

A New Family of Matrix Converters

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Abstract—A new family of matrix converters is introduced, that employs relatively simple voltage-clamped buses and can generate multilevel voltage waveforms of arbitrary magnitude and frequency. The basic configuration includes a nine-switch matrix that uses four-quadrant switch cells. Each four-quadrant switch cell resembles a full-bridge inverter and can assume three voltage levels during conduction. Semiconductor devices in a switch cell are clamped to a known constant dc voltage of a capacitor.

Control of the input and output voltage waveforms of the proposed converter can be achieved through space vector modulation. Simulation results show how the converter can operate with any input and output voltages, currents, frequencies, and power factors while maintaining constant dc voltages across all switch cell capacitors.

I. INTRODUCTION

Multilevel conversion has attracted significant attention, as a way to construct a relatively high-power converter using many relatively-small power-semiconductor devices [1,2]. This approach has the advantages of reduced switching loss and reduced harmonic content of output ac waveforms. The peak voltages applied to the semiconductor devices are clamped to capacitors whose dc voltages can be controlled via feedback. When the input and output voltage magnitudes differ significantly, it is also possible to reduce the conduction losses using multilevel techniques; this property can improve the energy capture of variable-speed wind power systems. Although multilevel conversion requires a larger packaging and parts count, the total silicon area can in principle be reduced because of the reduced device voltage ratings. Thus, higher performance is attained at the expense of increased control and complexity.

As the number of levels is increased, the bus bar structures of multilevel dc-link converter systems can become quite complex and difficult to fabricate. A solution to this problem is the use of the simple voltage-clamped switch cell illustrated in Fig. 2 [3]. This circuit locally clamps the voltages applied to the semiconductor devices to the value V . This switch cell is capable of producing the instantaneous voltages $+V$, 0 , and $-V$, when the devices conduct, and is capable of blocking voltages of magnitude less than V when all of the devices are off. One phase of a multilevel inverter that employs this switch cell is illustrated in Fig. 2. The difficulty

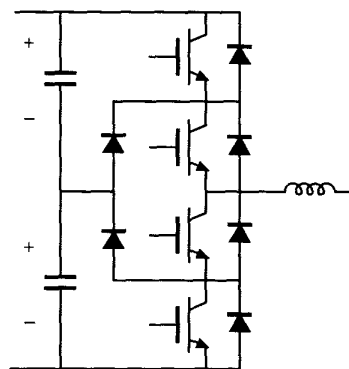


Fig. 1 Conventional three-level dc-link inverter. One phase is illustrated.

with this inverter is that the voltage sources V of each switch cell must generate the average power supplied by the inverter, and hence floating sources of dc power are required.

The objective of this paper is to describe an ac-to-variable-ac multilevel matrix converter system based on the simple switch cells of Fig. 1. The bus bar structures of the proposed converter are therefore relatively easy to construct. The use of a matrix configuration eliminates the need for the voltage sources V to supply average power. Therefore, these voltage sources can be replaced by simple capacitors.

A new approach to multilevel matrix conversion [4] is described in Section II. This approach is fundamentally different from the conventional matrix converter [5,6], as well as from the multilevel dc link approach, in several respects. It is capable of both increasing and decreasing the voltage magnitude and frequency, while operating with arbitrary power factors. The peak semiconductor device voltages are locally clamped to a dc capacitor voltage, whose magnitude can be regulated. The semiconductor devices are effectively utilized. Multilevel switching is used to synthesize the voltage wave-

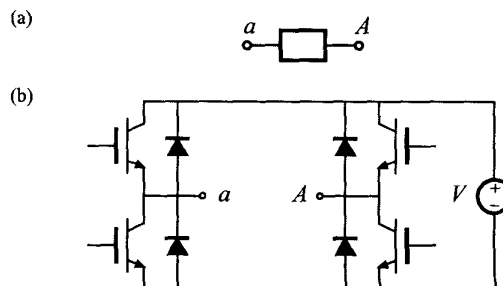


Fig. 2 Voltage-clamped switch cell: (a) switch cell symbol, (b) schematic diagram.

