Modeling and Control the Grid-Connected Single-Phase Photovoltaic System

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Abstract

This paper presents the modeling of the major electronic components of a single-phase grid-connected photovoltaic system. Besides, the control strategy of DC/DC converter is proposed in order to maximize the power from the photovoltaic generator and stabilize the DC output voltage. The grid-connected inverter transforms the power from PV to the grid by keeping constant DC voltage. Controlling separately active power and reactive power is applied to the inverter. Modeling and simulation results which are performed on the Psim software have demonstrated the effective control and dynami response of the grid-connected photovoltaic system.

Keywords: *Control, active power, reactive power, single-phase inverter, grid-connected.*

I. INTRODUCTION

With the increasing demand for energy in the world, solar power is becoming more and more popular. Compared to traditional energy sources such as oil and gas, photovoltaic energy is friendly with environment. However, the effectiveness and ability to control them are now the main constraints. In addition, operators of grid transmission systems are imposing tough standards [6] when the PV system is connected to the grid. The requirements for electrical system stability and power quality are the main requirements that power generators must comply with when connecting to the power grid. All photovoltaic systems are interfaced to the grid through a voltage inverter [5, 6] and a turbocharger. There have been numerous researches conducted to control these systems and to improve their behavior [2, 6, 7]. The tasks of controlling the solar power system connected to the grid are to improve the energy transfer performance and to control actively the active power and reactive power to the grid in order to maintain electricity system stability when there are fluctuations in frequency and voltage of the grid.

In this paper, we will describe the operation of a single-phase grid connected solar system, propose control loop of DC voltage, model and simulate system operation on the Psim software in changing environmental conditions in order to determine clearly the effects of the MPPT, the DC voltage control circuit and the operation of the power controllers.

II. SYSTEM STRUCTURE

Figure 1 shows the electronic circuit structure for connecting photovoltaic cells to a single phase grid. The circuit consists of main blocks such as photovoltaic cells, boost converter, DC lines, inverters, filters and grids. The control circuit includes maximum power point detection, DC voltage control, synchronization and power control.

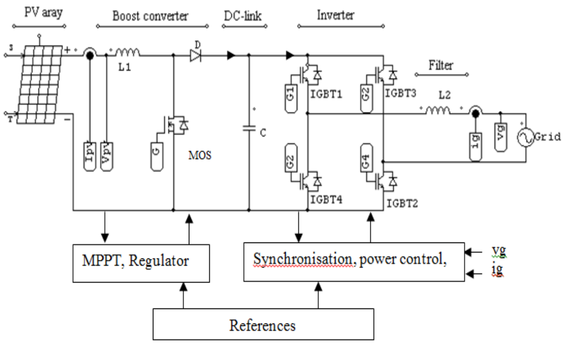


Fig.1: General diagram of grid connected photovoltaic system

1. The photovoltaic Generator - PVG

The photovoltaic generator is considered as a current source with an equivalent electrical diagram as shown in Fig 2 [3, 8]. The inputs are the intensity of solar radiation [W/m^2] and ambient temperature [0^C].

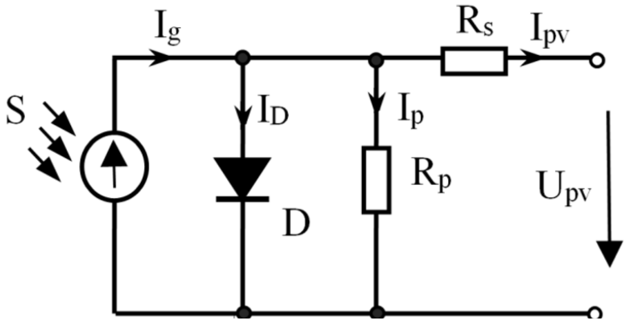
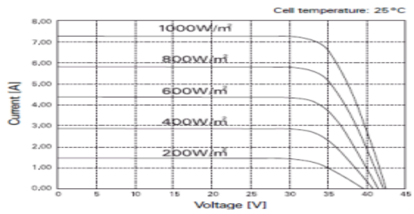


Fig.2: The equivalent circuit of the PV



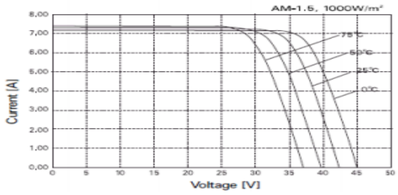


Fig.3: The I-V relationship of PV when the radiation intensity and environmental temperature change

I-V relationship of photovoltaic cells corresponds to the different radiation intensity and temperature shown in Fig.3 [3, 4].

