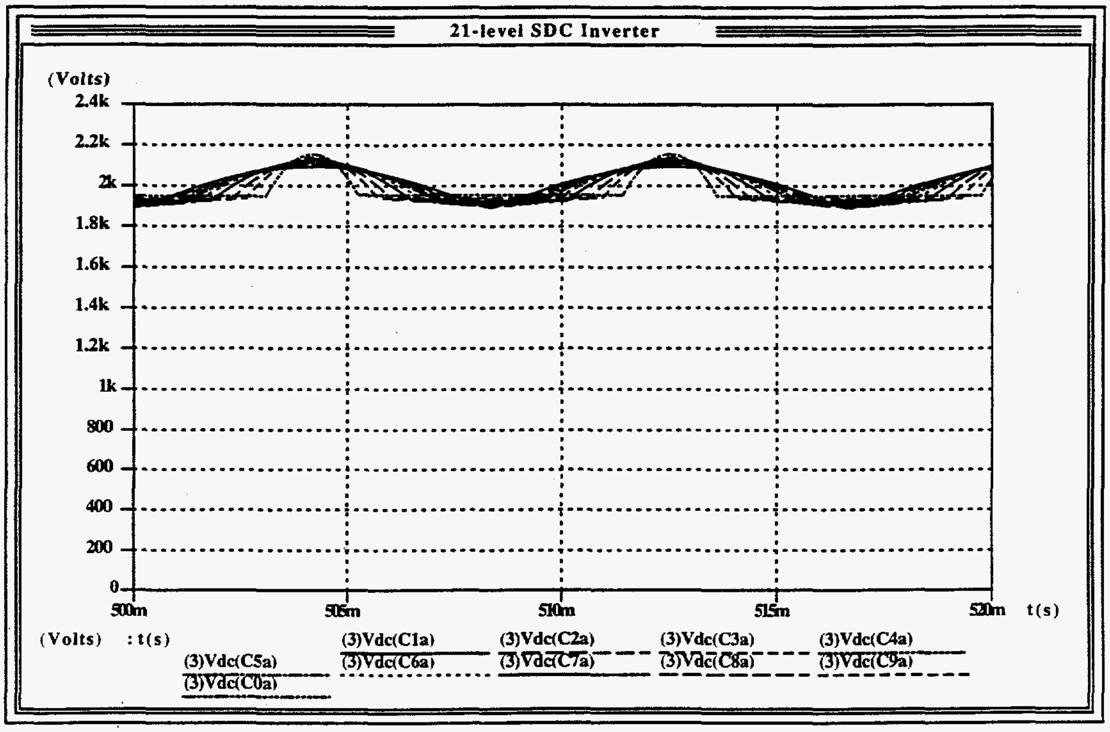


Fig. 14. Simulated capacitor voltages of a 21-level cascaded inverter with 10 separate dc sources.

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