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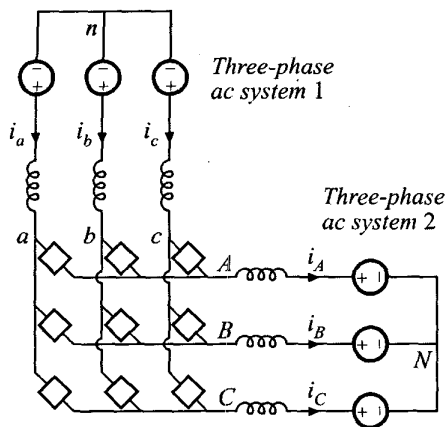


Fig. 3 Proposed new matrix converter, basic configuration.

forms at both the input and output ports of the converter.

Section III describes control of a basic version of the proposed family of matrix converters. It is shown that space vector control techniques can be adapted, for simultaneous control of the input and output waveforms of the converter. It is also shown that the capacitor voltages of the switch cells can be stabilized by use of appropriate control. Simulations confirm the operation of the basic form of the new matrix converters.

The proposed converters may find use in variable-speed ac drives, variable-speed wind power generation, and other polyphase ac-to-ac applications. They can take advantage of the substantial and ongoing advances in packaging and micro-controller technology, to improve the performances of ac-ac power converters.

II. CONVERTER DERIVATION AND OPERATION

A basic configuration of the proposed new multilevel matrix converter is shown in Fig. 3. Superficially, the converter resembles a conventional matrix converter through its use of a matrix of nine four-quadrant switch cells. However, the switch cells are realized as illustrated in Fig. 4. Each cell resembles the cells of Fig. 2, except that the cells do not require sources of dc power, and hence the dc voltage sources may be replaced by capacitors. The transistors and diodes within each cell are clamped to the dc capacitor voltage, which can be regulated to a known dc value. As with the switch cell of Fig. 2, this switch cell is capable of producing the instantaneous voltages $+V$, 0 , and $-V$, when the devices conduct, and is capable of blocking voltages of magnitude less than V when all of the devices are off.

The use of four transistors in the switch cell of Fig. 4 allows the average current to be doubled, relative to a conventional matrix converter whose four-quadrant switches are realized using two transistors and two diodes. This is true because the currents conducted by the IGBTs are thermally limited, and by proper control the current stresses can be

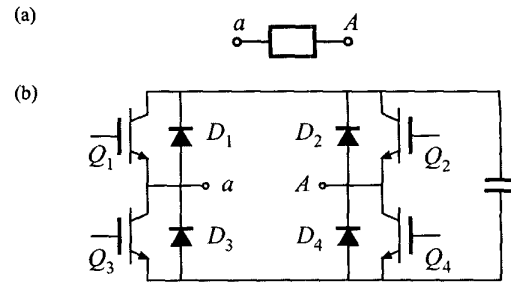


Fig. 4 Realization of the switch cells of the proposed matrix converter: (a) switch cell symbol, (b) schematic diagram.

spread over all four devices in Fig. 4.

The basic circuit of Fig. 3 is capable of limited multilevel operation. The semiconductor devices must be rated at least as large as the peak applied line-to-line voltage. The converter is capable of both increase and decrease of the ac voltage magnitude.

The number of voltage levels can be increased. Figure 5 illustrates one approach to increasing the terminal voltage, in which switch cells are connected in series in each branch of the switch matrix. This allows increase of the terminal voltages without changing the voltage ratings of the semiconductor devices.

The proposed multilevel matrix converter synthesizes the input and output voltage waveforms by switching the known dc capacitor voltages of the switch cells. This operation differs from that of the conventional matrix converter in which voltage waveforms are synthesized on one side, and current waveforms on the other. Because of the symmetry of the converter, both step-up and step-down of the voltages are possible.

