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# Determination of Maximum Power in Spread Photovoltaic Parks to avoid Transient Stability Problems

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**Abstract:** Nowadays there is a trend to use Photovoltaic Generation to replace the conventional one which involves fossil fuels. This obliges to carry out studies to analyze different aspects of the operation of these parks where both technologies either conventional or nonconventional ones coexists. One of the aspects to be studied is the analysis of the electric system dynamic behavior called Analysis of Transient Stability.

Photovoltaic generation systems, in contrast with conventional ones, are static, i.e. they do not have mobile parts, and nevertheless, changes in solar radiation produced by the presence of low and isolated clouds, modify the power delivered by the photovoltaic park. These changes of active power generated by photovoltaic parks are seen as a constraint by the electric system producing frequency variations in the electric system and the consequent speed variation in conventional generators in operation.

Therefore, the impact of solar radiation changes under the presence of traveling trains of clouds over the Transient Stability, considering not only concentrated but also disperse Photovoltaic Generation, is analyzed in this work. At the same time, it is presented a methodology to determine a *Penetration Index of Disperse Photovoltaic Generation* which allows the definition of the maximum power coming from photovoltaic generation in relation to the maximum power demanded as well as the Spinning Reserve Power that guarantee the Transient Stability of the Power System, taking into account the geographical distribution of photovoltaic generators.

**Key words:** frequency control, photovoltaic system, solar panels, solar power generation, power system stability

## 1. Introduction

Electric Power systems have a dynamic behavior since the conventional generation has mobile parts which must function within certain stiff ranges. These systems are very sensitive to constraints which may produce sudden or progressive changes in generation so they include control systems to avoid that those changes may produce loss of synchronism and further system collapse.

With the exception of totally cloudy or clear days, power systems face unforeseen changes of radiation due to variable cloud conditions. At the same time control systems of conventional generators in service must compensate them and avoid transient stability problems.

The control capacity of this phenomenon depends on three main factors: the geographical dispersion of photovoltaic parks (PVP), the relation between photovoltaic energy generation (PVG) and conventional one and the spinning reserve power supplied by the present conventional generation.

Photovoltaic generators instead, do not have mobile parts, but as solar radiation is its primary source any change in that radiation lead to changes in the power generation given to the network. This dependence in the solar radiation makes that the PVG be unmanageable, unpredictable and intermittent.

When complete and persistent cloudiness over panels is foreseen beforehand through satellite information, it is possible to compensate with conventional generation the decreased PVG.

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But in general, cloudiness appears randomly and therefore, during the operation of a PVP the presence of isolated or moving clouds which move constantly according to the wind speed producing intermittent solar radiation changes over photovoltaic panels cannot be controlled or predicted with total accuracy.

These changes, either in increase or decrease of solar radiation, always affect the active power generation supplied to the network which should be compensated by conventional generators (CG).

The fact that CG successfully accompanies the modification of photovoltaic energy generation depends on various factors such as:

- Relation between both types of generation;
- Dynamic characteristics of the CG in service;
- Spinning reserve supplied by CG in service.

## 2. Problem Analysis

### *2.1 Variation of Photovoltaic Energy Generation.*

During a normal operation in a PVP there are some variations related to different factors, among them:

(1) Solar radiation which affects solar panels due to:

- Direct Solar Radiation
- Diffuse Solar Radiation
- Reflected Solar Radiation

Direct solar radiation is the one that comes from the sun and affects directly over panels. The more perpendicular the solar rays over the solar panels the greater is the radiation and this is close related to the hour of the day. The diffuse solar radiation is the light of the environment which, although, it comes from the sun, it does not have direct incidence. And reflected solar radiation, is the light that reaches the panels reflected from elements nearby the solar panels.

Diffuse and Reflected radiations are non-significant in power generation and the greater or thicker the clouds the smaller they become.

Direct solar radiation then, is the most important one, and it is the one that most varies when there is a shadow over the panel due to the presence of a cloud.

The random variation of Irradiance over PVP due to isolated clouds produces fluctuations in the generated power. These fluctuations are the result of different factors such as:

- Type of cloud (density, thickness, height);
- Speed of wind;
- Photovoltaic Parks Size;
- Location of solar panels in field;
- Connection of solar panels;
- Orientation of solar panels respect the predominant direction of wind.

The irradiance and the electric power variation supplied by a PVP during a period of 15 minutes are shown in Fig. 1 [1].

In Fig. 1, irradiance is measured at a point of the PVP while clouds are passing and the power is measured at the connection point of the PVP to the electric network.

