Multi-level converters for three-phase photovoltaic applications*

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***Abstract*—This paper presents an approach to generate three-phase multi-level AC voltage output using a switching matrix device and photovoltaic (PV) panels. The approach is based on the dynamic reconfiguration of PV panels distributed in a matrix. The principle is similar to methods used in multi-level inverters related to the technique of matrix reconfiguration. The concept is to switch in and out solar panels in series to create a higher three-phase voltage level. The focus of the project is optimizing the PV array usage and improving the output current while generating three-phase multi-level waveforms.**

I. Introduction

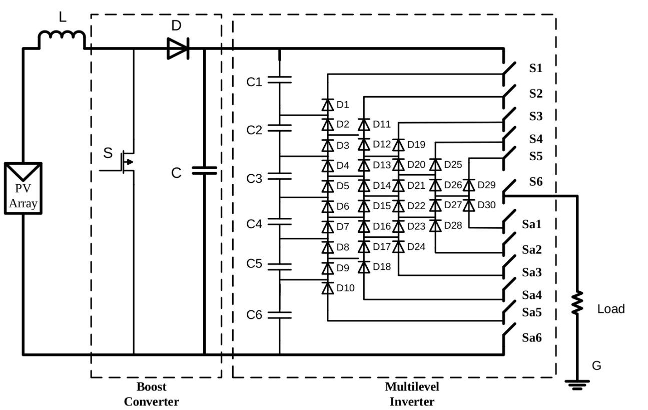

Fig. 1. Multi-level inverter for single-phase grid connected PV modules [1]

Multi-level inverters for AC generation have several benefits: they are simple to implement and they eliminate the number of transformers. Alternate current (AC) power generation using multi-level inverters minimizes the filter requirements and improves the harmonic quality of the output [1]–[3]. A typical multi-level inverter is shown in Fig. 1.

The single DC source input voltage charges the input capacitors. The output voltage is obtained by properly operating the switches as seen in the Table I. Each level of the staircase voltage is a fraction of the total voltage provided by the DC source. This means that the total power available from the DC source is not being used all the time, thus decreasing system performance.

There have been interesting extensions of the multi-level single-phase inverter concept to the case of multiple DC source inputs [3], [5], [6], especially when there are multiple solar photovoltaic PV panels. The number of PV panels that are connected to the load can be altered using dynamic switching. This kind of solution is an ideal match for photovoltaic (PV) arrays, since such system conveniently provides a multiple DC source environment. Instead of using fractions of the DC voltage as steps for the staircase waveform, those solutions use full DC output of each PV panel, but only when it is necessary according to the desired voltage level at that instant of time.

TABLE I
SWITCHING OPERATION FOR MULTI-LEVEL INVERTER FOR SINGLE-PHASE GRID CONNECTED PV MODULES [1]

V_a	S1	S2	S3	S4	S5	S6	Sa1	Sa2	Sa3	Sa4	Sa5	Sa6
$V_7 = V_{DC}$	1	1	1	1	1	1	0	0	0	0	0	0
$V_6 = \frac{5V_{DC}}{6}$	0	1	1	1	1	1	1	0	0	0	0	0
$V_5 = \frac{2V_{DC}}{3}$	0	0	1	1	1	1	1	1	0	0	0	0
$V_4 = \frac{V_{DC}}{2}$	0	0	0	1	1	1	1	1	1	0	0	0
$V_3 = \frac{V_{DC}}{3}$	0	0	0	0	1	1	1	1	1	1	0	0
$V_2 = \frac{V_{DC}}{6}$	0	0	0	0	0	1	1	1	1	1	1	0
$V_1 = 0$	0	0	0	0	0	0	1	1	1	1	1	1

A recently proposed single phase PV multi-level inverter is discussed in [6]. It uses dynamic configuration of the various power sources to adjust the level of each step of the staircase waveform. Although the number of levels is fixed, the proposed technique can adjust the voltage level by rearranging the DC sources in any series/parallel configuration.

A shortcoming of all the mentioned studies on PV multi-level single-phase inverters [1], [5]–[7] is that the system efficiency may be severely underutilized because, at most instances of time, many PV panels (or DC sources) are not in use or only a fraction of the total DC input is being used.

