9th International Conference.
Electrical Power Quality and Utilisation.
Barcelona, 9-11 October 2007

Assess the impact of photovoltaic generation systems on low-voltage network: software analysis tool development

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***Abstract* — The integration of photovoltaic generation systems into power networks can cause both benefits and drawbacks. However, utilities have to control and operate their systems properly, in order to assure the availability and quality power supply to the users. Therefore, utilities should consider technical constraints and existing regulation in order to assess the impact of photovoltaic systems and limit their integration. On the other hand, regulation includes few operation constraints and they are not implemented in current software analysis tools.**

In the present paper a tool for assessing the impact of PV integration on low-voltage networks is described. The voltage fluctuation, the inversion of the power flow and the increase of short-circuit capacity are the problems considered in the proposed tool. Further work will focus on harmonics distortion.

Keywords: photovoltaic generation, integration of distributed generation, , voltage fluctuation

I. INTRODUCTION

There is an increasing introduction of small-scale power generation systems into the grids, namely distributed generation (DG), like combined heat and power (CHP), wind power and photovoltaic (PV) generators. This integration is provoking control and operation problems to the utilities since the networks have not been designed taking into account these DG units.

DG is increasing due to evolved associated economic and environmental factors, and generation technology improvements, like power electronics interfaces and energy storage systems. Therefore, DG units connected to the grid are currently more and more promoted since they are technological mature and highly good remunerated. The goal is to achieve a green empowerment scenario. On the other hand, there is an increasing need for assessing the consequences of their integration.

Most of these dispersed generation units are renewable energy based sources: wind, solar radiation, etc. Then, its power production is unpredictable and mainly dependant on weather conditions. Moreover, they are usually connected to the grid through power electronic converters. This fact represents a significant difference from conventional generators.

Therefore, DG units can cause technical problems and instabilities to the grid. Moreover, since they are non-centrally planned and dispatched, and they are mostly operated by independent producers. Then, new ways of calculation are needed since current commercial software tools that utilities usually use are not properly designed to cope with this issue. Thus, specific analysis tools are needed to be developed.

According to this, this paper introduces a software tool that has been designed to assess whether a new photovoltaic generator unit can be connected to a low-voltage network. It should be mentioned that this tool is the continuation of a work started time ago [1]. The aim is to help utilities to predict the possible problems that a massive introduction of these systems can cause in a particular low-voltage grid.

II. CONCERNS ABOUT PV GENERATION UNITS

Utilities are worried about the previously quoted effects on the network caused by DG. Current networks have not been designed for operating with such new generation units. Then, current operation and control strategies will be unsuccessful and it will be more difficult to meet established power quality standards [2]. The integration of DG units, including both renewable and non-renewable sources, presents several challenges [3].

PV is regarded as one of the most promising energy sources for the future, as well as wind power. PV has diverse applications, as space applications and stand-alone systems. However, PV capacity connected to the grid has significantly grown during last decade in different ways for: small personal or household applications, built-integrated and large ground based systems. As PV generation systems are being connected to low-voltage grids, the effects on clients are more manifest.

The main technical effects of PV generation units on networks are: voltage variation, reverse power flow and the increasing of short-circuit capacity at the point of connection. They can also cause protection malfunctions. As well, PV units can draw harmonics into the grid because the power electronic converters.

A. *Voltage variation*

PV generation usually works on the low and medium-voltage networks injecting power instead of consuming. Networks have not been designed in this way. PV generation increases voltage at the point of connection. This can help somehow to compensate the voltage drop when a big load is connected, but can also lead to quick voltage variations in the whole network when a PV generator is continuously connected and disconnected. As tap-changers are usually adjusted manually according to network features, PV behavior can introduce significant fluctuations on voltage profile.

As PV has a stochastic behavior that mainly depends on weather conditions, it is very difficult to predict exactly their power production. Then, the difference in voltage with or without PV unit should be considered.