(2) Solar Panel Temperature

When solar panel temperature increases, the generated power value decreases. Therefore, panels should be installed in such a way that appropriate natural ventilation conditions are ensured, thus, panels temperature do not change harshly affecting dynamically the system functioning.

### *2.2 Restrictions for Photovoltaic Parks installation.*

Further than the economic limitations, which fortunately are decreasing, there are limitations to the expansion of PVP or EP (Eolic Park) which are

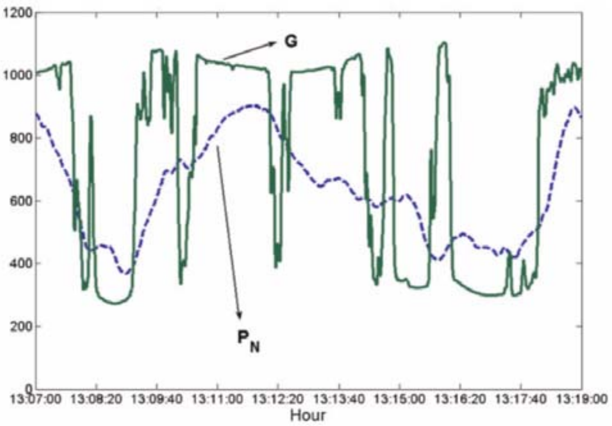

**Fig. 1 Power Variation ($P_N$) supplied due to irradiance variation (G).**

mainly related with technical aspects of the electric system operation. These restrictions are related to:

1) Stability Transient Problems.
2) Spinning Reserve Definition.
3) Voltage Control Problems.
4) Problems with the replacement of generators which operate in the base of the demand diagram.

1) Stability Transient Problems

The nature of PVP does not involve rotating parts and therefore they do not have inertia. The international experience in PVP operation, showed their potential to produce slopes of fast power and great magnitude in partially cloudy days. The active power generated by small PVP (< 10 MW) can suffer, various times a day, variations within a range of ±50% of its nominal power in an interval of 30 to 90 seconds and of ±70% within an interval of 5 to 10 minutes [2, 4, 5].

Fluctuations in the power generated by PVP appear when a train of low and thick clouds considerably decrease the irradiation which impact directly over solar panels, i.e., they pass over the park.

This decrease in generation produces a frequency decrease in the electric system. If frequency reaches or is less than 49.2 Hz, there is a reaction of loads disconnection relays due to sub-frequency. The action of these relays is absolutely undesirable since they represent cuts of supplies to consumers.

The greater the Photovoltaic/Eolic Penetration, the greater is the risk of having this undesirable effect.

The evolution of frequency in the Isolated Regional System Cuyo (CUYO) after a contingency for different values of PVG is described in Fig. 2. It is observed that for PVG values of 120 MW or more frequency reaches the value of 49.2 Hz, while for smaller PVG values the frequency is recovered.

2) Spinning Reserve Definition

The Spinning Reserve is the available percentage of active power generation from those generators which are functioning. For security, and in order to ensure the recovering of the electric system after losing a generator, it is stated that all generators should leave a spinning reserve of 5% [3]. If there is PVG, that percentage must be greater, i.e., more conventional generators than the usual ones in case of having only conventional generation should function which imply an additional cost.

Not all generators help to control frequency the only ones that do such a thing are those with speed regulators, which after a decrease in frequency they increase the power supplied by the generator.

This kind of influence is shown in Fig. 3 where it can be observed that for the same power installed of

