The Modified Control Method for the Single-Stage Three-Phase Grid-Connected Photovoltaic System

- **Phan Quoc Dzung**
- **Nguyen Truong Dan Vu**
- **Le Dinh Khoa**
- **Nguyen Bao Anh**
- **Le Chi Hiep**

University of Technology, VNU-HCM

ABSTRACT:

Single-stage topology and the maximum power point tracking (MPPT) algorithm have advantages such as simple configuration and high efficiency in grid-connected photovoltaic (PV) systems. In conventional systems, current and voltage sensors of PV system are normally used for MPPT. This paper presents a modified control algorithm for the single-stage three-phase grid-connected PV system without PV current sensor with a variable step MPP-tracker. This algorithm is not derived from complex state equations and is not dependent on any circuit parameters. It simply calculates the output power of the inverter to replace the input power of the PV systems in the MPPT algorithm. The modified algorithm is simulated by using Matlab/Simulink software and implemented in the experimental prototype. With the single-stage configuration and PV current sensorless method, the prototype is suitable for lowcost high efficient implementation in the practice.

Keywords: *Single Stage Configuration, MPPT, Photovoltaic System.*

INTRODUCTION

Nowadays, PV energy system is one of important source for sustainable development in most of countries all over the world. It features pure source and easy-to-install system. Moreover, it does not require complex and usual maintenance. Often, there are two categories for photovoltaic (PV) systems: 1) standalone system and 2) direct grid-connected system. Standalone systems are in low-power application and use many battery banks for power reservation. In direct grid-connected application, the PV system power is converted and directly injected into electricity grid.

The PV power and voltage have a non-linear relationship. Therefore, it is indispensable to operate a PV system in maximum power point.

The maximum power point (MPP) is dependent on environmental elements, such as irradiation, temperature. The maximum power point tracking (MPPT) algorithms are developed for those PV systems always produce the maximum power regardless of the environment. During years, many MPPT methods have been developed and implemented such as Hill Climbing/P&O, Incremental Conductance (IncCond), Fractional Open-Circuit Voltage or Short-Circuit Current methods, based on Fuzzy logic or Neural Network methods [1-7].

The maximum power point tracker (MPPTer) usually requires two sensors in the input side for PV system voltage and current. However, the PV system voltage, current and grid currents have relation based on mathematical equations. Thus, some strategies are developed to estimate the information of PV system voltage or PV system current without sensors. These algorithms are often affected by circuit parameters or based on complex theory of observer [8], [9]. These problems make the algorithms difficult to implement in practice.

The single-stage grid-connected PV systems have been presented in many publications [10-14]. In these systems, both current and voltage sensors of PV array are usually used to realize MPPT. In the other work [15], unlike other MPPT methods, only PV array's output voltage is required to be sensed to implement MPPT. However, the algorithm for this scheme is quite complex and suitable only for a single phase grid-connected inverter.

With a goal to minimize the cost and control complexity, this paper presents a low-cost single-stage three-phase grid- connected PV system without the PV array's output current sensor. The modified algorithm observes the output power of inverter instead of the input power of PV system.

CONVENTIONAL AND PROPOSED SINGLE-STAGE THREE-PHASE GRID-CONNECTED PV SYSTEM WITH MPPT ALGORITHM

Single-stage configuration is used to remove the DC/DC converter. This configuration is useful to increase the efficiency and decrease overall cost (Fig.1). Fig.2 and the equation (1) show the relationship between DC-link voltage, inverter and grid voltages.

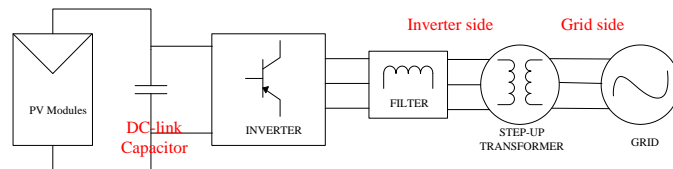$$\frac{2}{\pi} \cdot 0.9 \cdot U_{DC-link} = v_i = \sqrt{(\omega Li)^2 + v_g^2} \qquad (1)$$

Figure 1. Single-stage three- phase grid- connected PV configuration with step-up transformer
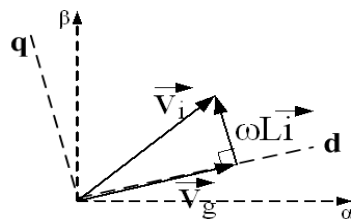

Figure 2. Relationship between DC-link, inverter and grid voltages

Conventional control algorithm for single stage PV system

MPPT algorithm for single-stage configuration is based on U_{dc}-controling ability of the inverter. The inverter changes the altitude of I_d (d-axis value of grid-current-space-vector in the grid-voltage-coordinate) to change U_{dc} into $U_{dc\text{-}reference}$. MPPTer detects the maximum power point (V_{ref} = V_{MPP}). Afterthat, the inverter will keep the U_{dc} approximately equal to this value as showing in *Figure 3a*.