For the three-phase studies [2]–[4] the same set of PV panels is used to generate the three-phase output. This means that the total current of the PV array is shared by all three-phases as it is shown in Fig. 2.

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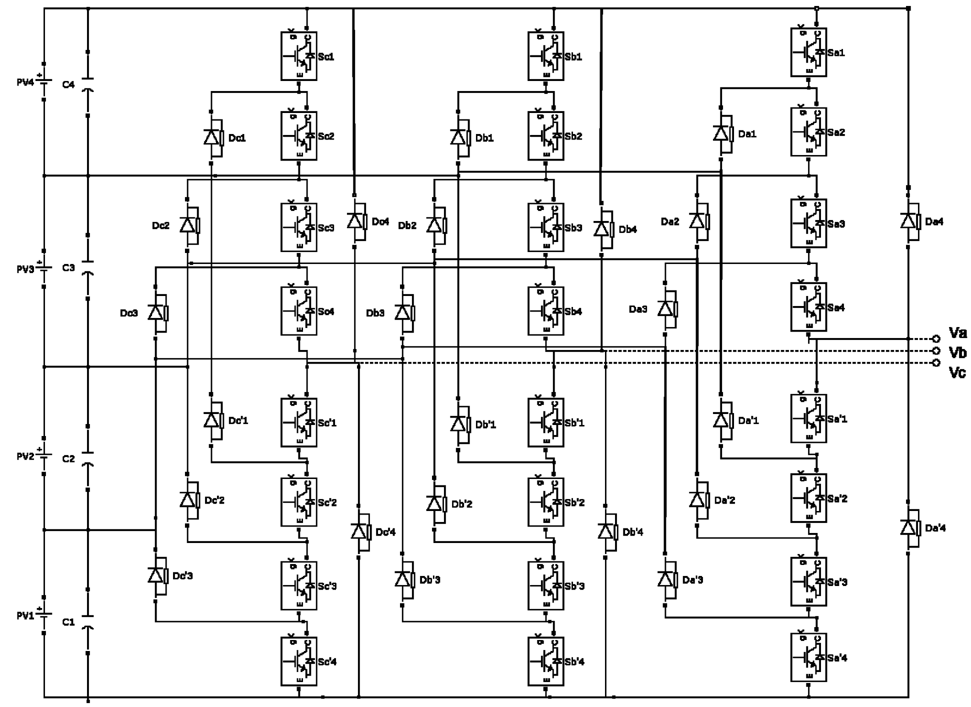


Fig. 2. Multi-level inverter for three-phase power output [4]

The purpose of this research is to extend the results of [4] and introduce a generalized three-phase multi-level PV array inverter. Our approach is to make use of a switching matrix that takes turn connecting the panels to a three phase load and allows the maximum flexibility for combining the PV panels. Harmonic quality is improved with the increase in the number of solar panels. The contributions of this research paper include:

- The introduction of an approach to generate three-phase AC output using PV panels and switching matrix;
- A method to directly generate phase voltage as opposed to line-line voltage, as in [4], for multi-level inverter.
- The presentation of a flexible PV array system that can be connected directly to the grid or operate in stand alone mode;
- Development of a method to maximize the usage of the current of a PV array and optimize PV output power, since each phase has its own PV string and respective current;
- Mathematical and a small scale lab experiment proof of concept.

II. AC GENERATION USING PV PANELS AND SWITCHING MATRIX

In recent studies [8], [9], the PV panels are dynamically arranged via a switching matrix in order to maximize a PV array's system DC output power to avoid losses caused by partial shading, faults, or defective panels. In other words, the switching matrix is only being used when there is a reduction in power output caused by problems within a few panels. The approach is then to reconfigure connections within the array to increase the DC output power [8], [9].

Nevertheless, the present project takes advantage of the flexibility provided by the switching matrix and uses it to generate three-phase staircase waveforms. In some sense, we combine the multi-level inverter presented in [4] with the reconfiguration matrix of [8]. The goal is to eventually construct a multi-level inverter that can adaptively self-heal itself and detect internal faults. However, this paper represents only the first step in the process: construction of a multi-level inverter with a generalized switch matrix.

The multi-level waveform is generated by building up the voltage levels by increasing or decreasing the number of PV panels in series. The negative cycle of the multi-level waveform can be obtained by inverting the output connections of this arrangement.