Because of the inductors at both sides of the converter, current must flow continuously through the input and output phases. Hence, operation of the switch cells must never lead to the open-circuiting of an input or output phase. Further, conduction of the switch cells must not form a closed loop within the branches of the switch matrix, since this could short-circuit the capacitors of the switch cells. Third, the voltage applied to an open switch cell must not exceed the magnitude of its capacitor voltage. These constraints limit the possible connections within the switch matrix. They imply that, at any given instant, exactly five of the nine branches of the switch matrix must conduct. Further, the following rules apply to the connections that are possible at a given instant:

There is exactly one connection path between any two phases.

If any phase on one side (i.e., the input or output side) is connected directly to two conducting branches, then there must be exactly one other phase from the same side also connected directly to two conducting branches. The third phase must be connected directly to one conducting branch.

If any phase on one side (i.e., the input or output side) is connected directly to three conducting branches, then the other two phases from the same side must be each connected directly to exactly one conducting branch.

TABLE I
POSSIBLE BRANCH CONNECTION CONFIGURATIONS

Phase A or a	Phase B or b	Phase C or c
1 branch	1 branch	3 branches
1 branch	2 branches	2 branches
1 branch	3 branches	1 branch
2 branches	1 branch	2 branches
2 branches	2 branches	1 branch
3 branches	1 branch	1 branch

Table I summarizes the possible configurations. There are a total of 81 valid choices of branch connections.

The proposed converter can interface two asynchronous three-phase ac systems. Both interfaces are inductive in nature, with intrinsically or through addition of series inductors. In the basic configuration of Fig. 3, the converter consists of nine branches that each consist of a switch cell as in Fig. 4. To avoid interrupting the six inductor currents, exactly five branches must conduct current at any instant in time. It is important to avoid the cross-conduction and shoot-through currents that can occur when the transistors of six or more branches conduct. However, turning off the transistors of five or more branches does not cause a calamity, because the antiparallel diodes can conduct current and provide a path for the inductor currents to flow. Energy stored in the inductors is then transferred to the capacitors of the switch cells. One simple method for controlling the switching transitions is to first turn off all transistors that are to be switched off, and then after a short delay, turn on the transistors that are to be switched on. Other soft-switching schemes are also possible [7].

Each switch cell of the multilevel matrix converter has three switch states corresponding to voltages of $+V_{cap}$, 0, $-V_{cap}$. This means that there are three switch states that a switch cell may assume when it is used in a conducting branch. Since there are five branches that may be turned on at any particular instant and three switch states per conducting switch cell, the number of possible device switching combinations for each case of branch connection is 3^5 , or 243, possible device switching combinations. With 81 cases of branch connections, the total number of device switching combination becomes $243 \cdot 81 = 19683$ possible device switching combinations.

Figure 5 shows an example of three different device switching combinations for one case of a branch connection with branches conducting between phases A-a, B-a, C-a, C-b, and C-c. This figure shows that it is possible to obtain five different output voltage levels from the multilevel matrix converter by switching only the devices of one switch cell (in branch C-c). For this example, it is assumed that the midpoint capacitor voltage V_{cap} is set to +240 V. Figure 5(a) produces 0 volts for all line-to-line voltages on both sides of the converter. This is done by operating all switch cells of the con-