Block MPPT: using any MPPT algorithms such as P&O, Incremental Conductance... Receiving PV system voltage and current, this block determines the optimal voltage for operating in next step. The output voltage V_{ref} is kept closer and closer the maximum power voltage.

Block Control: controlling three currents injected into grid. Some methods can be used to control the currents [16], [17]: PI control, hysteresis control (Fig.3b), deadbeat control... In this paper, the hysteresis algorithm is used because of simplicity and flexibility. Often, I_{q_ref} is kept zero so that the grid current and the grid phase voltage are in the same phase, unity power factor. Beside that, I_{q_ref} can be different from zero to compensate the reactive power as desired.
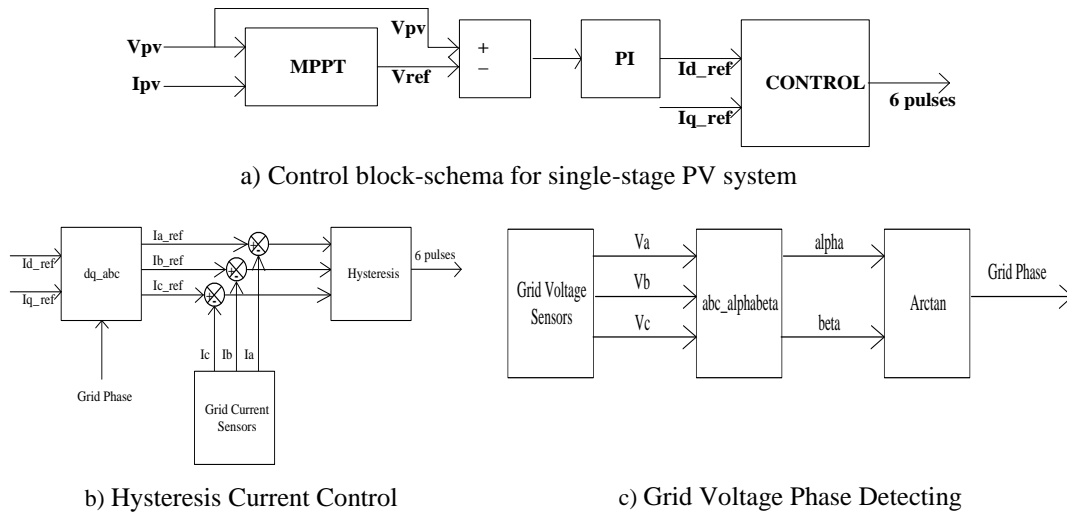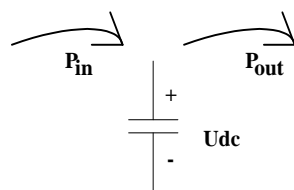

a) Control block-schema for single-stage PV system

b) Hysteresis Current Control

c) Grid Voltage Phase Detecting

Figure 3. Control block-schema for single-stage PV system

Pin = Pout : Udc constant
Pin > Pout : Udc increased
Pin < Pout : Udc decreased

Figure 4. Relationship between DC-link value and Power Flow

Principle of DC-link Voltage Balance

Active power P and reactive one Q are controlled by tuning the values of I_d and I_q of grid currents. Where (I_d, I_q) is two components of grid current space vector in the rotation grid voltage coordinate, d-axis is identical with the grid voltage space vector (Fig.3c). The simultaneous value of (P, Q) injected into grid must ensure the stability of DC-link voltage. As mentioned above, Q is often set to zero, only P is changed to stabilize DC-link voltage (Fig.4).

In addition, the active power P can be calculated in terms of the Id component:
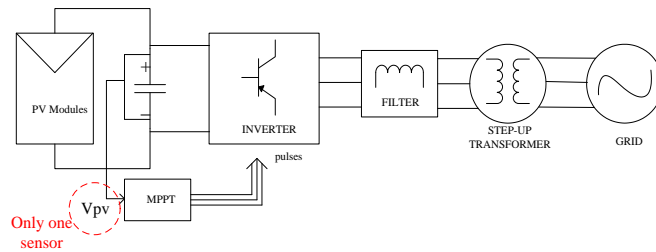
$$P = 3 \cdot V_{gd} \cdot I_d \qquad (2)$$

where Vgd is grid voltage and Id is grid current. Thus, control loop can change Id value to keep the DC-link voltage fixed.

$$\begin{cases} U_{DC} > U_{DC\_ref} : increase\ I_{d\_ref} \\ U_{DC} < U_{DC\_ref} : decrease\ I_{d\_ref} \end{cases} \quad (3)$$

The grid currents presented in this paper have the assigned direction from inverter to grid.