Fig. 3 shows an example of a switching matrix with ten PV panels (or ten sets of any DC source). Notice that phase A produces a negative value ($-2 * V_{DC}$, i.e. two PV panels in series), phase B and C produce $4 * V_{DC}$ (four panels in series).

The number of switches being used in this switching matrix depends on the number of PV panels in the rows and columns of the matrix. If the system has M rows and N columns, then the number of switches is 8 switches/intersection, being $8 \times N \times M$ switches for the switching matrix plus 8 switches/row for the phases connections. The total number of switches is $8 \times N \times M + 8 \times N = 8 \times N(M+1)$.

It is also observed that there is not an unique way for generating such voltages. The switching matrix allows many different layout arrangements for the same output. This pro-

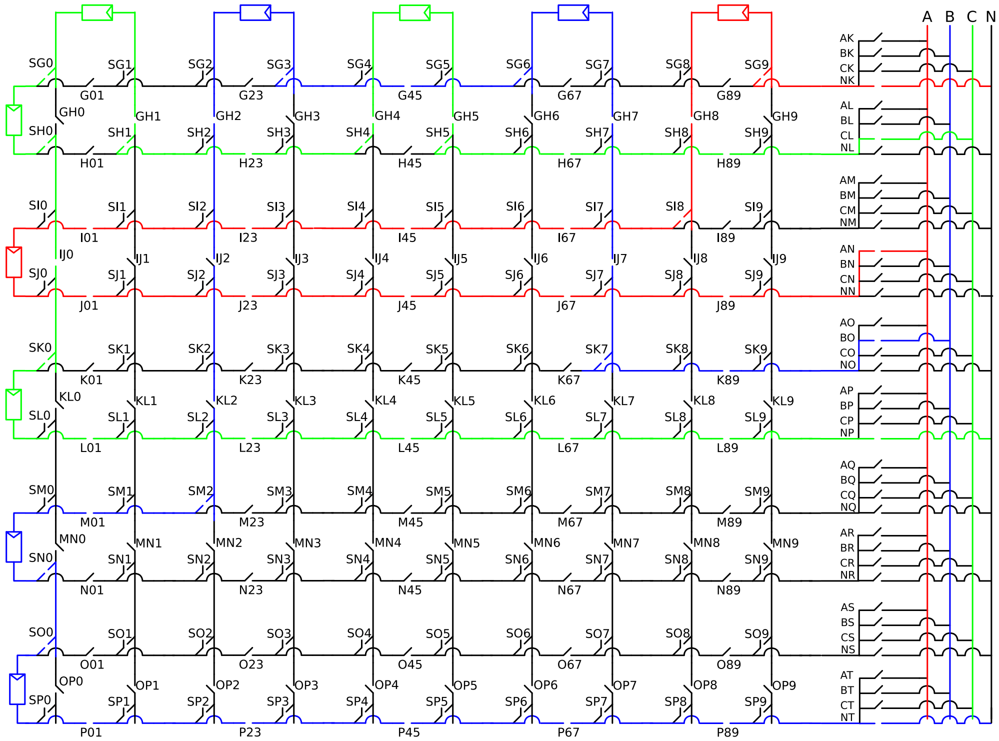


Fig. 3. Diagram of the three-phase multi-level inverter using switching matrix

vides excellent flexibility for the PV system. The circuit in Fig. 2 is a special case of Fig. 3.

A. *Single-phase versus three-phase*

Given that a PV system is composed of several PV panels, it is beneficial to try to use all of the PV panels at the same time. The multi-level feature for a single-phase waveform generation always leaves some idle PV panels, mainly while synthesizing the lower voltage levels. In this case, all the PV panels are used only when generating the maximum voltage output.

In the example shown in Fig. 4(a), the system has ten PV panels and generates 24 intervals of voltage. Some panels are not being used while generating the single-phase multi-level waveform. During one cycle of 60[Hz], the ten panels should be used 24 times if a 100% of utilization factor is considered. However, in this example, the total number of panels utilized in one cycle is 156 so the utilization factor is $\frac{156}{24 \times 10} = 65\%$. This utilization factor reflects directly on the total power output. If the system produces 100% of energy when all panels were used during the whole cycle, now it can only produce only 65% in the same time.