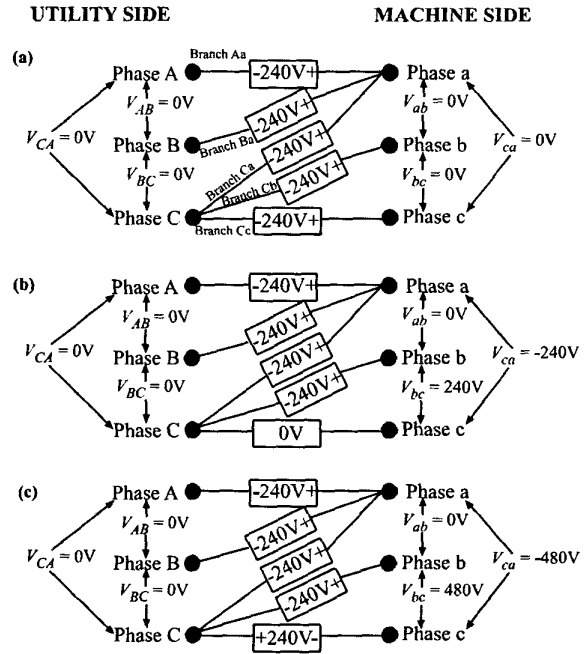


Fig. 5 Three possible switching combinations, for one choice of branch connections. Five levels of output line-to-line voltages are obtained.

ducting branches to produce voltages of +240 V. By changing the switch cell connecting branches C-c to produce a voltage of zero, the converter can produce line-to-line output voltages of -240 V, 0 V, and +240 V, as shown in Fig. 5(b). In Fig. 5(c) output line-to-line voltages of -480 V, 0 V, and +480 V are obtained. By alternating between the three device switching combinations of Fig. 5, the basic multilevel matrix converter can produce five-level voltage waveforms with voltage levels at -480 V, -240 V, 0, 240 V, and 480 V at one side of the matrix converter. In each case, the nonconducting switch cells block voltages of magnitude 240 V.

The basic version of the converter, having one switch cell per branch of the switch matrix, is capable of multilevel operation as illustrated in Fig. 5. However, the combinations having line-line voltages that are twice the capacitor voltages [e.g., the machine-side 480 V combination of Fig. 5(c)] require that zero voltage be applied to the opposite side [e.g., the utility side in Fig. 5(c)]. This effectively limits the multilevel operation of the basic version of the converter to operating points in which one side operates with low voltage. Nonetheless, such operation may find use in wind power and similar applications, where it is desirable to employ multilevel conversion to improve the converter efficiency at low speeds.

Figure 6 illustrates a multilevel version of the proposed matrix converter family, in which each branch of the switch matrix contains two series-connected switch cells. Each switch cell is again realized using the voltage-clamped bridge circuit of Fig. 4. This converter is capable of producing five-level line-line voltages at the full rated operating point, with sharing of voltage stresses among the switch cells.

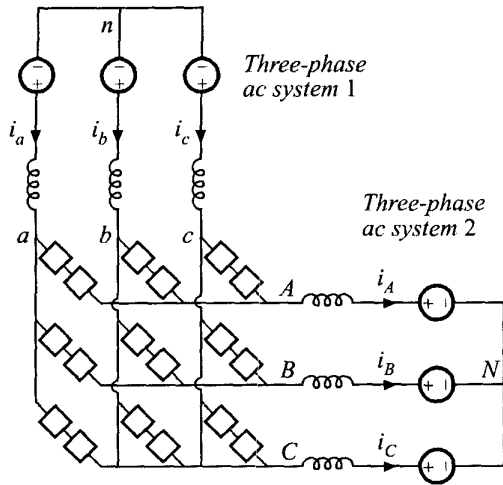


Fig. 6 A new multilevel matrix converter containing two of the switch cells of Fig. 4 in each branch of the switch matrix.

III. CONTROL

The controller of the proposed multilevel matrix converter must perform the following major tasks.

1. Maintain fixed voltage (charge regulation) across all midpoint capacitors.
2. Synthesize input and output voltage waveforms.

Control that simultaneously accomplishes the above two tasks is demonstrated here. The space vector modulation technique is extended to the case of controlling the input and output voltage waveforms of the proposed converter; at the same time, the controller regulates the capacitor voltages.