The proposed control algorithm for single stage three-phase PV system

The proposed algorithm uses only voltage sensor of PV array output and the MPPTer has to be detect the MPP (Fig.5).

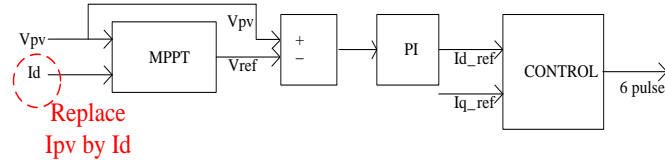**Figure 5.** Low-cost single stage three-phase grid-connected PV system

Figure 6. The block-schema of proposed control algorithm

In the block schema of proposed control algorithm (Fig. 6), the input of MPPT block includes V_{PV} and I_d. Due to principle of DC-link voltage control, the input power and the output power will be equal when Udc-link value balances out. Therefore, instead of P_{in} observation, the MPPT block can observe P_{out} to track the MPP. In this case, PV current value is unnecessary for MPPT because the MPPT block do not need to know the PV power, so the current sensor for PV array can be removed. The new

algorithm will control the PV voltage operation point to attain the maximum value of I_d.

At the beginning, the MPPTer will adjust the DC-link voltage (V_{PV}) to be equal to the initial voltage reference (V_{ref}). It may be done by using the fractional open circuit voltage MPPT method, as following:

$$V_{REF\_INIT} = (0.6 \div 0.8) \cdot V_{OC} \qquad (4)$$

where V_{OC} – the open circuit voltage of PV array

When the V_{PV} is steady, the I_d value will be observed. If the I_d value in this step is bigger than the previous step value, V_{ref} will be changed as same way as the previous step. Otherwise, V_{ref} will be changed as inverse way as the previous step (Fig.7). Thus, the stable V_{ref} is in the operation point having maximum I_d value.

The proposed algorithm is based on the method with variable step change of V_{ref}. Unlike other MPPT methods, the input power is substituted by I_d value which is easy to calculate (Fig.7). In addition, the I_{d_ref} is observed instead of I_d because the I_{d_ref} value has a little noise than I_d value and relatively identical to I_d in steady state.

In case of using fixed step, if the step size is large, the PV operation point will reach to MPP rapidly but oscillate around this point. In opposite way, if the step size is small, the operation point will be steady at the MPP but it takes a long time to reach to this point. To overcome this drawback, the proposed MPPT method uses variable voltage step size as below equation (5), the step size depends on the difference of $I_{d(k)}$ and $I_{d(k-1)}$. In this equation, the value of coefficient K is determined by using such as the optimization-based algorithm.

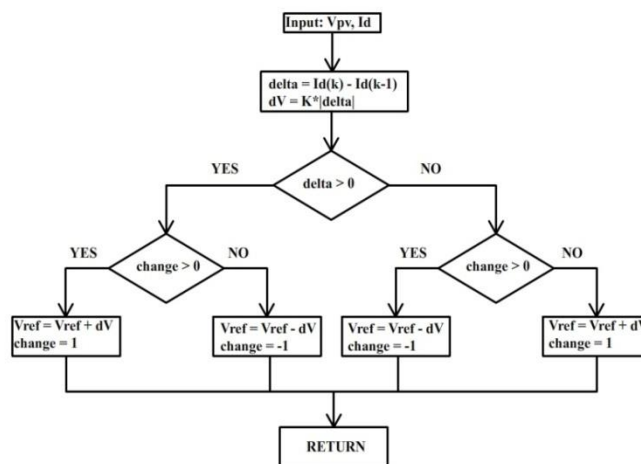$$dV = K\left|I_d(k) - I_d(k-1)\right| \qquad (5)$$

Figure 7. The flowchart of proposed variable step change of MPPT algorithm

The variable step size can combine two advantages of small step size and large step size; they are fast response time and stable operation point. At the starting, the operation point is far from MPP, the difference ($I_{d(k)} - I_{d(k-1)}$) is big, so the step size dV is also big to get MPP rapidly. After a short time, the operation point is moved to MPP, the difference ($I_{d(k)} - I_{d(k-1)}$) is small gradually and is equal to zero when it reaches to MPP, so dV is smaller than the previous one and remains zero at MPP to get the stable operation point.

Model of estimating power loss and efficiency of VSI

Estimating efficiency of solar inverters is usually based on calculating power loss of switching device [20-23]. Calculating the power loss of semiconducting switches is expressed as the following.

