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Photovoltaic reactive power limits

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Abstract-- **Today, Photovoltaic (PV) inverters are working with very small values of reactive power. Then, the Power Factor (PF) is very close to the unit. So, the PV installations only inject active power into the grid. This paper aims to investigate the limits of reactive power capacity in PV generators. In this way, PV generators could be used as a controlled reactive power sources. In this paper, an introduction to the voltage control in photovoltaic generators is described and implemented in *Simulink/Matlab* and *PSS/E*.**

Index Terms-- **Power Quality, Photovoltaic (PV), reactive power, over-voltage.**

I. INTRODUCTION

Currently, there are installed a capacity of 13.7 GW of electricity from solar PV generation systems in the Organization for Economic Co-operation and Development (OECD) countries. This capacity represents approximately a 1 % of the total renewable electricity production for these countries. Germany leads the OECD's solar PV production with 32.9 % of the total. Next leaders are Spain (32.5 %), Japan (11.9 %) and the United States (8.4 %), [1]. In Spain, on December 2010, had installed 4000 MW approximately from solar PV technology *i.e.* 4 % of total mix of generation, covering 2 % of annual electric demand, [2].

Today, reactive power has not been taken into account in PV installations. This is because the PV inverter works in very small values of reactive power, *i.e.* power factor (PF) very close to unit. Although, current legislation, [3], requires measurement of reactive power to all PV facilities, new standard, [4], define a required range of PF between 0.98 inductive to 0.98 capacitive values for PV generators. Also, PV generators over 10 MW will have the capability to vary PF according to instructions from Distribution Systems Operator (DSO), as well as follow a set-point signal of voltage at a particular bus of the power system. Knowing the limits of power from PV installations allows not only, connect it into the grid with its power capacity, but also, use it as support for power grid, without a poor power quality [5], when there are long-term disruptions in the Point of Common Coupling (PCC) voltage.

In this paper, PV operating limits to absorb and generate reactive power to control voltage, and its limitations, have been established and have been simulated for a 5 buses system in *Simulink/Matlab*. Moreover, the capability to absorb reactive power in order to reduce over-voltages when PV generators are disconnected has been studied for the New England 39 bus Test System, and implemented in *PSS/E*.

II. OVER-VOLTAGES IN PV SOURCES

There are several researches that take into account over-voltages in power systems with PV generation. Such is the case of [6] where a system with 200-800 kW PV sources connected to MV, 6.6 kV, are studied, and over-voltages of distribution lines are one of the factors influencing real power losses of PV systems connected into the grid. Over-voltages often occur in areas with great concentration of PV generation and when loads are diminished, *i.e.* consumption decrease.

Research [7] ensures that over-voltages can occur, it could be transmitted and damage electronic equipment connected to LV, during the disconnection of PV inverters (in LV or MV). Also, the behaviour of inverters for different connection topologies is studied to determine which are the less harmful, with respect to the generation of over-voltages. These surges can damage equipment for measuring devices, rectifiers, etc.

In [8], over-voltages that can occur in micro-grid are studied. Over-voltages could be: ground fault over-voltages, related to voltage regulation, switching over-voltages of inner micro-grid, transfer over-voltages from distribution network due to lightning (15 p.u.) and switching over-voltages, resonant over-voltages (21 p.u.), being the last two the most serious for micro-grids.

In section III the description of the PV system is shown; its reactive power capacity is defined in section IV; the use of this capacity is presented in section V in order to reduce over-voltages, and; finally, in section VI, the results of the reactive power capacity and its control in the New England 39 bus Test System, when a PV generator is loosed, are displayed.

III. SYSTEM DESCRIPTION

The main PV system elements are shown in this section. A typical grid-connected PV system consists of a PV array, a boost DC-DC converter, a Maximum Power Point Tracking (MPPT) algorithm control, a three-phase DC-AC inverter, and its control.