Nevertheless, if the system has twenty PV panels, they can be arranged to generate three-phase multi-level waveforms using our proposed approach as shown in Fig. 4(b). In this case, the utilization factor is 96.67%. For example, during t_4 there are 3 PV panels being used by phase A (red), 7 PV panels in phase C (blue) and 10 PV panels for phase B (green). The simple idea is to create switching patterns that allow the PV panels to be connected to any of the three phases. So, when one phase does not need a panel to create a low voltage, another phase can use that same panel.

B. *Switching frequency and step intervals*

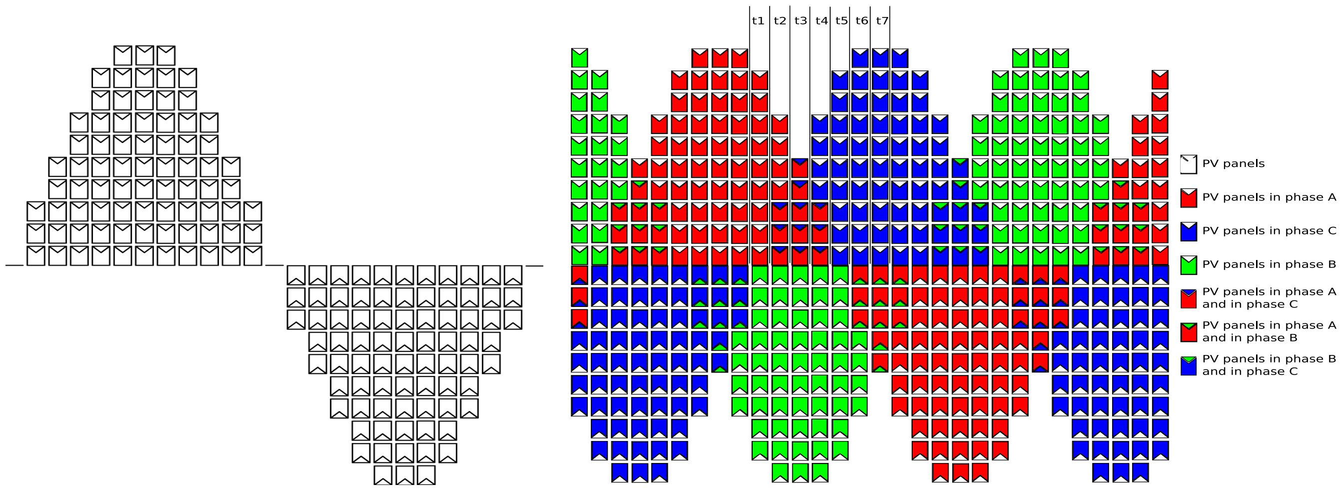
Fig. 4(b) shows each phase with its own quantity of PV panels depending on the instant of time. In t_1 and t_5 there are 18 PV panels being used at the same time. During t_2,t_3, t_4, t_6 and t_7 there are 20 PV panels being used. A problem occurs if the switching event is not synchronized for all phases. This fact is represented in Fig. 5. During the interval t_1 in Fig. 5, the green phase is using 10 PV panels, the blue phase is changing from 5 to 3 PV panels and the red phase is changing from 7 to 9 PV panels. Instead of 20 PV panels, the actual example system would need 22 PV panels in order to provide such waveforms.

C. *Analysis and simulations*

A simulation software was developed in Matlab in order to compute some alternatives for number of intervals and PV panels and also to calculate waveforms, RMS and THD values.

The script first calculates the divisors of 120° in order to find the number of intervals (steps) of a 60 [Hz] cycle. The waveforms are then synthesized by using a sinusoidal waveform as the reference, divided by that number of intervals. Each interval has a value based on the cosine of its midpoint.