When a switch is operating, there are four types of power loss: conducting loss, off-state loss, switching loss, driving loss. Comparing with conducting loss and switching loss, off-state loss and driving loss are so small that they can be

neglected. The switching loss depends on the switching energy (E_{ON} and E_{OFF}) and switching frequency, the conducting loss depends on voltage (V_{CEO}), resistance (R_{CEO}) and value of current which is through the semiconducting device. The above parameters is provided by the producers, they can be selected appropriately according to operating condition and operating mode.

Energy converting efficiency of VSI is based on estimating the total power loss of semiconducting switches and it is calculated by the following formula:

$$\eta = \frac{P_{dc} - P_{L\_total}}{P_{dc}} \cdot 100\% \qquad (6)$$

With η is efficiency, P_{in} is input power of VSI, P_{Ltotal} is power loss of semiconducting switches.

The input power of VSI is determined by the formula:

$$P_{dc} = V_{in} \cdot I_{in} \qquad (7)$$

Estimating power loss of IGBT

Power loss of IGBT consists of conducting loss and switching loss, it is calculated by the following formula:

$$P_{IGBT} = \left(V_{CEO} \cdot I_{C(AV)} + R_{CEO} \cdot I_{C(RMS)}^2\right) + \left(E_{ON} + E_{OFF}\right) \cdot \frac{V_{CE\_bl}}{V_{CE\_ref}} \cdot \frac{i_C}{I_{C\_ref}} \cdot f_{sw}$$

$$(8)$$

With V_{CEO} : on-state zero-current collector-emitter voltage

R_{CEO} : collector-emitter on-state resistance

E_{ON} : turn –on energy

E_{OFF} : turn –off energy

$I_{C(AV)}$: average value of collector current

$I_{C(RMS)}$: RMS value of collector current

V_{CE_bl}: blocking collector-emitter voltage

V_{CE_ref}: blocking collector-emitter voltage from datasheet

I_{C_ref} : collector current from datasheet

i_C : collector current

f_{sw} : switching frequency

Estimating power loss of Diode

Power loss of a didoe is similar to above, it is calculated by the following formula:

$$P_{Diode} = \left(V_D \cdot I_{D(AV)} + R_D \cdot I_{D(RMS)}^2\right) + E_{rr} \cdot \frac{V_r}{V_{r\_ref}} \cdot \frac{i_d}{I_{d\_ref}} \cdot f_{sw}$$

$$(9)$$

With V_D: on-state voltage

R_D : on-state resistance;

E_{rr} : reverse recovery energy

$I_{D(AV)}$: average value of forward current

$I_{D(RMS)}$: RMS value of forward diode current

V_r : reverse voltage

V_{r_ref} : reverse voltage from datasheet

I_{d_ref} : forward current from datasheet

i_d : diode current

f_{sw} : switching frequency

Power loss P_{L_total} is the sum of power losses of IGBTs and diodes.

SIMULATIONS OF THE PROPOSED CONTROL METHOD FOR LOW-COST SINGLE STAGE THREE-PHASE PV SYSTEM

Whole simulation model is built in Matlab/Simulink with SimPowerSystem Toolbox (Fig.8).

The simulation model includes:

PV system: V_{OC} = 800V, I_{SC} = 4A, P_{max} = 2380 W (normal irradiation).

2-level inverter : Switch parameters: R_{CEO}=0.05Ω, V_{CEO}=2.5V, E_{on}=0.005, E_{off}=0.006, V_{CE_bl}/(V_{CE_ref}. I_{C_ref})=0.0117; R_D=0.01Ω, V_D=0.8V, E_{rr}=0.006, V_r/(V_{r_ref}. I_{d_ref})=0.0117.

Filter: L = 50 mH.

Grid phase voltage: V_g = 220 Vrms, f = 50Hz

Irradiation : $0 \leq t \leq 0.5s$, G =1; $0.5 \leq t \leq 1s$, G =0.7.

The simulation results for the irradiation change case are shown in Fig.9.

The input power is measured to demonstrate the operation points of PV system easily. In addition, the estimated power can be used to plot and test without measuring input power. The estimation is based on expression (2), where V_{gd}

is grid phase voltage (rms) and I_d is in rms (Fig.10a).