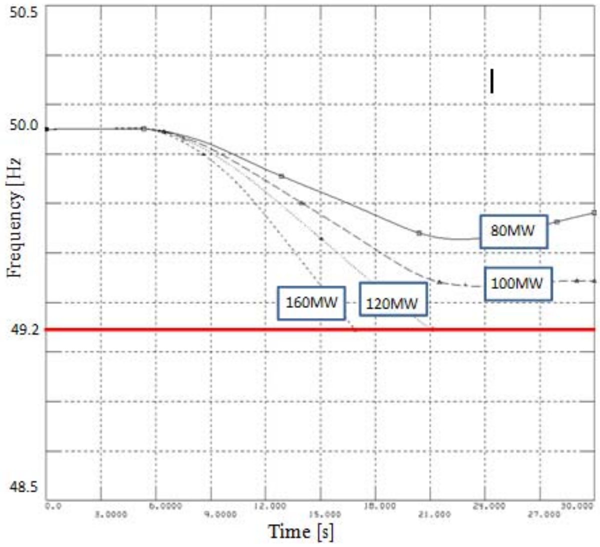

**Fig. 2 Variation of frequency for different PVP powers in CUYO.**

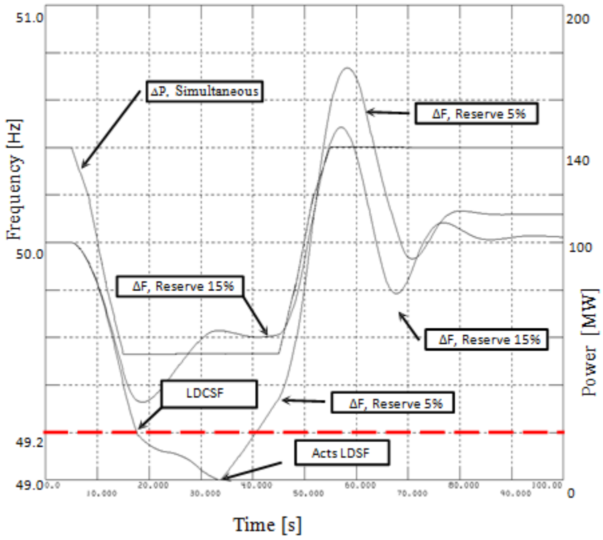

**Fig. 3 Spinning reserve influence, variation of frequency and power.**

PVP and for greater spinning reserve a best behavior of frequency can be expected after generation faults due to clouds.

The dot red line represents the frequency threshold for which the load disconnection scheme is activated after sub-frequency (LDSF).

3) Voltage Control Problems

AC Electric networks need to interchange active and reactive power with generators. The last one is a kind of energy used to maintain voltage along electric lines and it is required by different electric devices, which require a magnetic field to function such as electric motors.

In general, a decrease of active power generation in the PVP will produce a voltage decrease and it will be necessary that the PVP generates the required reactive power to control voltage. This is possible within certain limits but only if PV penetration does not overpass a certain maximum limit. In order to accomplish those required conditions for voltage control the following conditions should be fulfilled [2]:

- The PVP must be able to modify the reactive power interchanged in its connection point to the network in a band of ±0.33 Nominal Power ($P_N$) for all its power range.
- It must be able to vary its power factor in the range of ±0.95.
- PVP linking transformers with the network should count with:
  - Nominal voltages that do not limit the normal operation of the network.
  - Voltage regulation under load in a range of ±10%.

The effect of the reactive power variation delivered by the PVP after the voltage change in the interconnection node to the system is shown in Fig. 4. It is observed that the greater the Reactive Power variation capacity (ΔQ) the less results the variation of Voltage (V). This is possitive for the system dynamic behaviour since this would avoid phenomena like voltage collapse.

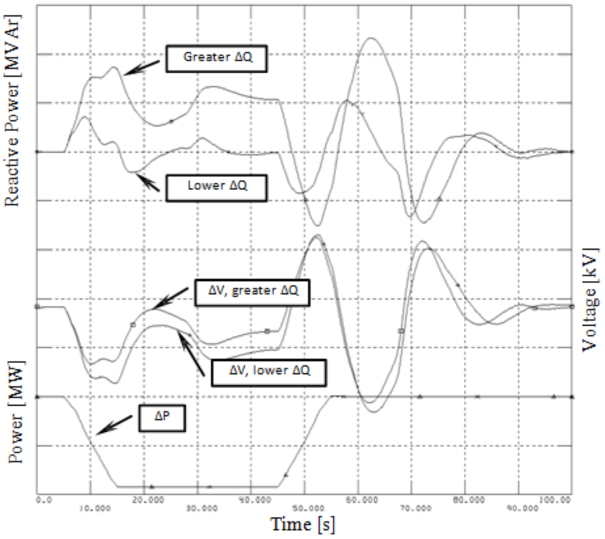

**Fig. 4 Influence on the variation of the reactive power of the PVP.**

4) Problems with replacement of generators operating at the base of the demand diagram.

The base of the demand diagram is generally supplied by a generation that due to its technical features must or should function all day. That is the case of passing hydraulic power plants, nuclear power plants and thermal power plants.

Many times, due to network constraints, there are thermal generators that should be forcedly dispatched, sometimes to control voltage and others to avoid overloads in the equipment. Although these generators do not need to be dispatched during all hours of the day, they generally should be during peak hours and this may coincides with the maximum generation of PVP (midday).