After that, the cosine values are rounded and an integer number of PV panels is chosen as exemplified at Table II. This procedure is necessary because it normalizes the



(a) Ten PV panels grouped to generate a single-phase multi-level waveform

(b) Twenty PV panels grouped to generate a three-phase multi-level waveform

Fig. 4. Illustrative graphic to show the differences between single-phase and three-phase waveform generation

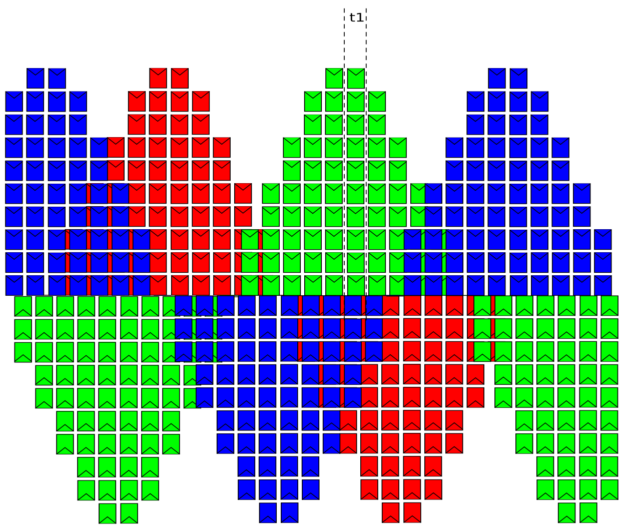


Fig. 5. The overlapping of PV panels if they are not being switched at the same time

sinusoidal waveform and provides an initial guess for the required number of PV panels. In fact, the quantity of PV panels available will determine the number of PV panels to be used.

The root mean square (RMS) value for each waveform is calculated by the equation (1).

$$RMS = \sqrt{\frac{1}{T}\int_0^T f(t)dt} = \sqrt{\frac{1}{T}\sum_{n=0}^{T} f(n)\Delta t} \quad (1)$$

The total harmonic distortion (THD) value for each waveform is calculated by the equation (2).

$$THD = \sqrt{\frac{\sum_{h=2}^{m} {V_h}^2}{{V_1}^2}} \quad (2)$$

where h is the harmonic index and V_1 is the amplitude of the fundamental value.

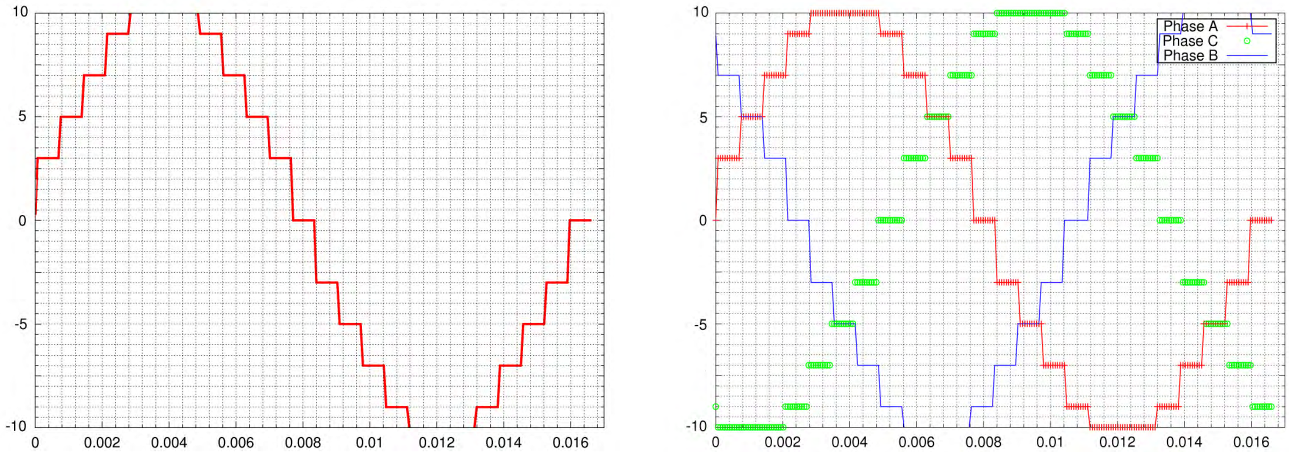
TABLE II
AN OPTION FOR OBTAINING THE NUMBER OF PANELS PER PHASE FOR 24-STEP THREE-PHASE VOLTAGE

Angle (rad)	Cosine	Rounding	# panels considered
$\frac{\pi}{12}$	0.2575	0.3	3
$\frac{\pi}{6}$	0.5	0.5	5
$\frac{\pi}{4}$	0.704	0.7	7
$\frac{\pi}{3}$	0.865	0.9	9
$\frac{5\pi}{12}$	0.9625	1.0	10
0	1.0	1.0	10

In this work the sinusoidal waveform was discretized in 24 steps, each value was rounded and an approximation factor was used to transform the result in an integer number (quantity of PV panels) as it is shown at Table II. Therefore, the waveform for this 20 panel, three-phase and 24-step example results in a THD of 7.6% and RMS of 0.7.