2. The DC/DC converter

The DC/DC converter includes L1 inductance, MOS switch and D diode. They increase the voltage and stabilize the voltage at the required level. At the same time, we also implement the detection algorithm for the maximum power point of photovoltaic cell (MPPT). DC/DC has two energy accumulators; therefore, it has two control variables. They are V_{pv} photoelectric and I_{pv} photoelectric.

3. The DC line

In general, the DC line voltage fluctuates between two levels depending on the environmental condition, it means temperature and solar radiation. It is represented by the following formula:

$$\frac{dv_{dc}}{dt} = \frac{1}{C}(I_{dc} - I_{in}) \qquad (1)$$

where C_{dc} is the Capacity of the capacitor [F], I_{dc} is the output current of the MPPT, I_{in} is the input current of the DC/AC converter.

4. Inverter

The grid-connected inverter has four IGBT switches, coded IRG4BC40FPbF. It also has a harmonics filter inductance to reduce current distortion. The inverter needs to act as a power controller between the DC link and the grid [2, 5].

5. Grid

According to Thevenin, we can represent a single-phase grid with a voltage of 220V 50Hz in series with impedance Z = R + jX, which includes the output impedance of the inverter (Fig.4).

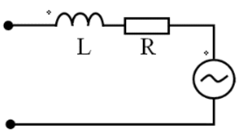


Fig.4: Thevenin equivalent circuit of the utility grid single phase

III. CONTROL SYSTEM

The control system includes the detection and maintenance of a maximum power operation point, maintains of constant voltage at DC line when condition changes, synchronization and the pump power types into the grid.

1. The control of the detection of a maximum power point of operation

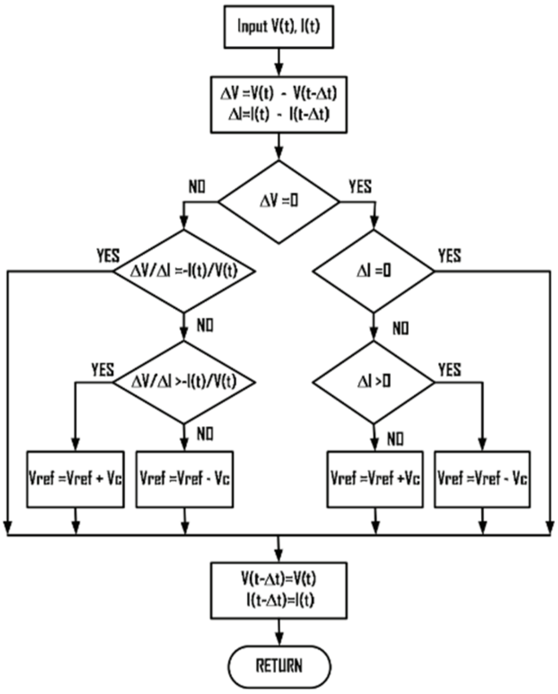


Fig.5: The flowchart of the incremental induction algorithm

As the environmental condition (solar radiation and temperature) fluctuates continuously, a maximum power point of photovoltaic cell is also continuously changing according environment (Fig.2). Therefore, it is necessary to control the photovoltaic cell always working at the maximum power point in order to improve the efficiency of the generator. There are many MPPT algorithms, such as constant voltage algorithm, disturbance and observation algorithm, incremental induction algorithm, fuzzy control algorithm [1, 3, 4], ... In this paper, we use the incremental induction algorithms to identify and maintain the maximum power point of photovoltaic cell. The flowchart of the incremental induction algorithm is shown in Fig.5 [3].

2. The DC line voltage control

The DC voltage is applied to the inverter to convert into the 50Hz AC connected to the grid. Voltage regulation circuitry is set up to maintain the unchanged voltage when the photovoltaic cell's voltage changes because of changing environment. Structure diagram of the DC voltage control loop is shown in Fig.6. The voltage signal from the DC link through the voltage sensor is compared to the reference voltage $V_{DC\text{-}ref}$, deviation is controlled via the PI regulator and then combined with the output signal of MPPT algorithm. This leads to the PWM modulation for opening-closing the control block of the DC/DC block.

