A Grid-connected PV Power Supply based on Flying Capacitor multicell converter with modified MPPT based Control for Active Power Filtering

M. Sadeghi, M. Khederzadeh and M. Agha-Shafiyi

Abstract — This paper presents a grid connected photovoltaic system, which acts as both power generator and active power filter (APF), based on Flying Capacitor Multicell (FCM) converter. Increase in the number of output voltage levels, natural self-balancing of flying capacitors and dc link voltage and lower power rating of components are the main futures of FCM converter compared with conventional multilevel converters. Furthermore, in this paper a new control method based on instantaneous reactive power (IRP) theory and Predictive Current Control using modified phase shifted sinusoidal PWM modulation method has been presented and applied to proposed APF. Also, using a simple method for maximum power point tracking (MPPT), maximum available power of PV array has been injected to system. Finally, the control strategy and the whole system is simulated by PSCAD/EMTDC software and results are presented to validate the performance and advantages of proposed system as well as its control strategy.

Index Terms - component; Active Power Filter (APF); Flying Capacitor Multicell converter (FCM); instantaneous p-q theory; photovoltaic (PV); Maximum Power Point Tracking (MPPT)

I. INTRODUCTION

DISTRIBUTED generation (DG) has already been an important issue due to the valuable role of renewable energy resources in the battle of carbon dioxide levels stabilization. Among DG production plants that can be connected to LV network the PV systems seem to be a rather beneficial choice, since its vast availability [1-3]. However, the PV array loses the output capability when the irradiation is weak or it is night, which forces the whole system to be removed from the grid [2-4]. Consequently, to overcome the disadvantage of the grid-connected PV system, some multi-functional PV systems have been proposed. The systems include additional function as an active power filter or STATCOM [3-6].

Nowadays there is an increasing interest in the use of shunt active power filters (APF) in power systems, to cancel harmonic currents generated by non-linear loads and compensate fundamental reactive power. The use of switched electronic devices on the electric networks is continuously growing up. So, the line voltages and currents waveforms are affected by considerable distortion levels, which cause problems either to transmission and distribution network or to industrial and civil users. APFs can improve the energy quality of the electric suppliers and can positively influence the symmetry and the values of power factor [2-6].

Consequently, it is reasonable to utilize a PV system to supply local loads as well as employ it as an AF compensator to reduce the total costs without additional hardware. As a result, PV systems can play two significant roles; firstly supplying loads and secondly; removing undesired (harmonic/imbalanced) currents in a utility grid [2-4].

Most of the published literature on PV-APF is based on two-level or 3-level inverters [1-5]. As the power rating of the APF increases, high voltage switching devices have to be used to reduce the current rating of the converter. High voltage switching devices are comparatively costlier and can not be switched at high switching frequency. Further more, because of injected harmonics and high THD of the output voltage, large filters must be used. To overcome these problems several new inverter topologies can be used [6-9].

The Flying Capacitor Multicell converter, have many attractive properties for medium voltage applications including, in particular, the advantage of transformer-less operation and the ability to naturally maintain the flying capacitors voltages at their target operating levels [10]. This important property is called natural self-balancing and allows the construction of such converters with a large number of voltage levels [11]. Furthermore, the main future of this configuration is making possible to share the voltage constraint on several switches; so the voltage ratings of capacitors and the semiconductor losses are reduced.

However, PV based Active Power Filter configuration based on the FCM converter has not been presented yet. Considering the mentioned properties, in this paper a new topology of PV-APF based on a 4 - cell - 7 - level full bridge 3-phase FCM converter based shunt APF is proposed.

In such multi-functional system, there are two challenging issues in controlling the system. The first issue is the MPPT of the PV array. There are several techniques available for it [4-5]. In this paper in order to track MPP a Boost converter along with simple approach is used. The second issue is determining the reference current and the firing angles of FCM converter; so, a new modified control strategy in accordance with P-Q

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Theory and Phase Shifted PWM method and using Predictive Current Control will be applied to proposed PV-APF. Finally, simulation results will be demonstrated to verify the validation of this proposed topology of APF advantages and its modified control method.

II. Proposed FCM Based Photovoltaic System for Active Power Filtering

A conventional topology of grid connected PV system is shown in Fig. 1. As it can be seen from the figure, the PV-APF system contains a PV array, Boost converter, dc link, a voltage source converter and a coupling transformer. This APF uses a control strategy to generate the desired output voltage and current for the unbalanced and harmonic utility grid with linear and non-linear load, besides injecting the PV energy to the grid.