These restrictions make that the installation of PV/E generators have a limit, making that those organisms involved in the dispatch and control of interconnected systems stated conditions that should be fulfilled, many of which will prevent from installing further PVP in the future.

## 3. Study Methodology

### 3.1 Studied System

Studies were carried out over the CUYO since the provinces of this region have very favorable climatic conditions for installing large size PVP, not only for the great solar radiation but also because of the large deserted unproductive extensions non available for other types of activities.

The variability of solar energy is characterized by a daily and seasonal standard, where the production peak occurs in the central hours of the day and in summer. Therefore, the study was done considering the demand and generation states of Summer Peak occurred in the region in the year 2016 so as to count with a great PV generation capacity.

The system modeling was performed using the analysis software operating static and dynamic PSS/E 32.0, and the following databases were prepared:

1) ***Static Data Base,*** with the topological network configuration. It includes static parameters of lines, transformers, generators, compensators.
2) ***Dynamic Data Base,*** with the model of conventional and photovoltaic generators in service. It includes all dynamic parameters of generators, speed and voltage regulators, stabilizers, etc.
3) ***Protections Data Base***, which includes sub-voltage and sub-frequency relay parameters present in the system.

### *3.2 Location of Photovoltaic Parks in the Field*

High power PVP (>10MW) occupy a large extension.

When a great amount of clouds passes over a PVP there is a significant decrease in the active power that the park supplies to the network.

The decreased generation as well as the effects produced in the network will depend on the clouds size, their speed and their height.

The PVP size, its disposition and the connection of solar panels have great influence and it is shown that it is convenient to count with the same power installed distributed in various PVP geographically spread instead of having it concentrated in only one place.

The frequency variation in case of counting with four PVP in different locations in contrast to the same power installed but concentrated in only one PVP is shown in (Fig. 5).

The installment of four PVPs located in Tulum Valley, near the capital of San Juan was simulated having into account the beneficial effect of PVP geographical spread and taking as basis the real CUYO composed by San Juan and Mendoza provinces and modeled as previously described.

The four PVPs have the same nominal power ($P_N$) and they were connected to the network through 132 kV lines.

The location and name of the four modelled PVPs is detailed in Table 1.

### *3.3 Model of Contingency*

Two different contingencies in relation to their severity were modeled giving the following cases:

**Case P10:** this one simulates clouds covering completely each PVP producing the decrease of generated power to 10 % of its Nominal Power ($P_N$).

**Case P40:** this one simulates clouds covering completely each PVP producing the decrease of generated power to 40% of its $P_N$.

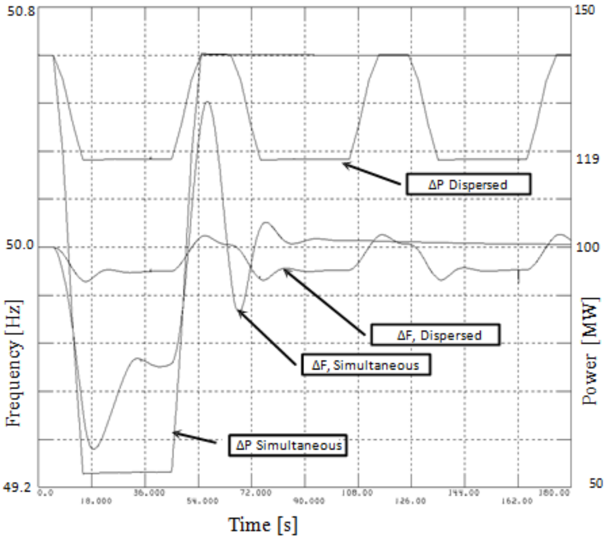

**Fig. 5 Influence in the variation of frequency in relation with the dispersion of PVP.**

**Table 1 Detailes of the PVPs modeled.**

| PVP | ZONA | Node of linking | Distance and direction of San Juan City |
|---|---|---|---|
| North | Angaco | Chimbas-Albardón | 50 km (N-E) |
| South | Sarmiento | Cañada Honda | 55 km (S) |
| East | 25 de Mayo | Caucete | 82 km (S-E) |
| West | Ullum | La Bebida | 25 km (N-W) |

Both cases were simulated according to two different conditions of cloudiness:

1) Simultaneous reduction of power in the four PVPs.
2) Reduction of power in each PVP with a delay in time among the four PVPs.

The decrease or fall in the energy supplied by the park, the permanence in minimum power and the increase in power is modeled according to the description of Table 2.