Upon analysis of all possible switching combinations, it is found that the nineteen space vectors illustrated in Fig. 7 are

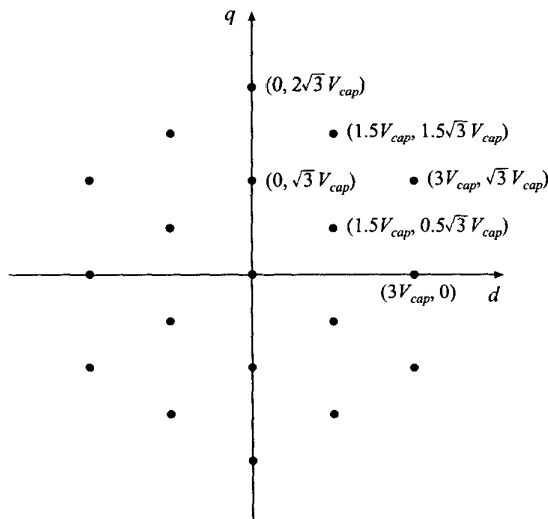


Fig. 7 Space vectors attainable by the basic converter of Fig. 3. Values for the first quadrant are labeled; the remaining quadrants are symmetrical.

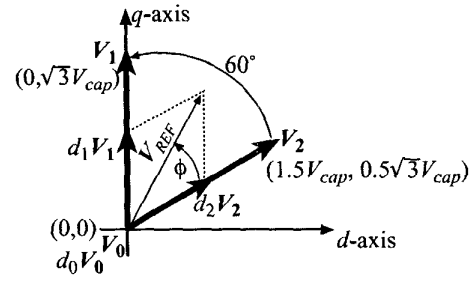


Fig. 8 Reduced space vector diagram, control example.

attainable at each side of the converter. Control of the input-side voltage is achieved by modulating between space vectors adjacent to the desired reference vector [6]. Simultaneously, similar control is applied to control the output-side voltage. Even when both the input and output-side voltages are controlled, there exist additional degrees of freedom that can be used to control the dc capacitor voltages.

For example, consider the space vector modulation illustrated in Fig. 8. At a given point in time, it is desired to produce the reference space vector V_{REF} . This is accomplished by modulating between three adjacent space vectors V_0 , V_1 , and V_2 . The reference space vector V_{REF} is expressed as a linear combination of the space vectors V_0 , V_1 , and V_2 :

$$V_{REF} = d_1 V_1 + d_2 V_2 + d_0 V_0 \quad (1)$$

The duty cycles d_1 , d_2 , and d_0 represent the durations for device switching combinations producing the space vectors V_0 , V_1 , and V_2 , relative to the space vector modulation period. Since only three space vectors are used in this example, the three duty cycles must add to unity. The duty cycles are found by solution of the geometry of Fig. 8:

$$\begin{aligned} d_1 |V_1| \frac{\sqrt{3}}{2} &= |V_{REF}| \sin(\phi) \\ d_1 &= \frac{2}{\sqrt{3}} \frac{|V_{REF}|}{|V_1|} \sin(\phi) = M \sin(\phi) \\ d_2 |V_2| \frac{\sqrt{3}}{2} &= |V_{REF}| \sin(60^\circ - \phi) \\ d_2 &= \frac{2}{\sqrt{3}} \frac{|V_{REF}|}{|V_2|} \sin(60^\circ - \phi) = M \sin(60^\circ - \phi) \\ d_0 &= 1 - d_1 - d_2 \\ M &= \frac{2}{\sqrt{3}} \frac{|V_{REF}|}{|V_1|} = \frac{2}{\sqrt{3}} \frac{|V_{REF}|}{|V_2|} \end{aligned} \quad (2)$$

The term M in (2) is the modulation index, and its value cannot exceed unity in the above modulation scheme. Thus, the reference space vector V_{REF} is synthesized by modulating through switch configurations producing the space vectors V_0 , V_1 , and V_2 during a given SVM period.

With the above approach, the proposed multilevel matrix converter is capable of operating with universal input and output voltage, frequency, and power factor.