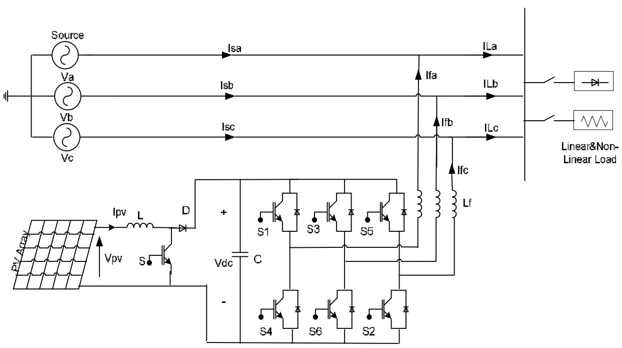

Figure 1. Conventional topology of PV based shunt Active Power Filter.

Due to the main role of voltage source converter as a heart and generator of desired output voltage and current, In this paper, a new configuration of shunt APF based on the FCM converter is proposed to increase the number of output voltage levels and as a result, reduce the output voltage THD with reduced ratings and losses of flying capacitors and semiconductors. A 4-cell-5-level single phase FCM converter is shown in Fig. 2.

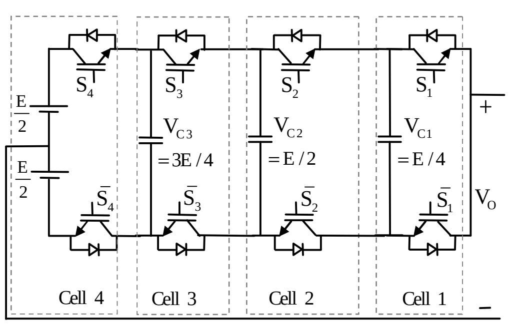

Figure 2. 4-cell FCM converter configuration.

In addition to transformer-less operation and the natural self-balancing ability of FCM converter, increase (redundancy) in the number of combinations required to obtain a desired voltage level and reduction in the voltage ratings of capacitors and stored energy in the flying capacitors as well as the semiconductor losses are the other advantages of this converter [11-12]. Because of mentioned properties, in this paper a 7-level full bridge three phase FCM converter, as shown in Fig. 3, is adopted to be used in PV-APF system. As shown in Fig. 2, there are two dc capacitors for dc link of each single phase FCM converter, therefore for three single-phase FCM converters, six dc capacitors are required. While, as shown in Fig. 3, in this configuration only one dc link is used for three single-phase FCM converters and the number of voltage levels has been doubled. As a result, the required dc capacitors for dc link are decreased from six to one. Also just one three phase transformer will be used to inject the currents. Further more, compared with other multilevel converters, just one PV array with its associated boost converter can be used as a DG source to inject the energy due to one dc link requirement.

III. Proposed control strategy of FCM based shunt APF with PV system

In accordance with the presented FCM based PV-APF system, three main control considerations must be paid to attention as follows:

- Generating the proper reference signals for compensating
- FCM converter control considerations for saving the converter properties and advantages
- MPPT control considerations to inject the maximum power of PV system

In an active filter control, the main target is to find a method to generate the compensating currents. So, first the reference current that the APF should inject must be determined, and then this reference current should be converted to reference voltage. Finally, this reference voltage must be generated according to proposed control scheme. In continue, the procedures of generating reference current and voltage with the proposed control strategy considering SM modulation method are introduced. Also, a control method for the boost converter of PV system has been presented to achieve maximum power point tracking of PV.

A. Reference current generation

The reference signals are provided by the external control, from operator instructions and system variables, which determine the functional operation of the shunt APF.

The reference current of shunt APF are generated based on the identification of instantaneous values of active and reactive power, using Instantaneous reactive power (IRP) theory. This theory was initially proposed by Akagi [8]. This theory is based on the transformation of three-phase quantities to two-phase quantities in α–β frame and the calculation of instantaneous active and reactive power in this frame.