### *3.4 States of Simulated Photovoltaic Energy Generation*

Once the electric system to be studied as well as those cases to be analyzed are modeled **(P10 Case and P40 Case)** the pass of clouds over the PVP was simulated in a set of power flows with different PV generation values embracing a range which goes from 10 MW up to 560 MW with jumps of 20 MW between each case.

## 4. Results

Various simulations are analyzed for different $P_N$ modules at each PVP and it is determined which of them present problems that make unacceptable its functioning so as to obtain the maximum admissible values of Nominal Power for the PVP which guarantee the transient stability and good dynamic behavior of the system.

Those results obtained from simulations carried out with the PSSE 32.0 software for the variation of Power supplied by the PVP were included in Table 3. The maximum admissible values of Nominal Power of the four simulated PVPs placed together are shown there, considering different values of spinning reserve for those cases in which shadowness occurs simultaneously in the four PVPs and when there is a delay of the shadowness in time.

The Simultaneous case is equivalent to considering that the four PVPs are located geographically together forming only one large park.

When a delay is simulated in the reduction of supplied power by the different PVP, it must be considered that each PVP has a different location and their behaviors are more or less independent in time.

The convenience of the disperse location of PVPs is shown in Table 3.

**Table 2 Model of generation variation produced by train of clouds.**

| Cases | Time [s] | | |
|---|---|---|---|
| | Failure period | Permanence | Increase period |
| P10 | 10 | 30 | 10 |
| P40 | 10 | 30 | 10 |

**Table 3 Results of Maximum Power of PVPs**

| Spinning Reserve | Case | Delay [s] | | | | |
|---|---|---|---|---|---|---|
| | | Simultaneous | 30 | 60 | 90 | 120 |
| 5% | P10 | 60 | 160 | 260 | 260 | 260 |
| | P40 | 100 | 240 | 360 | 360 | 360 |
| 15% | P10 | 100 | 200 | 320 | 360 | 360 |
| | P40 | 140 | 300 | 460 | 460 | 460 |

### *4.1 Indexes of PV Penetration*

The aim of the study is to define a procedure to determine the *Maximum Photovoltaic Penetration* at a regional electric system and the *Maximum Photovoltaic Instantaneous Penetration* for a given operation state, having into account the limits imposed by the transient stability and the geographical dispersion of PVPs.

A form of defining the Maximum Penetration of Photovoltaic Generation is through the definition of the "*Index of Photovoltaic Penetration*" as the relation of Photovoltaic Installed Generation respect the Total Installed Generation.

$$I_{PP}[\%] = \frac{PVG}{(CG + PVG)} \bullet 100$$

Where:

**$I_{PP}$ [%]:** Index of Photovoltaic Penetration in %

***PVG*:** Photovoltaic Generation Installed in MVA

***CG*:** Conventional Generation Installed in MVA

Both generation values, Photovoltaic and Conventional one, vary during the operation of the Electric Energy Supply System and it can be very different according to the demand state and the electric connectivity of the system.

Another interesting relation to be analyzed is the one that exists between the Installed Photovoltaic Generation and the Demand, this index is called "*Index of Instantaneous Photovoltaic Penetration*" (**$Ii_{PP}$ [%]**).

The *Maximum Penetration Indexes* respect the Installed Generation and the Demand for the limit cases defined for PVP either concentrated or disperse ones are shown in Table 4.

**Table 4 Maximum indexes of photovoltaic penetration in relation to their location and spinning reserve.**

| PVP | Spinning Reserve | $P_N$ [MW] | $I_{PP}$ [%] | $Ii_{PP}$ [%] |
|---|---|---|---|---|
| Concentrated | 5% | 100 | 10.9 | 10.1 |
| Concentrated | 15% | 140 | 14.9 | 14.2 |
| Spread | 5% | 360 | 40.9 | 36.4 |
| Spread | 15% | 460 | 48.0 | 46.5 |

## 5. Conclusions

This work shows the main effects that PVPs proliferation would cause in the electric systems and the way in which those organisms encharged of the operation impose conditions for the operation of such generation parks due to the occurrence of generation intermittence. Besides to the need that those PVPs do not influence negatively in the control measures and/or automatisms implemented to avoid problems in the normal supply to consumers.

It is clearly shown the convenience of implementing Disperse PVPs so as to avoid a strong decrease of frequency which may lead to load disconnection by sub-frequency.

The used methodology helps to obtain maximum indexes of PV penetration and it can be used to determine the behavior of the electric system after contingencies that may compromise its stability hindering the fulfillment of defined operation criteria.

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