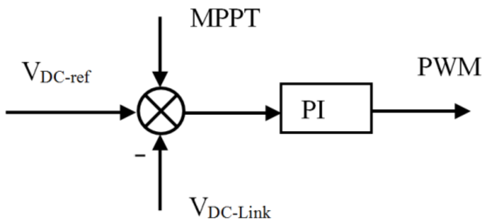


Fig.6: The DC voltage controller

3. Grid Power control

The block diagram of grid-connected inverter is shown in Fig.7, where R and L are resistor and inductance of the grid and of the filter, E is the effective value of the inverter's output voltage, V is the value of the grid voltage, I is the current flowing in the circuit.

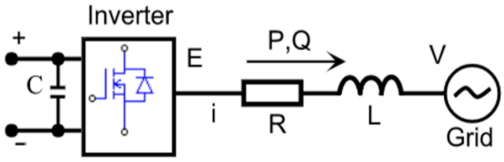


Fig.7: Block diagram of the grid-connected inverter

3.1.Single-phase active power and reactive power on synchronous reference (dq)

The expression of active power and reactive power of a grid-connected single-phase inverter can be written as below:

$$\begin{cases} P = \dfrac{1}{2} V_m I_{m1} \cos \varphi_1 \\ Q = \dfrac{1}{2} V_m I_{m1} \sin \varphi_1 \end{cases} \qquad (2)$$

Where V_m and I_{m1} are the amplitude values of the grid voltage and the basic component of the grid, φ_1 is the phase difference between the two components. We convert these capacities to orthogonal two-phase systems from a single-phase signal. Because the essence of the system is one-phase, we need to create a virtual phase into two phases. The signal in this virtual phase is perpendicular to the real phase signal. Then, it is possible to represent a single-phase electronic energy conversion system on the static reference system (αβ) to the synchronous reference system (dq). These conversions are simple and easy to analyze, especially when determining the active power and instantaneous reactive power of a single-phase system.

There are many ways to create a second orthogonal signal component to implement a two-phase virtual system. The simplest is to move the phase-angle translocation of one-phase signal at 90^0 angles, or use second-order generalized integrator (SOGI -second-order generalized integrator) [7].

Similar to the three-phase system, the active and instantaneous reactive power in the static reference system can be defined:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (3)$$

Applying (3) for grid voltage (v) and current (i) without regard to harmonics, we construct the orthogonal two-phase system as follows:

$$\begin{cases} v_\alpha = V_m \sin \omega t \\ v_\beta = -V_m \cos \omega t \end{cases} \qquad (4)$$

$$\begin{cases} i_\alpha = I_{m1} \sin(\omega t - \varphi_1) + \sum\limits_{n=3,5,...} i_{\alpha n} \\ i_\beta = -I_{m1} \cos(\omega t - \varphi_1) + \sum\limits_{n=3,5,...} i_{\beta n} \end{cases} \qquad (5)$$

In expression (5), in and in are the n-wave components of the current.

From (3), (4), (5), after a few simple transformations, we obtain:

$$\begin{cases} p = V_m I_{m1} \cos \varphi_1 + \\ \quad + V_m \sum\limits_{n=3,5,...} \left(i_{\alpha n} \sin \omega t - i_{\beta n} \cos \omega t \right) \\ q = V_m I_{m1} \sin \varphi_1 + \\ \quad + V_m \sum\limits_{n=3,5,...} \left(-i_{\alpha n} \cos \omega t - i_{\beta n} \sin \omega t \right) \end{cases} \qquad (6)$$

Refer to (6), we have:

$$\begin{cases} p = 2P + V_m \sum\limits_{n-3,5,...} \left(i_{\alpha n} \sin \omega t \text{ - } i_{\beta n} \cos \omega t \right) \\ q = 2Q + V_m \sum\limits_{n=3,5,...} \left(-i_{\alpha n} \cos \omega t \text{ - } i_{\beta n} \sin \omega t \right) \end{cases} \qquad (7)$$

It is assumed that the mean values of $\overline{p}$ and $\overline{q}$ respectively, received by using the low pass filter, we have:

$$\begin{cases} P = \dfrac{\overline{p}}{2} \\ Q = \dfrac{\overline{q}}{2} \end{cases} \qquad (8)$$

In fact, the switching scheme which uses pulse width modulation can easily remove current ripples from instantaneous power in formula (7) by low pass filter (LPF) with cutoff frequency is lower than the conversion one. Expression (8) shows the value of instantaneous virtual power calculated for a two-phase virtual system equal to 2 times the actual one-phase system value. Because the capacities in the two-phase virtual system are directly related to real single-phase power, we can use them to control the active and reactive power of a single-phase system.