For example, it is possible to generate a single-phase multi-level waveform using 10 PV panels (Fig. 6(a)). In this case less than 10 panels are being used during most of the time. The utilization factor is 65% as stated before.

For a three-phase system it is possible to create an arrangement that utilizes all the PV panels almost all the time. One example of such case can be seen in Fig. 6(b) and Table III.



(a) Single-phase waveform using 10 panels

(b) Three-phase waveform using 20 panels

Fig. 6. Number of PV panels versus time [s] for 24-step waveform

TABLE III
NUMBER OF PV PANELS TO GENERATE A 24-STEP THREE-PHASE VOLTAGE.

phase A #panels for A	0° 0	15° 3	30° 5	45° 7	60° 9	75° 10	90° 10
phase B #panels for B	−120° (9)	−105° (10)	−90° (10)	−75° (10)	−60° (9)	−45° (7)	−30° (5)
phase C #panels for C	120° 9	135° 7	150° 5	165° 3	180° 0	195° (3)	210° (5)
Total #panels	18	20	20	20	18	20	20

In this case, the utilization factor of 96.67% is the same as the previously mentioned case.

It is possible to use 20 panels at the same time to generate a three-phase waveform that is quite similar to the single phase shown in Fig. 6(a) (which results in the same 24-step case, but is generated by 10 panels).

III. EXPERIMENTAL RESULTS

An experiment using 4 PV panels was set in order to test the feasibility of the proposed system as presented at Table IV and Fig. 7. In this case, while one phase has 2 PV panels generating higher voltage, the other two phases have only 1 PV panel each generating an opposed signal voltage.

TABLE IV
NUMBER OF PV PANELS TO GENERATE THE 6-STEPS THREE-PHASE VOLTAGE USED IN THE EXPERIMENT.

phase A #panels for A	0° 1	60° 2	120° 1	180° (1)	−120° (2)	−60° (1)	0° 1
phase B #panels for B	−120° (2)	−60° (1)	0° 1	60° 2	120° 1	180° (1)	−120° (2)
phase C #panels for C	120° 1	180° (1)	−120° (2)	−60° (1)	0° 1	60° 2	120° 1
Total #panels	4	4	4	4	4	4	4

The switching matrix was replaced by the *HP Agilent 34970A - Data Acquisition /Switch Unit* with *34904A* - 4×8 *Matrix Switch* module using mechanical relays. The equipment

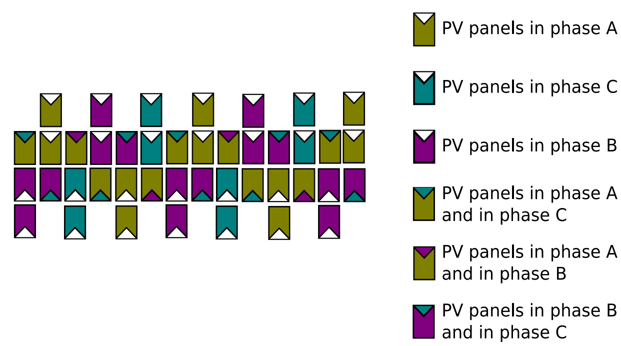


Fig. 7. Four PV panels grouped to generate a three-phase multi-level waveform

was programmed using RS-232 communication and Matlab script.

Four PV panels PF-R7 from *PowerFilm* were used to generate the three-phase voltages. The open circuit voltage for each panel is about 20[V].

The results of the experiment can be seen at Fig. 8. Although the frequency of the waveforms is limited due to the slow speed of the specific equipment, the results can be used as proof of concept. The peak voltage is 40[V] for each waveform, thus confirming the open circuit voltage for the PV panels. The RMS value for each resulting waveform phase is 27.4[V]. The AC frequency is 0.75 [Hz].