According to IRP or p-q Theory the voltage (v_L) and the current (i_L) are transformed from the abc to αβ, using Clarke's transformation as follows [5-8]:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \quad (2)$$

Since, there are no zero-sequence current components in balanced three phase three-wire systems, the instantaneous active and reactive powers are define on the following coordinates [1, 7 and 8]:

$$P = v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta \quad (3)$$

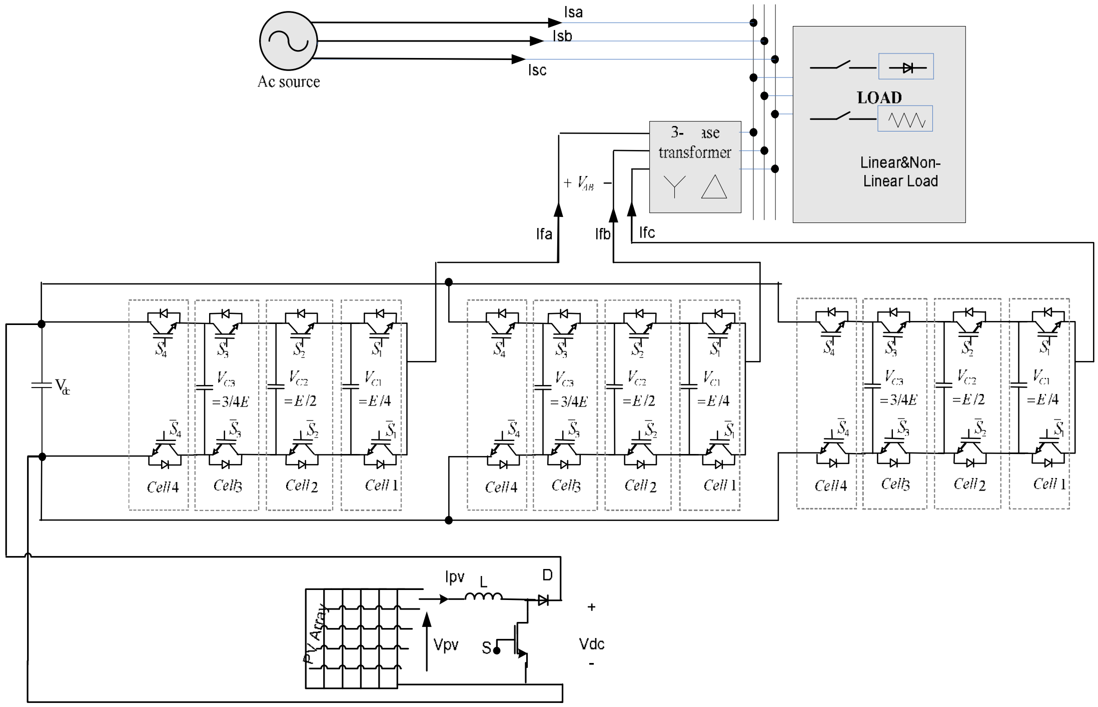

Figure 3. 4-cell FCM converter configuration.Power circuit of the proposed PV-APF based on full bridge three phase 5- cell - 7 - level FCM converter configuration.

$$Q = v_a \cdot i_b - v_b \cdot i_a \tag{4}$$

Where v_a, v_b, i_a and i_b are the α-components and β-components of current and voltage. Considering (3) and (4), the reference currents can be evaluated as the following equations:

$$i_{a,ref} = \frac{v_a \cdot \tilde{P} - v_b \cdot \tilde{Q}}{\sqrt{v_a^2 + v_b^2}} \tag{5}$$

$$i_{b,ref} = \frac{v_b \cdot \tilde{P} + v_a \cdot \tilde{Q}}{\sqrt{v_a^2 + v_b^2}} \tag{6}$$

Where, $\tilde{P}$ and $\tilde{Q}$ are the oscillatory (ac) part of the real and reactive instantaneous powers, respectively. Finally, using reverse Clark's transformation, the reference currents of APF in abc form will be achieved.