The grid current phase is identical to the grid voltage phase. When the irradiation changes, the magnitude of grid current is decreased (Fig.10b).
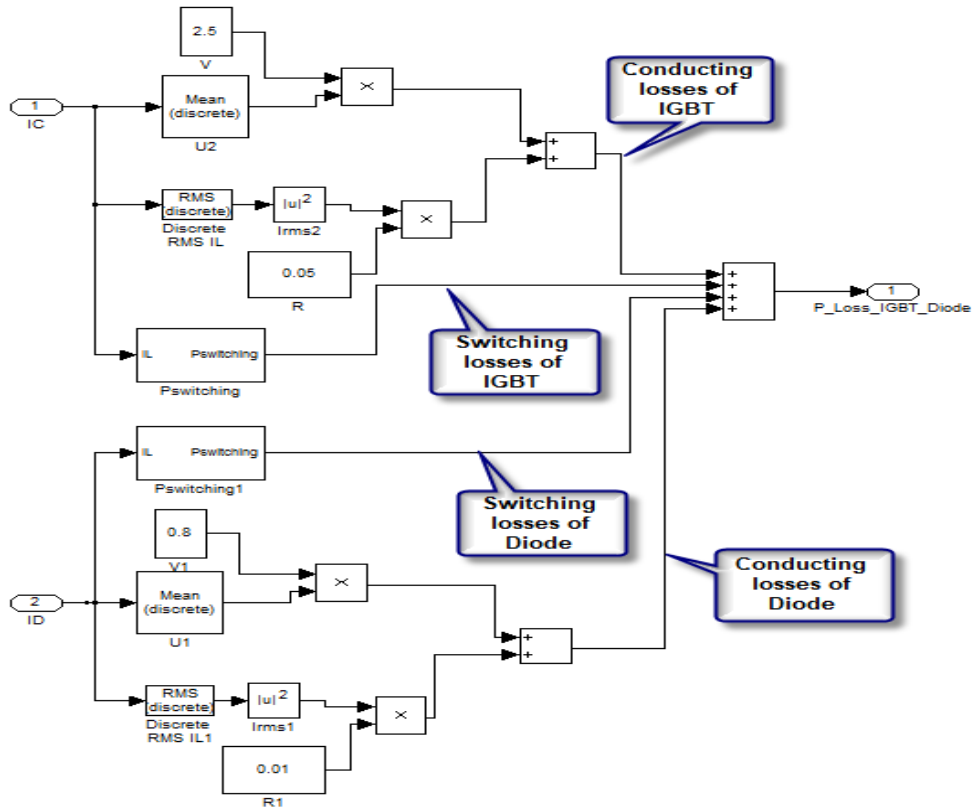
The efficiency of VSI is evaluated by using the estimation block (Fig.8c), which is based on expressions (6)-(9). The high efficiency of PV inverter is obtained as shown in Fig.10c, while the irradiation changes from 1 to 0.7 at 0.5s.
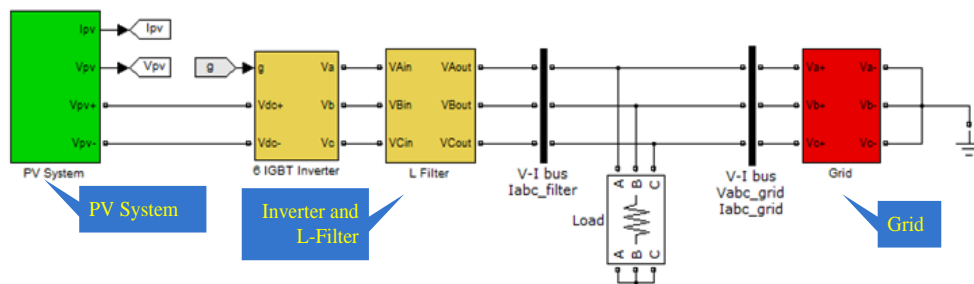
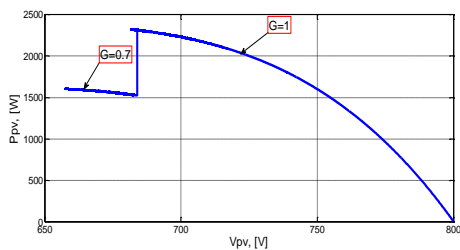a) The low-cost single-stage three-phase grid connected PV system
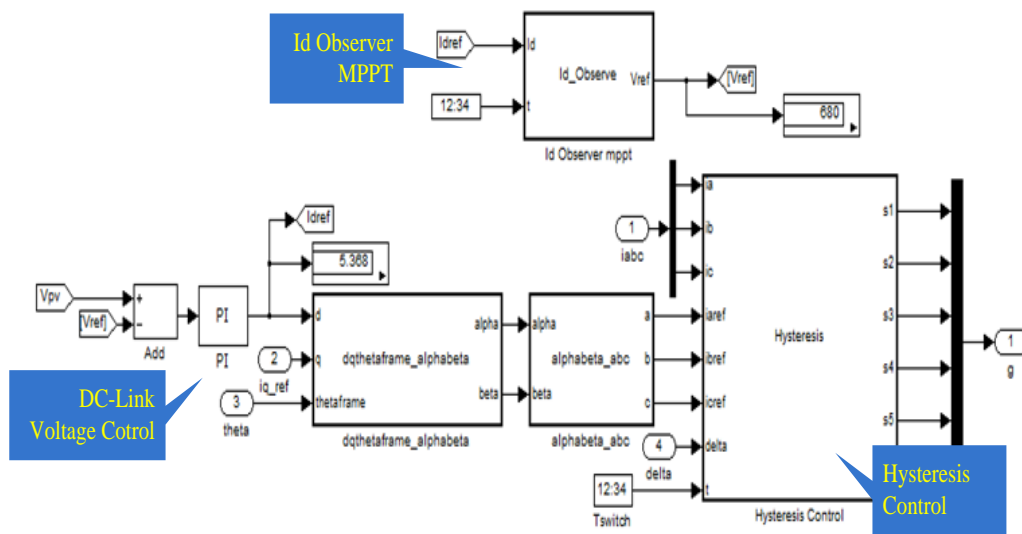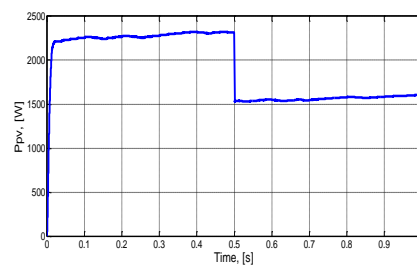
b) Control Block