To illustrate operation of the proposed new matrix con-

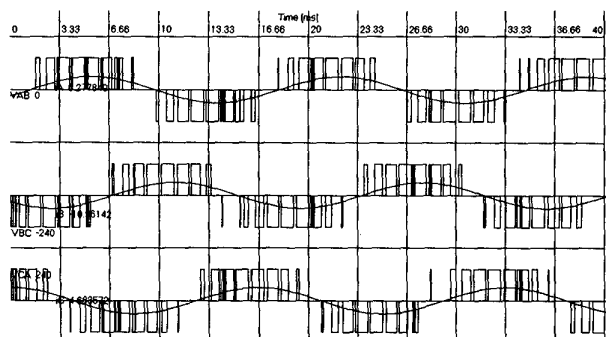


Fig. 9 Simulated utility-side SVM line-line voltages and inductor currents, operating point 1.

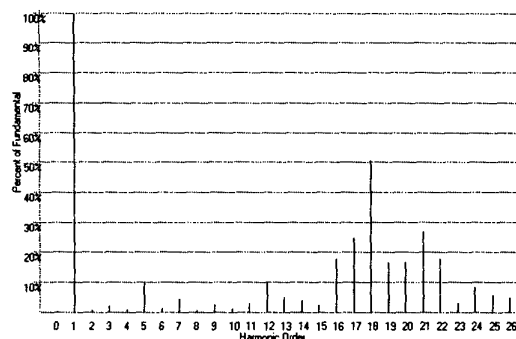


Fig. 10 Harmonic spectrum of the utility-side voltage of Fig. 9.

verter, simulations of operation at two different operating points are given in Figs. 9 to 13. In these examples, the new matrix converter interfaces a variable-speed wind generator to a 60 Hz utility. The basic (three-level line-line) operation of the new matrix converter is shown. Figure 8 shows simulated voltage and current waveforms for the three-phase ac utility side, at operating point 1. The utility side is at 240 V, 11 A, 60 Hz, and unity power factor. For this operating point, the generator side is at 240 V, 25 Hz, and unity power factor. The converter switching frequency is set to 1 kHz. The simulator implements the space vector modulation described above to control the new matrix converter, and hence synthesizes the desired PWM input and output voltage waveforms. The pulse-width modulated waveforms in Fig. 9 are line-to-line voltages and the sinusoids are phase currents. Since this is a positive phase sequence, the set of phase currents lags the set of line-to-line voltages.

Figure 10 shows the harmonic spectrum of utility side line-to-line voltage V_{AB} . Notice the high magnitude harmonics in the vicinity of the 18th harmonic. These are due to the switching frequency of 1 kHz.

Figure 11 shows the generator-side voltage and current waveforms for the same operating point. The simulator is programmed to select appropriate device switching combinations to maintain constant dc voltages across all switch cell capacitors in addition to synthesizing the desired input and output waveforms. Figure 12 shows the regulated capacitor voltages across all nine switch cells. Using nine switch cells consti-

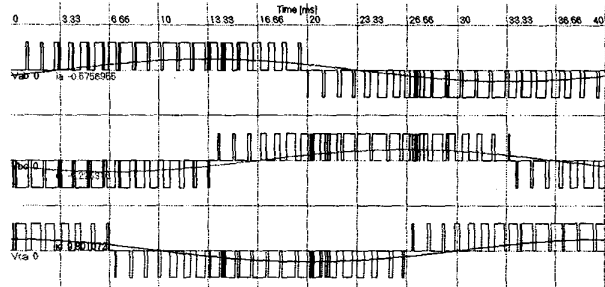


Fig. 11 Simulated generator-side SVM line-line voltages and inductor currents, operating point 1.