B. Extraction of Reference Voltage

Using Predictive current control the reference voltage will be achieved. If the coupling transformer shown in Fig.3 is modeled as a simple inductor, the deferential equation of the inductor can be written as [1-3]:

$$v_f = L_t \frac{d}{dt} i_f + v_s \tag{7}$$

Where v_f, i_f and L_t are the output voltage and current of APF and the inductance of coupling transformer, respectively. Equation (7) can be represented in a discrete form as follows:

$$v_f^*(n+1) = v_s(n) + L_t \left(\frac{i_f^*(n+1) - i_f(n)}{T_s} \right) \tag{8}$$

Where $v_f^*(n)$ and $i_f^*(n)$ are the output voltage and current of APF for the n^{th} step time, respectively. Using Kirchhoffs current law at the common coupling point and substituting it in accordance with reference current in (8), the reference voltage can be given as:

$$v_f^*(n+1) = v_s(n) + L_t \left(\frac{i_s(n) - i_s^*(n)}{T_s} \right) \tag{9}$$

Where $v_s(n)$ and $i_s(n)$ are the output voltage and current of system for the n^{th} step time, respectively.

C. FCM Converter Control Considerstion

The flying capacitors voltages of FCM converter balancing occurs naturally without any feedback control using pulse wide modulation (PWM) control method. A necessary condition for self-balancing is that the average flying capacitors currents must be zero. As a result, each cell must be controlled with the same duty cycle and a regular Phase Shifted Pulse Width Modulation (PSPWM) in which the phase shift between the carriers of each cell must be [11-13]:

$$\theta = \frac{2\pi}{n} \tag{10}$$

where, n is the number of cells. The PSPWM for the 5-level single phase FCM converter is shown in Fig. 4 in which the M symbol dedicates the modulation index.

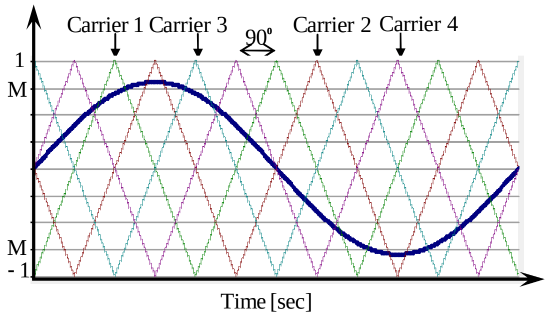

Figure 4. Phase shifted pulse width modulation for 5-level single phase FCM converter.

Usually, in order to accelerate the self-balancing process of flying capacitors voltage an output RLC filter (balance booster circuit) is needed. This filter, which consists of a resistance, inductance and a capacitance connected in series, accelerates the self balancing process and is connected in parallel with load.

D. MPPT considerations of PV control

Considering the PV array power diagram it can be inferred that the curve is zero at the MPP point, positive on the left of the MPP, and negative on the right. Consequently:

$$\begin{cases} \dfrac{dP}{dV} = 0 & \text{at MPP} \\ \dfrac{dP}{dV} > 0 & \text{left of MPP} \\ \dfrac{dP}{dV} < 0 & \text{right of MPP} \end{cases} \qquad (11)$$

In order to drive dP/dV to zero a proportional integral (PI) control are used and its output will be used as the duty cycle (D) of boost converter as shown in Fig. 5.

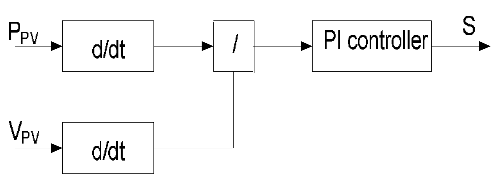

Figure 5. The applied MPPT control to boost converter of PV

Using the mentioned control Considerations, the block diagram of the main control system of the proposed FCM based PV-APF is shown in Fig. 6.

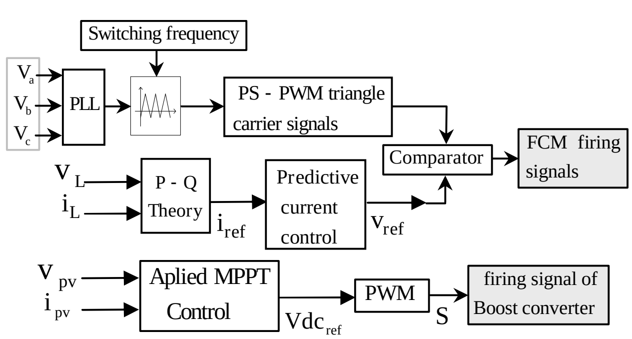

Figure 6. The main proposed control system of the FCM based PV-APF.