c) Efficiency estimation block for one pair of IGBT-Diode

Figure 8. The simulation model of proposed control algorithm

a) P-V curve in normal irradiation (G=1) to G=0.7

b) Input power characteristic

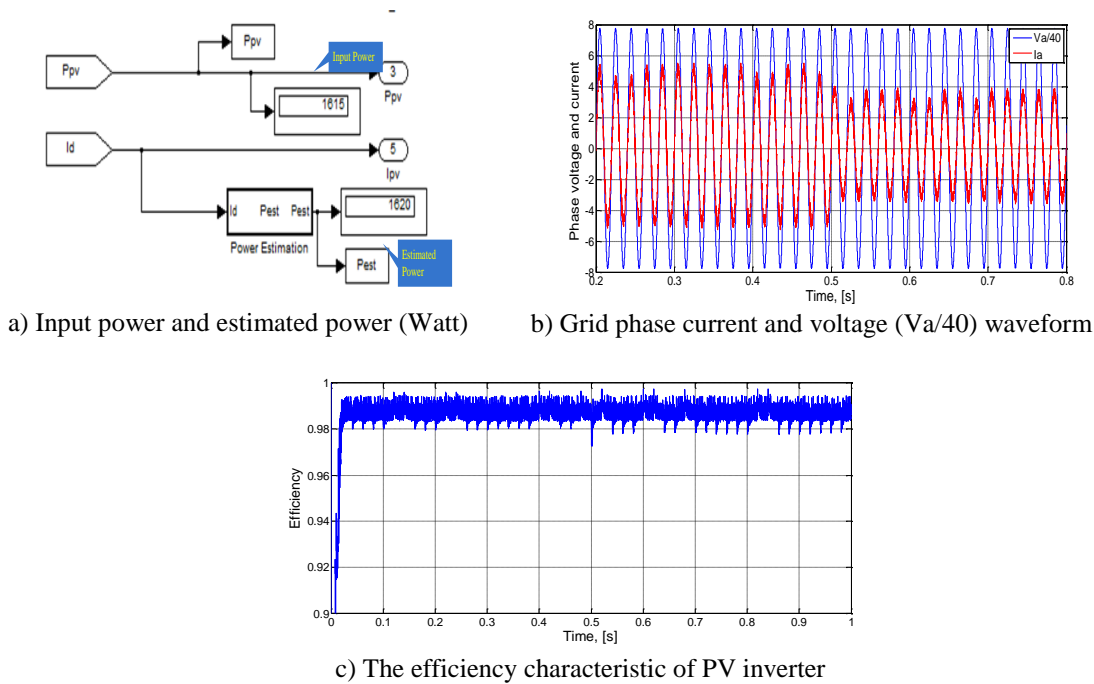**Figure 9.** Simulation results of PV and input power characteristic

a) Input power and estimated power (Watt)   b) Grid phase current and voltage (Va/40) waveform

c) The efficiency characteristic of PV inverter

Figure 10. Simulation results of estimated power, grid current and voltage, efficiency

EXPERIMENTAL RESULTS

A prototype is used to verify the proposed algorithm. In the experiments, a PV system current sensor is additionally used to measure input power. Similar to simulation, an estimated power is calculated for plotting and checking based on the relationship expression between output power and I_d value.