For practical implementation, continuous measurements of voltage and current grid, and the irradiation and the temperature on the PV panels are necessary. The scheme used for the model implemented and all the measurement requirements are shown in Fig. 1.
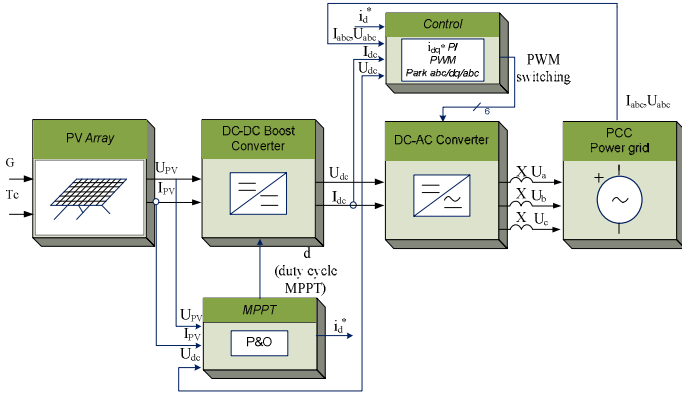
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Fig. 1.   Grid-connected PV system

Fig. 2.   Equivalent circuit model of a PV cell

Fig. 3.   DC-DC boost converter

A. PV array

All PV array datasheets bring mainly the following information: the nominal open-circuit voltage (U_{oc}), the nominal short-circuit current (I_{sc}), the voltage at the Maximum Power Point (MPP), (U_{mp}), the current at the MPP (I_{mp}), the open-circuit voltage/temperature coefficient (K_V), the short-circuit current/temperature coefficient (K_I), and the maximum experimental peak output power ($P_{max,e}$). This information is always provided with the reference to the nominal condition or Standard Test Conditions (STCs) of temperature and solar irradiation. Also, some manufacturers provide *I-U* curves for several irradiation and temperature conditions.

An accurate equivalent circuit for a PV cell is shown in Fig. 2. The output current from a PV cell is given by (1) that mathematically describes the *I-U* characteristic of the ideal PV cell [9]:

$$I_{cel} = I_{sc} - I_D - \frac{U_{cel} \cdot R_s}{R_p} \tag{1}$$

Where I_{sc} is the current generated by the incident light (it is directly proportional to the irradiation), I_D is the Shockley diode equation, R_s is the sum of several structural resistances of the device and R_p is the parallel resistance. The value of R_p is generally high and some authors neglect this resistance to simplify the model. The value of R_s is very low, and sometimes this parameter is neglected too, [9].

The diode current is given by (2):

$$I_D = I_0 \cdot \left[exp\left(\frac{q_e U_{cel}}{a_i k T_c}\right) - 1 \right] \tag{2}$$

Where q_e is the electron charge (1.60217646×10^{-19} C), k is the Boltzmann constant (1.3806503×10^{-23} J/K), T_c (in Kelvin) is the temperature of the *p-n* junction, a_i is the diode ideality constant ($1 \leq a_i \leq 1.5$) and I_0 is the diode saturation current and its dependence on the temperature may be expressed by (3), proposed by [9]:

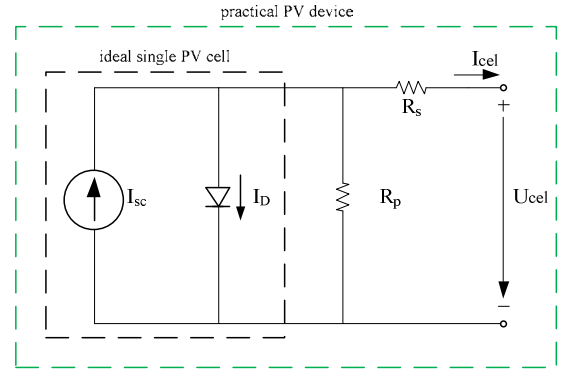$$I_0 = \frac{I_{sc} + K_I \cdot (T_c - T_n)}{exp[(U_{oc} + K_V \cdot (T_c - T_n))/a_i U_t] - 1} \tag{3}$$
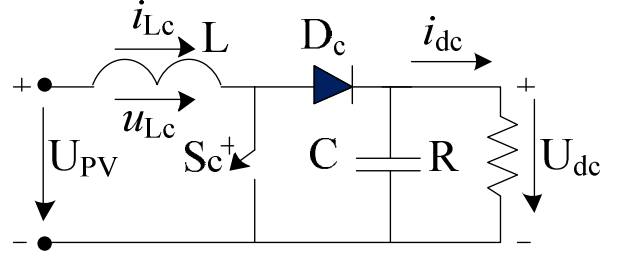
with U_t being the thermal voltage of N_s series-connected cells at the nominal temperature T_n.

B. DC-DC converter

Some inverters include a DC-DC converter to control and limit its dc voltage. The resulting over-voltage is lower than an inverter without DC-DC converter [7]. For this reason a DC-DC converter is used, Fig. 3.