IV. Simulation Results

In this section, a computer simulation of the proposed FCM based PV-APF system as well as proposed control strategy method is provided using PSCAD/EMTDC software in order to verify its good performance. The proposed FCM based PV-APF is simulated and implemented in a simple power system based on the proposed configuration shown in Fig. 3. The source line to line rms voltage is 380V with frequency of 60Hz , the load is assumed as a tyristor based rectifier which feeds a resistive-inductive load and a linear load. The simulations are done in different operational conditions of PV and in balanced and sinusoidal supply voltage with different loads to prove the capability of proposed system to track the MPP of PV array and compensation of non- linear load currents.

The inductance of coupling transformer is 1mH and the proposed APF's switching frequency is chosen equals to $f_{switching} = 10kHz$. The parameters used in the simulation are given in Table1.

TABLE I. Main parameters of power system

Parameters	Values
Nominal source RMS voltage	311 V
Fundamental system frequency	60 Hz
Main nonlinear Resistive-Inductive load	10Ω; 65mH
Linear Load	15Ω; .02H
Transformer inductance	1mF
Switching frequency of converter($f_{switching}$)	10kHz
Output RLC filters	20Ω ; 0.1mH ; 2.7μF
dc link capacitor	2mF
flying capacitors (C)	0.8mF
Boost converter frequency	3.5kHz
Boost converter inductance	300mH

The proposed system was simulated to evaluate the system capability in response to variations of PV power caused by changing in light intensity and temperature levels. Fig. 7 shows three stages provided by changing in light intensity and temperature. In the first stage light intensity is about 800W/m2 and temperature is about 35ºC. This stage is endured for about 0.2 sec (0<t<0.2sec). The second stage starts when the light intensity underwent a step to swell to 1100W/m2, and temperature remains constant. This stage continued up to 0.3 sec. In the third stage, which starts at 0.3sec and continue up to 0.5sec, temperature boomed to 10ºC and light intensity remains constant.

According to explained stages which are shown in Fig. 7, the Power-Voltage curves of PV array are identically changed as shown in Fig. 8. Consequently, the duty cycle of Boost converter effectively changes to track the next MPP in the next stages as shown in Fig. 9. Also Fig. 10 shows the variations of power of PV array.

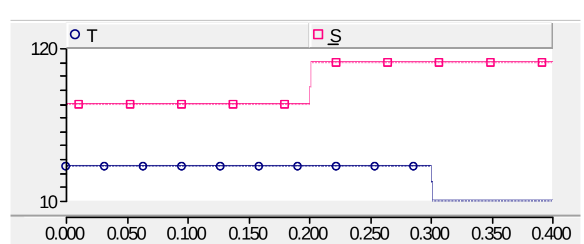

Figure 7. The variation in light intensity and temperature.

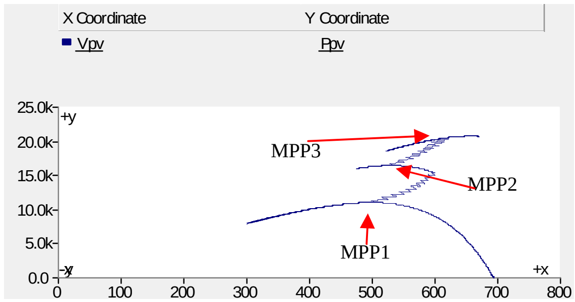

Figure 8. The variation in P-V curves of PV array due to mentioned stages.

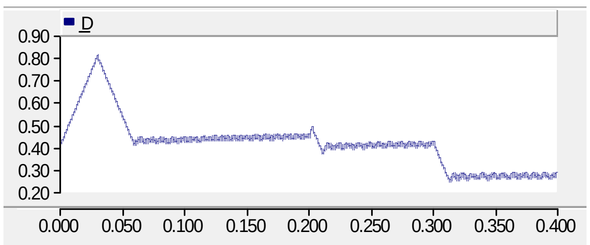

Figure 9. The variation of boost converter's duty cycle due to mentioned stages

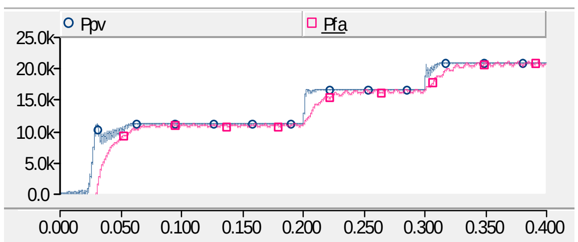

Figure 10. The variation of PV power due to mentioned stages

The load currents with THD of 20.45 and the compensated source currents with THD of 2.01 are shown in Figs. 11 and 12, respectively. As demonstrated from figs. 11 and 12, the PV-APF system compensates the load current and also feed it which decreases the main source current values.