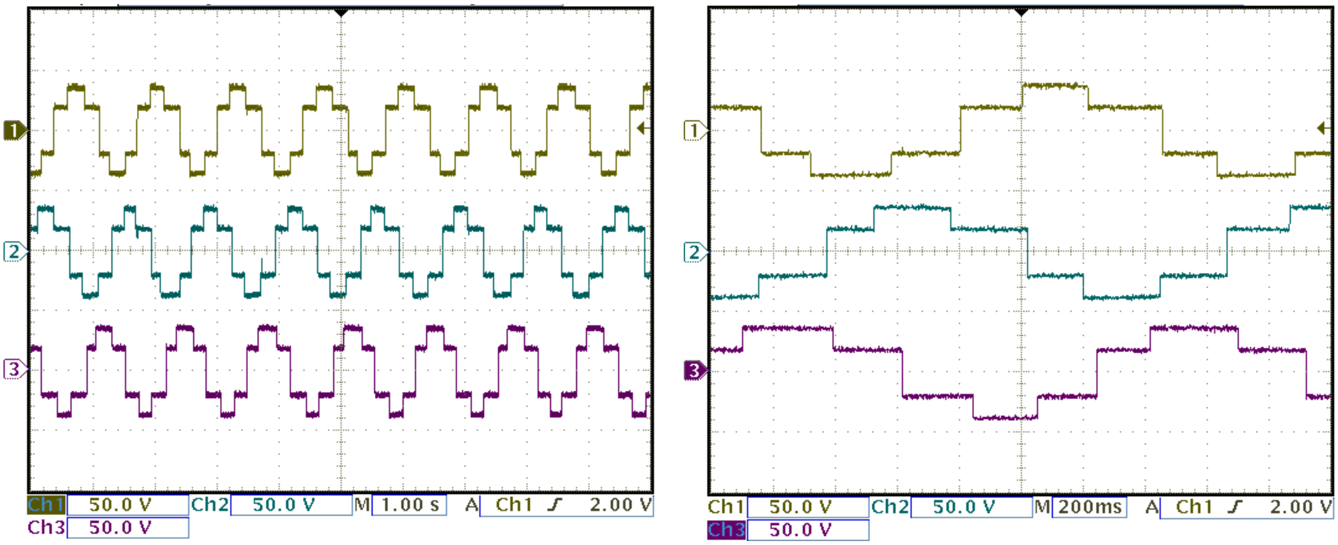
A 6-level three-phase sinewave has been created.

Further the switching matrix might be implemented using transistors instead of relays [8] in order to easily permit 60 [Hz] frequency output.

IV. CONCLUSIONS

The contributions of this work can be summarized as follows:

- The project extend the results of [4] by introducing a



(a) Three-phase voltages

(b) Zoomed view for the three-phase voltages

Fig. 8. Experimental results

generalized switching matrix approach to create a three-phase multi-level inverter.

- The switching matrix allows the PV array layout to be flexible. This flexibility can also be used to maximize the power output and reduce power loss from damaged panels or shading [8], [9];
- The Δt (interval) for each voltage level is evenly distributed: this is important because the system must maximize the usage of the PV panels. Therefore, the maximum number of PV panels allowed must be used at the same time. This goal can be reached with less effort if all three-phase voltage levels are generated at the same time;
- A method for calculating the number of intervals is presented: this number must allow the creation of a balanced three-phase waveform where all phases present 120° of difference (phase shift) between each other. Not all combination of numbers for PV panels can result in a good solution for generating three-phase waveforms.

This paper also suggests the following open research issues:

- What is the best way to approximate the sinusoidal waveform using integer number of solar panels? Calculation methods might consider:
  - The cosine of the midpoint value of each interval;
  - The average value of the cosine for each interval;
  - The latest value of cosine for each interval.
- The study of different topologies for the switching matrix or how to arrange the PV panels in rows and columns. For example, Fig. 2 taken from [4] becomes a special case of the switching matrix;
- The study of the transient behavior of the PV array facing the switching events;
- The different methods to control the switching matrix: optimal control theory, artificial intelligence algorithms (neural networks, fuzzy logic, etc.);
- Including the results of [8] in order to allow the multi-level inverter to adapt its operation in response to shadow patterns, faults, or other failures within the arrays.

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