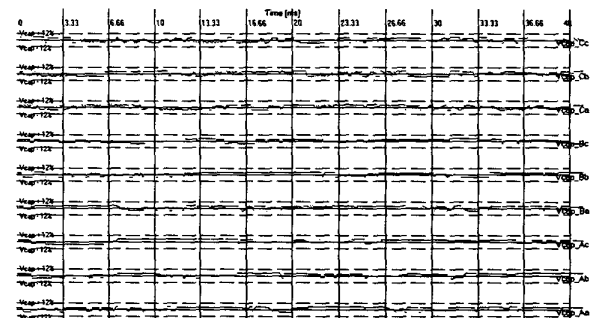


Fig. 12 Regulation of capacitor voltages, operating point 1.

tutes the most basic converter configuration with one switch cell per branch. All capacitor voltages are maintained within $\pm 12\%$ of their nominal values.

Figure 13 illustrates the effect on the spectrum of increasing the switching frequency to 20 kHz. The harmonic spectrum of the utility side line-to-line voltage V_{AB} is plotted. Notice that all of the high magnitude harmonics of Fig. 10 are moved to higher harmonic numbers, corresponding to the 20 kHz switching frequency.

Operation at nonunity power factor is illustrated by operating point 2. At this point, the utility-side voltage and current are 240 V, 11 A, 60 Hz, 0.5 power factor, with 1 kHz switching frequency. The generator side operates at 60 V, 6.25 Hz, and unity power factor. The utility-side waveforms are illustrated in Fig. 14. Figure 15 shows regulation of the capacitor

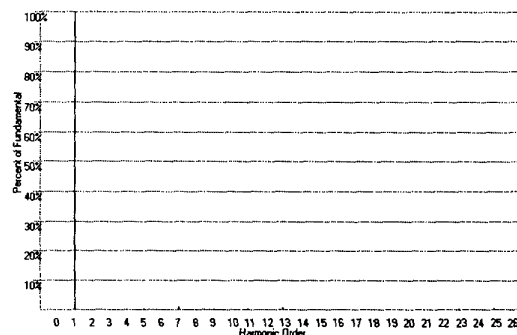


Fig. 13 Effect of increasing the switching frequency to 20 kHz, on the spectrum of the utility-side line-line voltage V_{AB} , operating point 1.

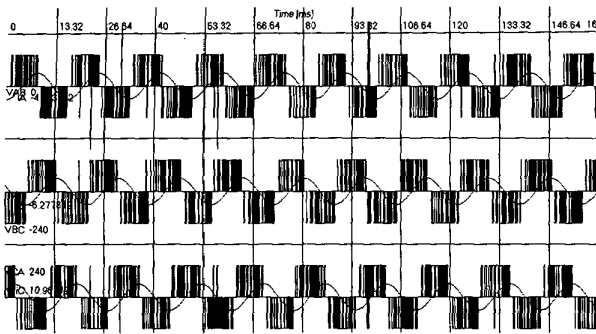


Fig. 14 Utility-side voltages, operating point 2.



Fig. 15 Regulation of the capacitor voltages under nonunity power factor voltages at this operating point.

Thus, operation of the basic (three-level line-line) form of the proposed new matrix converter is confirmed. The utility-side and generator-side waveforms can be controlled simultaneously and independently. The dc capacitor voltages of the switch cells can also be regulated.

IV. CONCLUSIONS

A new family of matrix converters is introduced, which are fundamentally different from existing known approaches. These converters can both increase and decrease the voltage amplitude and can operate with arbitrary power factors. With series connection of switch cells in each branch of the matrix, multilevel switching can be attained with device voltages locally clamped to dc capacitor voltages. The advantages of conventional multilevel converters can therefore be attained in a matrix converter, including reduced switching loss and reduced waveform harmonic content. In principle, the number of voltage levels can be increased arbitrarily, by increasing the number of switch cells in each branch. Even in the basic version having one switch cell per matrix branch, multilevel operation (five line-line voltage levels) can be attained.

Space vector modulation to control the input and output voltage waveforms is demonstrated. It is also demonstrated that the controller can stabilize the dc voltages of the capacitors. Operation of the basic version of the new family of matrix converters has been confirmed.

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