C. MPPT

The major control challenge in the use of PV sources is imposed by its nonlinear current–voltage (*I–U*) characteristic, which result in a unique MPP on its power–voltage (*P–U*) curve, Fig. 4. The matter is further complicated due to the dependence of these characteristics on solar radiation and temperature. As these parameters vary continuously, MPP also varies [10].

The MPPT is used in the DC-DC converter, whose duty cycle is modulated in order to track the instantaneous MPP of the PV array. Although, Perturb and Observe (P&O) is an algorithm that can fail under rapidly changing atmospheric conditions [11], to ensure that the MPP is tracked, even under sudden changes in irradiance, the sampling rate is optimized to carry out the MPPT correctly, [12]. In P&O the duty cycle is varied to reach the maximum active power value of PV array.

D. DC-AC inverter

It is modelled as Voltage Source Converter (VSC), and it is connected to the power grid through a first order filter (resistance is neglected). Also, in power grid block is taken into account a transformer to connect PV source into the network, Fig. 5 that is a portion of whole system in Fig. 1.
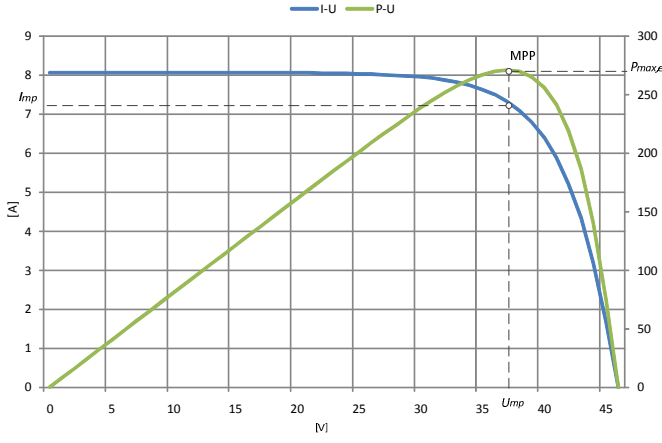
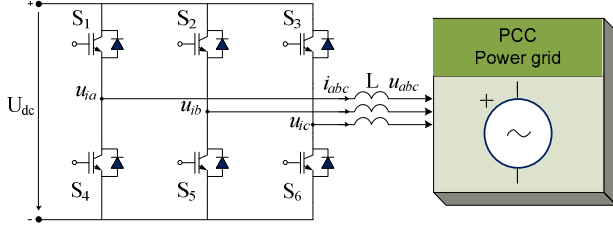Fig. 4. *I-U* and *P-U* curve for a single commercial PV panel

Fig. 5. DC-AC inverter

This PV inverter not only could inject active power into the grid, but also can control the reactive power injected/absorbed taking action on control voltage, U_g in PCC.

Applying the equations for the three-phase voltages (4) is obtained.

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{U_{dc}}{L}\begin{bmatrix} d_a \\ d_b \\ d_c \end{bmatrix} - \frac{1}{L}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \qquad (4)$$

Being d_a, d_b and d_c the duty cycles on PV inverter phases a, b and c, respectively. From (4), equations for *abc* can be rewritten to *dq* coordinates (5) and (6), using Park transformation [13].

$$u_d = u_{id} + L \cdot \omega \cdot i_q - L \cdot \frac{di_d}{dt} \qquad (5)$$

$$u_q = u_{iq} - L \cdot \omega \cdot i_d - L \cdot \frac{di_q}{dt} \qquad (6)$$

Where u_{id} and u_{iq} are inverter voltages in *dq* coordinates, respectively. Being $u_i = U_{dc} \cdot d$, the inverter voltage, it is the DC voltage input multiplied by its duty cycle, *i.e.* d_a, d_b or d_c.

IV. CAPACITY OF REACTIVE POWER IN PV SOURCES

A. Capacity of reactive power in PV sources

1) *Current inverter limit*

The PV inverter injects a maximum current, I_i. This maximum current imposes the limit of *P* and *Q*, which can be injected by the PV generator through the PV inverter. This limit is determined by the equation of a circle (7), [14]:

$$P^2 + Q^2 = (U_g I_i)^2 \qquad (7)$$

Where U_g is the one-phase voltage in the grid, I_i is one-phase current in PV converter, and *P-Q* represents the active power

and reactive power of the network at the PCC, respectively. From (7) it is possible to write (8) as follow:

$$I_i = \frac{\sqrt{P^2 + Q^2}}{U_g} \qquad (8)$$

The *"current inverter limit"*, (8) have c_2 and r_2 that represents the center and radius, (9).