3.2. Structure of power control circuit

As analyzed above, this section will build the structure of the active power and reactive power control circuits forthe single-phase inverter system by transferring them to the two-phase virtual system and using the couplers. Calculate results as for the three-phase system shown in[5].

The relationship between the state parameters in Fig.2 can be expressed as a differential equation:

$$e = L\frac{di}{dt} + Ri + v \quad (9)$$

Switch to the d, q projection. We have:

$$\begin{vmatrix} e_d \\ e_q \end{vmatrix} = L\frac{d}{dt}\begin{vmatrix} i_d \\ i_q \end{vmatrix} + wL\begin{vmatrix} 0 & -1 \\ 1 & 0 \end{vmatrix}\begin{vmatrix} i_d \\ i_q \end{vmatrix} + R\begin{vmatrix} i_d \\ i_q \end{vmatrix} + \begin{vmatrix} v_d \\ v_q \end{vmatrix}$$

After the transformation:

$$\begin{cases} e_d = L\dfrac{d}{dt}i_d - \omega L i_q + R i_d + v_d \\ e_q = L\dfrac{d}{dt}i_q + \omega L i_d + R i_q + v_q \end{cases} \quad (10)$$

From (10), we have the structure of the current control circuit shown in Fig.8. The input is the reference current that is compared to the measured current of the grid. The error between them is passed through the PI controller and passed to the synthesizer. The results are the required voltage values, e_d and e_q, in reference system d, q. These voltage values are converted to the α, β reference frame, the eα component into a sinusoidal pulse width

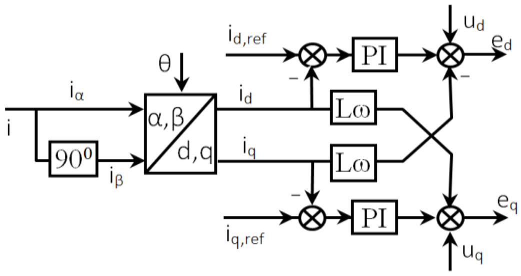


Fig.8:The current control loop

The reference currents $i_{d,\,ref}$, $i_{q,\,ref}$ are synthesized from the Circuit of power control structured as Fig.9

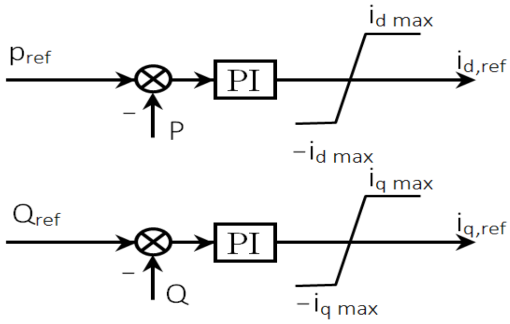


Fig.9:Structure of power control loop

The active power and reactive power transferred from the inverter to the grid are compared to the corresponding powers. Their deviation is passed to the PI set; the output of the PI is the reference current. P and Q are estimated according to (3) and (8).

A block diagram of the grid-connected one-phase inverter control system is shown in Fig.5. The different voltage between the active and reactive components of the current and their first values are put into the PI controller in the synchronous reference system. It generates the reference voltage for the converter. This voltage is then applied to the sinusoidal pulse width modulator (SPWM). To generate two orthogonal signals, we use angle translocation of 90^0.