Fig. 13 shows the point of common coupling (PCC) voltage, where the proposed PV-APF connected to the main bus. As shown in Fig. 13, the generated voltage of APF has the minimum effect on the bus voltage which is one of the main advantages of using SM multilevel converter in proposed shunt APF. Furthermore, Fig. 14 shows the dc link voltage and the internal flying capacitors voltage of FCM converter for one phase of proposed FCM based PV-APF that confirms the appropriate natural self-balancing ability of FCM converter.

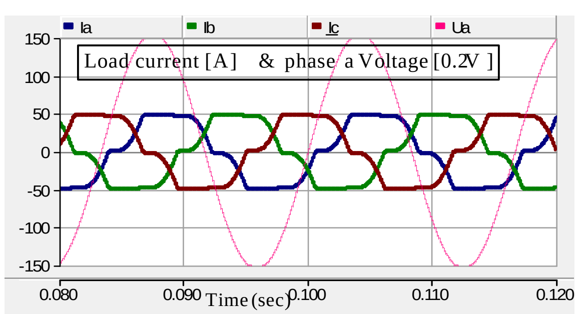

Figure 11. The load currents with THD of 20.45.

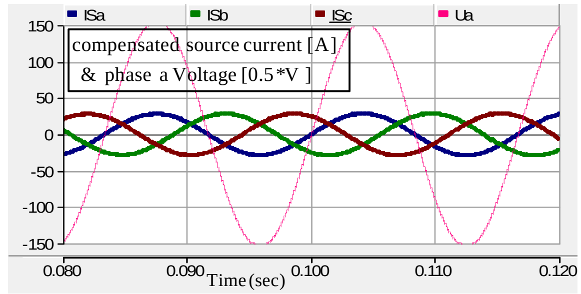

Figure 12. The compensated source currents with THD of 2.01.

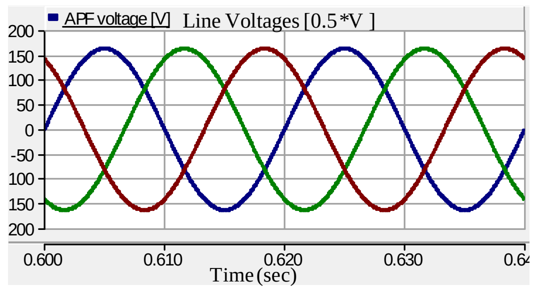

Figure 13. the point of common coupling (PCC) voltage.

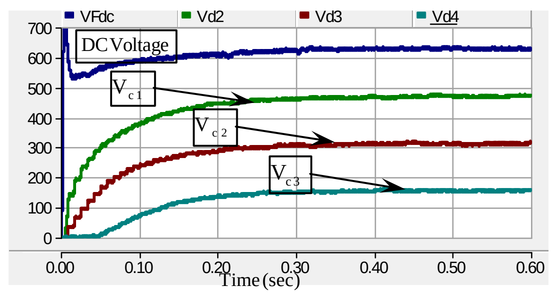

Figure 14. Main DC and flying capacitors voltage of the FCM converter based PV-APF

V. CONCLUSION

A new FCM converter based grid connected PV system for both Active Power Filtering and energy injecting has been proposed in this paper to improve the performance and futures of this component, especially in high-power/medium-voltage applications. In addition to transformerless operation and the natural self-balancing ability of FCM converter, reduction in the voltage ratings of capacitors and stored energy in the flying capacitors as well as the semiconductor losses are the other advantages of this converter used in PV-APF. Furthermore, in the proposed configuration of three-phase PV-APF the number of dc link capacitors is decreased from 6 to 1 and the output voltage levels and its RMS are doubled. Using modified phase-shifted PWM based predictive current control strategy and IRP theory, the accuracy of the generated reference signals are increased and the dc link voltage balanced without any feedback control. Also, the maximum power of PV system has been injected due to applying MMPT control by a simple boost converter. The effectiveness of the proposed FCM based PV-APF has been verified by simulations with EMTDC/PSCAD simulator.

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