$$c_2 = (0,0); \; r_2 = U_g I_i \qquad (9)$$

2) *Voltage inverter limit*

The maximum PV inverter voltage, U_i, imposed this restriction. This voltage defines an additional capacity limit of *P* and *Q* described by (10).

$$P^2 + \left(Q + \frac{U_g^2}{X}\right)^2 = \left(\frac{U_g U_i}{X}\right)^2 \qquad (10)$$

U_i, and I_i represent the one-phase voltage and current of the PV inverter, respectively. In addition, U_i depends on the continuous voltage from the inverter input, the modulation technique and the rate of amplitude modulation, [15]. X represents the reactance seen from the inverter terminals. From (10) is possible to write (11):

$$U_i = \sqrt{P^2 + \left(Q + \frac{U_g^2}{X}\right)^2} - \frac{U_g}{X} \qquad (11)$$

"Voltage inverter limit", (11) is an ellipse with the following characteristics: a (semi-major axis); b (semi-minor axis); c (focal semi-distance); ecc (eccentricity); c_1 (center); k (constant of ellipse).

$$a = b = \frac{U_g U_i}{X}; c = \sqrt{a^2 - b^2} = 0 \qquad (12)$$

$$ecc = \frac{c}{a} = 0 \; ; 0 < ecc < 1 \qquad (13)$$

$$c_1 = \left(0, -\frac{U_g^2}{X}\right) \qquad (14)$$

$$k = 2a = 2\frac{U_g U_i}{X} \qquad (15)$$

3) *Photovoltaic active power limit*

It is the maximum active power that can be obtained from the PV field, which is 1 p.u.

Fig. 6 shows the operation limits of a PV inverter. This figure is the result of all the restrictions shown above and taken into account all together.

The viable operation area of a PV inverter is gray marked. As it can see, in first quadrant, inverter can inject both active and reactive power. As well as, in fourth quadrant, an inverter is capable to inject active power and absorb reactive power.

V. PV INVERTER LIMITS AND OVER-VOLTAGES REDUCTION

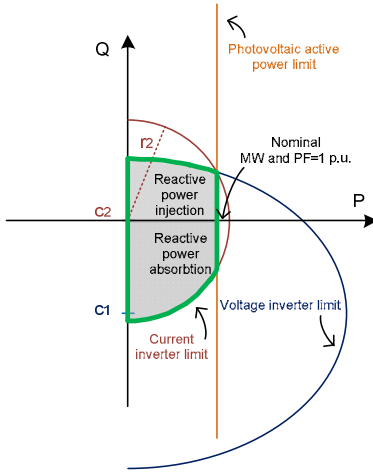The PV inverter limits, in a five buses electrical system,

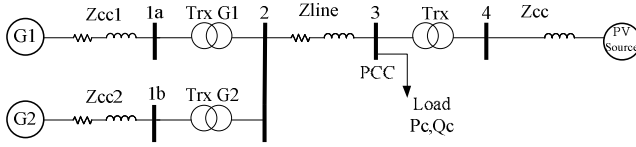Fig. 6.   Active and reactive power capacity of PV generator

Fig. 7.   Electric system implemented

will be studied. Also, the reactance variation effect on PV inverter capability and an over-voltage situation will be studied.

A. Electric system implemented

The electric system implemented, Fig. 7, is composed by following: a synchronous generator connected to a MV line through a transformer 30 kV/15 kV (buses 1a-2), a synchronous generator connected to a MV line through a transformer 30 kV/15 kV (buses 1b-2), a 15 kV MV line (buses 2-3), a load connected to the PCC (bus 3, where PCC is), and a 1 MW PV generator connected to the grid through a transformer 400 V/15 kV (buses 4-3).

B. Reactance network variation effects

The reactance of the power grid is a parameter that influences directly to voltage inverter limit. In Fig. 8, limits of operation of the PV inverter for different values of the reactance in the network, X, are represented, also a PF=1 p.u. is considered.

If X increases a 10 %, the capacity of reactive power is increased by 10 %, from 0.30 p.u. to 0.33 p.u., point 1 to 2. For P=1 p.u., PV inverter could absorb 0.48 p.u. and inject 0.15 p.u. of reactive power.