The experimental model (Fig. 11) includes:

PV system: 15 panels, Kyocera KC50T, installed in series

$$\begin{cases} V_{OC} = 21.7V, I_{SC} = 3.31A, P_{\max} = 50W : everypanel \\ V_{OC} = 325.5V, I_{SC} = 3.31A, P_{\max} = 750W : wholesystem \end{cases}$$

DC-link Capacitor: 1800 μF, 400V maximum

Controller: dSPACE 1103

2-level inverter : 6 IGBTs Fairchild G60N100

Driver : opto HCPL A3120

Voltage and current sensors: LEM LV-25P, LEM HX-20P

L-Filter: L = 20mH

Isolated Transformer: 370/75 V, line voltage

The Power Analyzer Fluke 43B is utilized to show the power factor, grid current harmonics…

The proposed control method is programmed by dSPACE 1103. The user interface (Fig.12), for controlling and plotting, is built in ControlDesk.

As shown in the Fig.12, the measuring value and the reference value is relatively equivalent, such as V_{PV} and I_d. The estimated power is very close to the input power which determined by sensors. However, the estimated one is not completely steady. It slightly changes around the measured power. The secondary currents mean the current in the inverter side, not in the grid side because of step-up transformer.

The true P-V curve, not estimated, is easier to observe the maximum power point (Fig.13a).

The algorithm control the secondary current phase to be the same as the grid voltage phase for unity power factor (Fig.13b). Because the grid

voltage and the secondary votage have the same phase, the power which measured in the secondary side has the maximum power factor (Fig.14a).
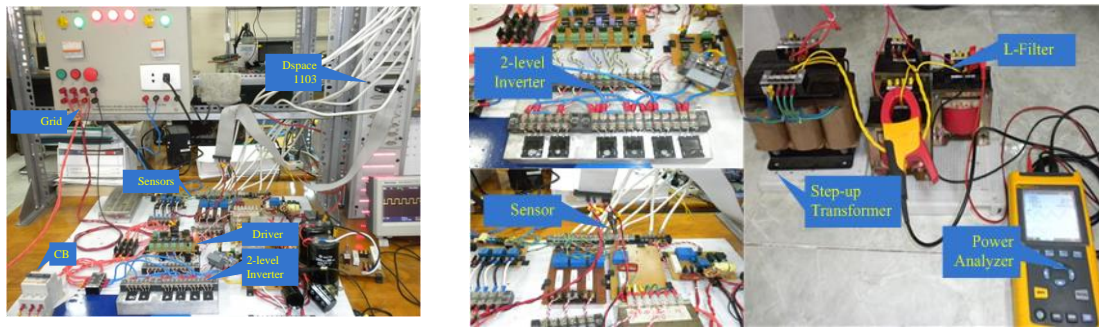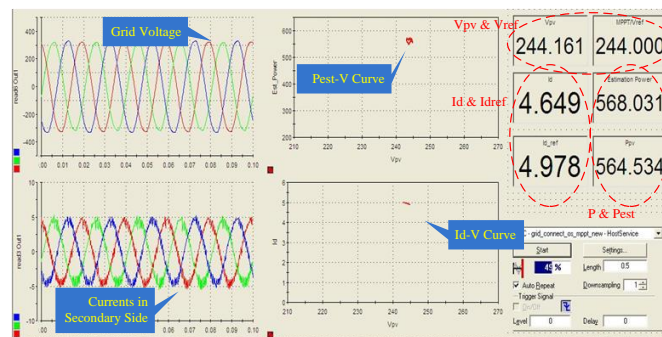

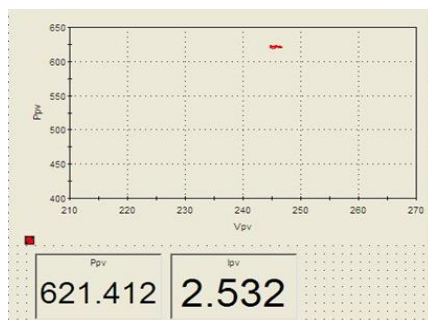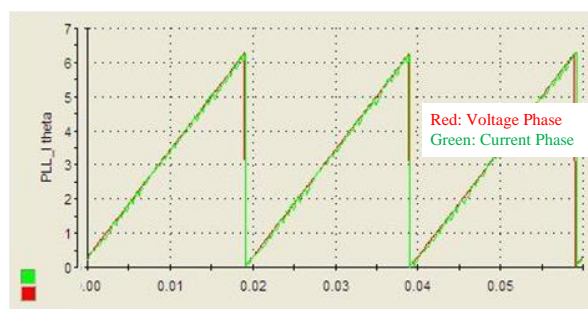**Figure 11.** Experimental Model