4. Synchronization

Synchronization between the photovoltaic cell and grid system is accomplished by the Park lock set

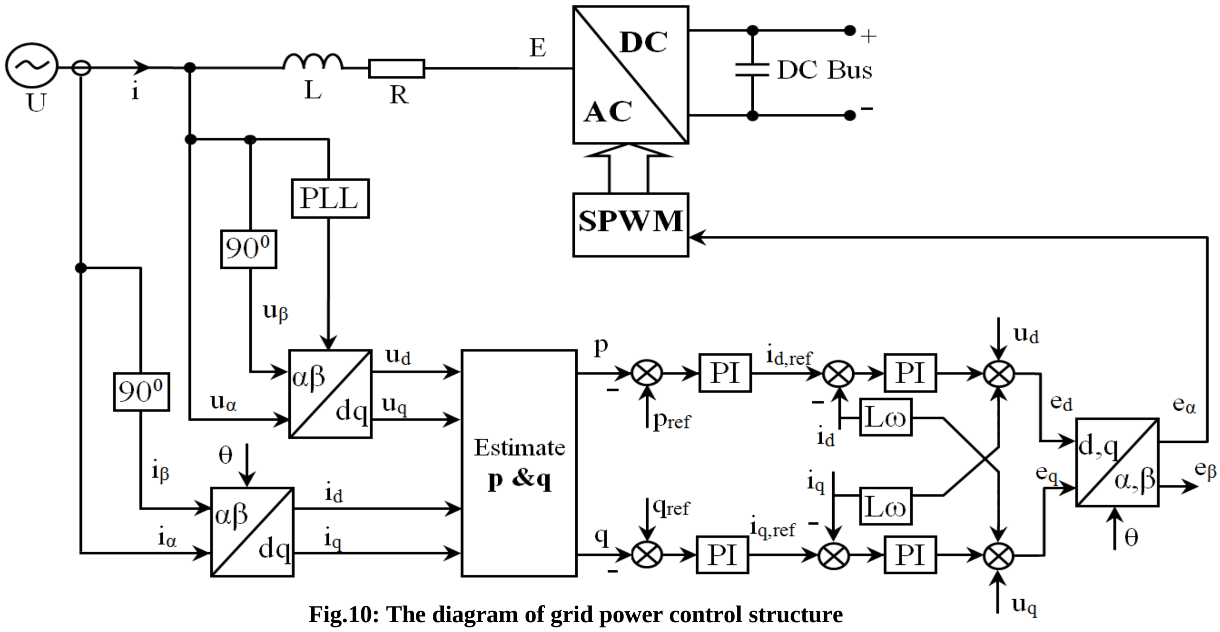


Fig.10: The diagram of grid power control structure

modulator (SPWM) to generate the control pulse of the switch block.

as Fig.11.

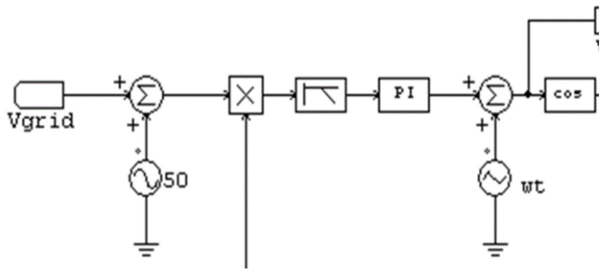


Fig.11: Phase lock loop

IV. SIMULATION RESULTS

The simulation of system operation is done on PSIM software with the parameters used for simulation as follows:

- Parameters of photovoltaic cell as Fig.12, the intensity of solar radiation changes two levels of 1000W/m^2 and 600W/m^2, temperature of 25^{0}C;

- Boot converter has L = 0.02H, switching uses Mosfet type, D diode;

- H-bridge inverter uses 4 IBGs;

- Reactance filter has L = 50mH;

- Grid voltage 220V/50Hz, grid impedance is r_{grid} = 100mΩ; L_{grid} = 10mH.

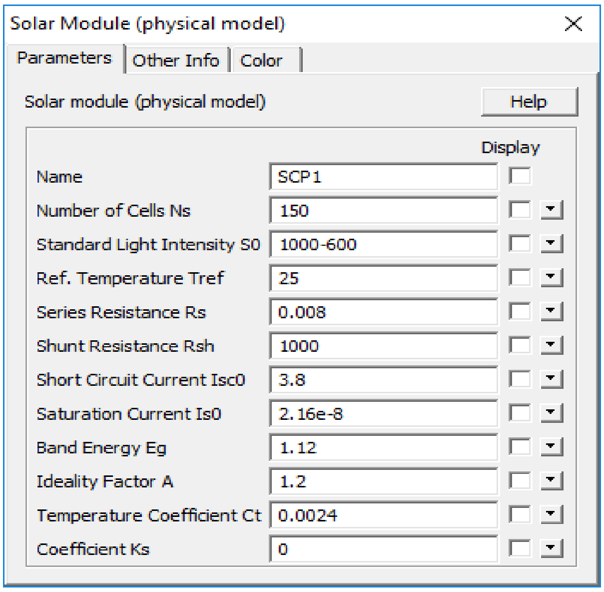


Fig.12: Parameters of photovoltaic cell

The simulation results are shown on Fig.13 to Fig.17. Where:

- Fig.13 shows the maximum affinity of photovoltaics with INC algorithm when the solar radiation level varies from 1000W/m^2 to 600W/m^2

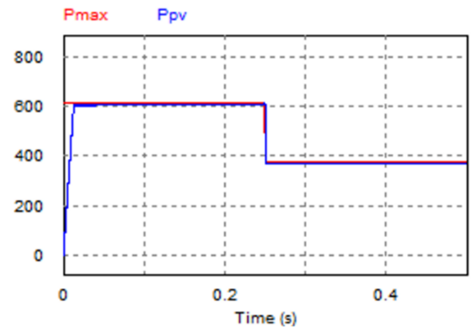


Fig.13: The response of output voltage of PV

- Fig.14 is the DC link voltage response when the solar radiation changes.

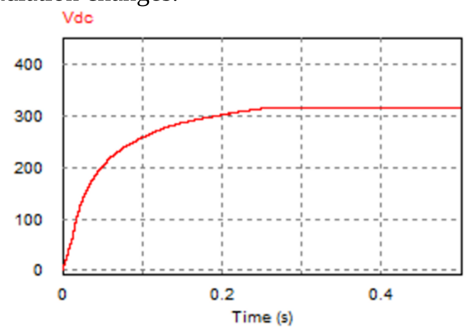


Fig.14: The DC link voltage response

- Fig.15 is the response of the pump power to the grid.

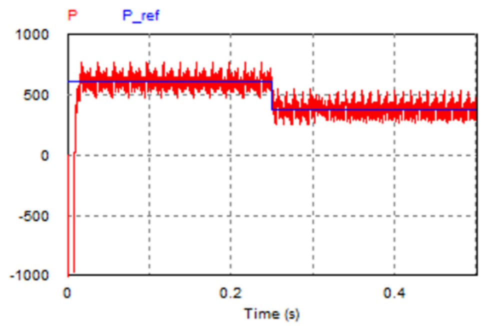


Fig.15: The response of active power

- Fig.16 is the reactive power curve.

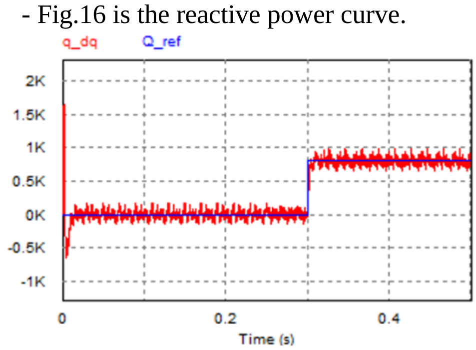


Fig.16: The reactive power response

- Fig.17 is the voltage and current of the grid

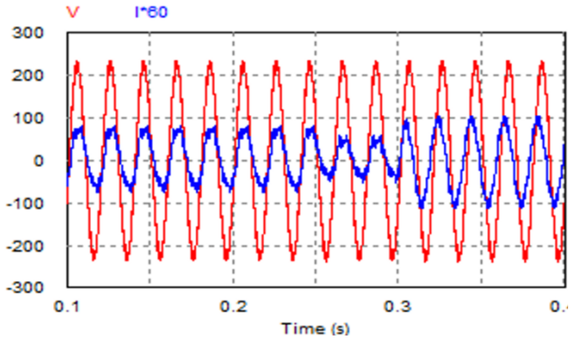


Fig.17: Voltage and current (i*60)

V. REMARKS AND CONCLUSIONS

The simulation results show the dynamic response of the system, and the voltage and current waveforms that meet the requirements. However, there are some shortcomings such as: the transition time is relatively long, measuring both voltage and current which leads to large error, harmonics disturbance in the transition period. These are also issues that need further researches and find solutions to overcome.

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