C. Reactive changes for P=1 p.u. when an over-voltage occur

Incorporate reactive power capability of PV units can reduce over-voltages in power networks. Nowadays, PV sources only inject active power (point 1), as it can be seen in Fig. 9. In the case of an over-voltage, absorbing reactive power by PV units can enhance voltage response of the power systems, reducing over-voltages (point 3). On the other hand, if the inverter injects reactive power, over-voltage gets worse (point 2).
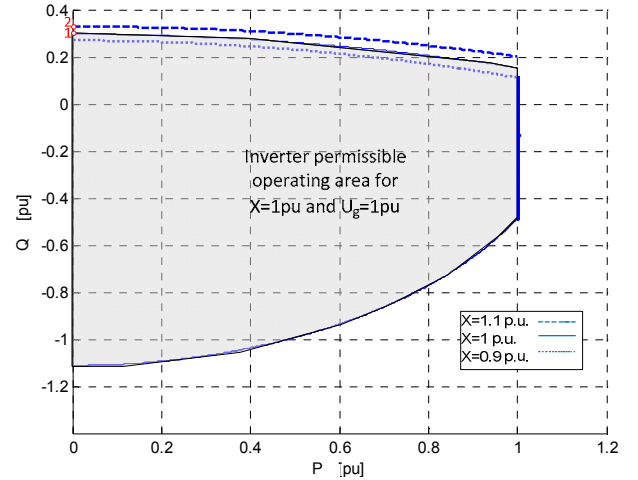

Fig. 8.   PV inverter limits varying reactance in network between 0.9-1.1 p.u.
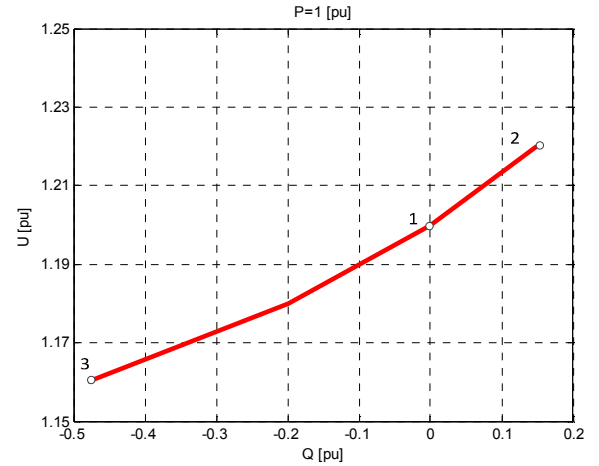

Fig. 9.   Voltage in PCC for allowed Q in PV inverter with P=1 p.u.

VI. PV CONTROL IN NEW ENGLAND 39 BUS TEST

As in [16], the New England 39 bus Test System is implemented in *PSS/E*, [17], in order to use a tool where develop the PV control and to obtain the voltage responses simulated. The PV plants are connected at buses 30, 32 and 38. For this aim, *Fortran* is one of the programming languages that work with *PSS/E* and it was used to build the PV control. New England 39 bus Test System is shown in Fig. 10, and PV penetration, compare to total global power are presented in TABLE I.

TABLE I
PV PENETRATION

PV plant at Bus 30	PV plant at Bus 32	PV plant at Bus 38	Penetration
400 MW	300 MW	480 MW	25 %

When PV plant at bus 38 is disconnected, an over-voltage occurs at this bus and, the faster the drop, the higher the over-voltage is, then the voltage control response is presented for different time scenarios, Fig. 11. This active power drop depend on time is shown in Fig. 12. The Fig. 13 shows the frequency response depending on time, and is can be seen that using reactive capability of PV generators, is possible to
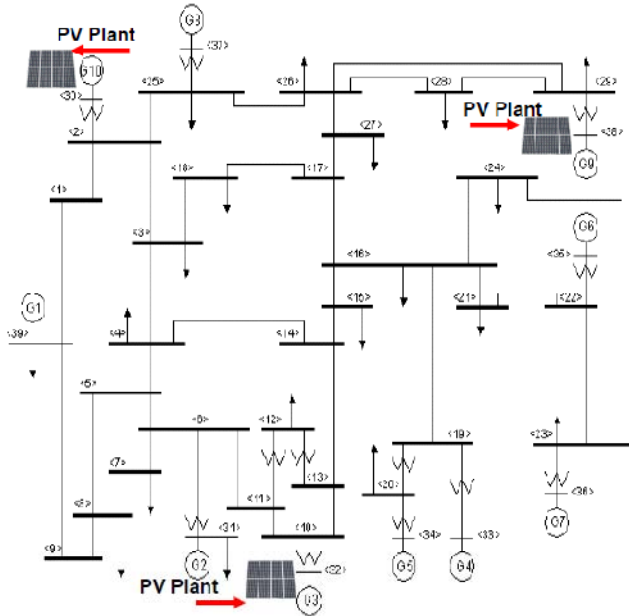
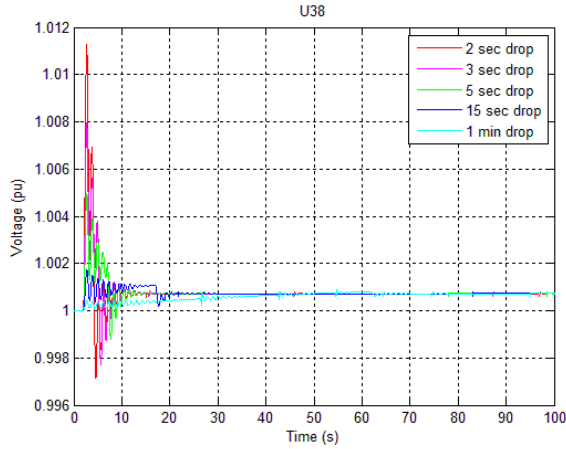Fig. 10. PV plants at the New England 39 bus Test System