Figure 12. User Interface for monitoring, measuring voltage (V), current (A) and power (W)

a) Power (w), current (A) and voltage(V) of PV, measured by sensors

a)   Grid voltage and current phase

Figure 13. Experimental results

a) Power analysis in the secondary side

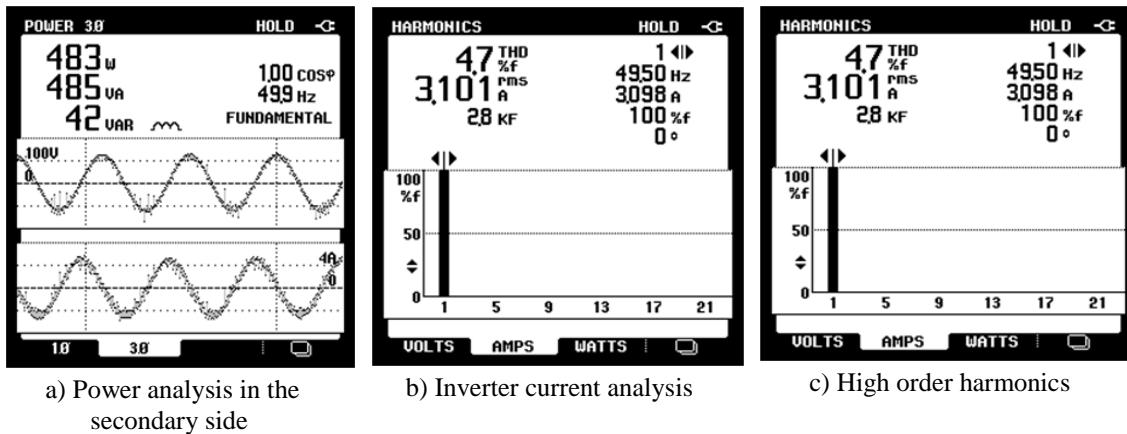b) Inverter current analysis

c) High order harmonics

Figure 14. Power quality analysis

The quality of output currents is shown in Fig.14b. The THD is smaller than 5% and can be reduced when the PV system power increases. The magnitude of high order harmonics is much smaller than the basic harmonic (Fig14c).

The experimental results demonstrate good responses as shown in above figures. The responses of electrical quantities in low-cost single-stage three-phase PV system are obtained quickly and precisely.

CONCLUSION

This paper presented a modified control method for single-stage three-phase grid-connected PV system, which has the advantages of the high efficiency, cost-effectiveness and simplicity. Unlike other MPPT methods, the input power is substituted by I_d value which is easy to calculate. Moreover, the output power, actually I_d, is observed to replace the input power. Hence, the PV array output current sensor can be removed. Beside that, the proposed MPPT algorithm is based on the method with variable step change of V_{ref} in order to accelerate the MPPT response.

In this work, the hysteresis current control and L-filter are implemented. Advanced methods of current control, such as PI, deadbeat, and LCL-filter could be considered to improve the quality of grid currents. The DC-link voltage balancing principle has been used. However, other configurations are being researching to apply this new MPPT idea possibly.

The simulation results validate the performance of the proposed schema. Experiments performed with a laboratory prototype have shown encouraging results.

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- **Lê Chí Hiệp**

Trường Đại học Bách khoa, ĐHQG-HCM

TÓM TẮT:

Cấu hình một tầng và thuật toán dò tìm điểm công suất cực đại (MPPT) có ưu điểm vì đơn giản và hiệu suất cao khi kết lưới nguồn pin mặt trời (PV). Trong các hệ truyền thống, cảm biến dòng và áp của hệ thống PV được sử dụng để thực hiện MPPT. Bài báo này trình bày một thuật toán cải tiến cho hệ thống PV kết lưới ba pha, cấu trúc một tầng, không sử dụng cảm biến dòng với bước dò tìm MPP tự động thay đổi nhằm rút ngắn thời gian thực thi. Thuật toán này không cần giải tích từ các công thức tính toán phức tạp và không phụ thuộc vào bất cứ thông số mạch nào. Thuật toán cho phép tính toán công suất ngõ ra của bộ nghịch lưu thay vì công suất ngõ vào của PV khi thực hiện MPPT. Thuật toán cải tiến được mô phỏng bằng Matlab/Simulink và được kiểm chứng bằng thực nghiệm. Cấu hình một tầng và không dùng cảm biến dòng thích hợp cho các ứng dụng giá thành thấp và hiệu suất cao.

Từ khóa: cấu hình một tầng, điểm năng suất cực đại, hệ thống PV.

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