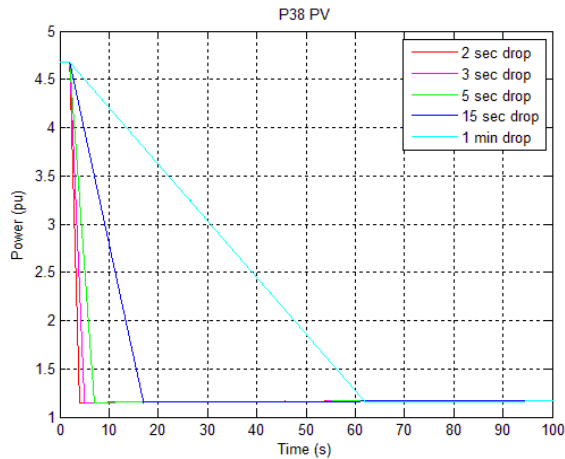Fig. 11. Voltage response with 25% penetration at bus 38

Fig. 12. Power response with 25% penetration at bus 38

maintain voltage stability for short disconnection times. In Fig. 13 is shown that for times greater than 15 seconds, it is possible to ensure a good response from 60 Hz up to 59.85 Hz at bus 38.
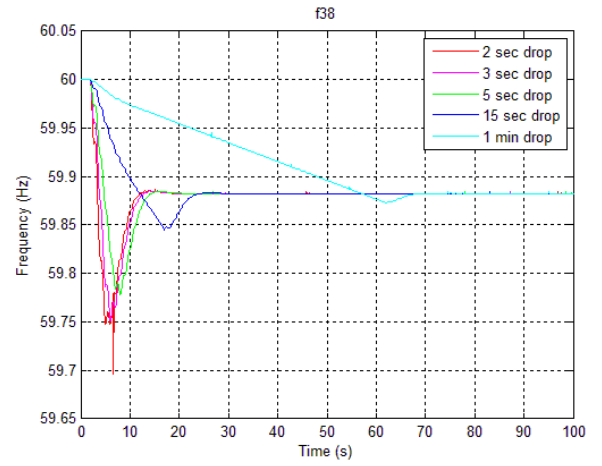

Fig. 13. Frequency response with 25% penetration at bus 38

VII. Conclusions

In this paper a grid-connected PV system has been implemented in *Simulink/Matlab* and *Fortran-PSS/E*. The limits of active and reactive power in PV inverters, *i.e.* PV generators, have been studied. PV inverters operating limits are three: 1) "*Current inverter limit*", with shaped of a circle, in which P and Q generated depends on U_g and I_i.; 2) "*Voltage inverter limit*", with the shaped of an ellipse, in which P and Q generated, depends on the reactance of the network, U_g, and U_i; 3) "*PV active power limit*", is a vertical line that defines the maximum power obtained from the PV field. A *P-Q* curve is obtained. In turn, PV inverters have the capability to inject and absorb reactive power. Being absorption reactive power capability greater than injection one. Moreover, over-voltages could be reduced by PV generators due to reactive power absorption, and dynamic stability maintain when a single generator is disconnected from the power grid if this disconnection takes more than 15 seconds for the case under test.

VIII. Acknowledgment

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