If several PV units are connected in a limited area, the problem could be amplified and their effects multiplied because more and more non-controlled power is introduced to the grid. And if the PV units are single-phase, they can introduce considerable voltage unbalance.

As well, voltage can not only increase or decrease arbitrary but it can also be higher that the allowed limits at some load state. Then, it causes problems not only in the point of connection but also in the whole area where this network is spread and the customers connected to it.

B. *Reverse power flow*

Low and medium-networks are supposed to bring energy from transmission system to the final consumer. But they have not been designed to work the other way round. If power generation connected in a network is bigger than demanded power, a reverse power flow should be expected. That means that, globally, the network would introduce power from the low-voltage level to the medium-voltage.

Since several protection devices work regarding the direction of power flows, this could lead them to not operate properly. Besides, when the power flow is inverted, the voltage at the end is higher than the voltage at the beginning. And that is not desired at all nowadays. It will imply a shift in controlling and operating the network. As low-voltage grids are widespread, it would mean a high investment and a long-time process.

C. *Increased short-circuit capacity*

As PV units are power generators, when a fault occurs, the short circuit current is increased. This leads to an increase in short-circuit power and therefore, makes it more violent.

That is so, because they act as power injection. If a short-circuit occurs in a certain point where PV panels are next to, they will provide more power to the short-circuit and, therefore, the short-circuit will have worse consequences.

Protection devices are regulated against short-circuits according network configuration. They are not thought for the new power capacity. When a short-circuit appears, the short-circuit current could be much higher than expected and it may lead to malfunctioning of the short-circuit protections.

D. *Protection malfunction*

When a fault occurs at the end of a low or medium-voltage power line, PV units give part of the short-circuit current that flows. That makes less current flow from the substation and therefore, it may be difficult or even impossible for the protections place there to distinguish between a short-circuit and a usual overloading process.

That can be dangerous if a real fault occurs, because the protection devices would not be working when supposed to, and, therefore, it can lead to non-desired consequences. That is, this may induce problems when isolating the fault and as a consequence, large short-circuit effects.

Project supported by the Endesa Red's Chair in Energy Innovation

E. Harmonics

PV systems draw harmonics to the network since they are connected to the grid through electronic power converters. Harmonics can produce negative effects on neighbor facilities, as over-heating of electric devices, false measure readings and resonances with capacitors banks.

III. SOFTWARE DESCRIPTION

The aim of the tool here described is to assure a proper integration of PV units according to existing regulation [4] and network operation requirements defined by the utility. Then, it evaluates some of the possible effects that in the worst case such generation can cause.

The tool has been developed in Matlab because its ease in programming and in graphical interface creating. The graphical interface follows a clear structure in order to allow a useful and easy operation.

Network features are defined in Excel files got from the utility. Nameplates of transformers and low-voltage power lines follow utility's standards. And networks are modeled as single-line diagram.

A. Hypothesis

In order to be able to develop such software, several hypotheses were considered:

- Networks are all radial. Then, admittance matrix is considered as a sparse matrix, since branches are ramified and buses have few connections. Thus, the percentage of zeros becomes high. If it is not radial, the software shows an error message.
- Networks are composed by a distribution transformer and one or more low-voltage power lines.
- Transformer features are: transformation ratio (kV), nominal power (kVA), short-circuit voltage (%) and primary and secondary short-circuit powers (MVA).
- Medium-voltage network short-circuit power is known at the primary of the transformer. It is considered inductive.
- All buses are considered as PQ-buses, less slack bus.
- PV generators are considered as negative loads connected to a new bus.
- Loads are classified in five groups depending on their use: domestic, industrial, services, street-lightning and special loads. In order to calculated minimum and maximum demand, loads are affected by low and peak coefficients respectively.
- Four scenarios are supposed: peak consumption with and without PV generator, and low consumption with and without PV-generator.
- ∏-model is used power lines. Then, the number of buses is less than for T-model. The former needs 2 buses, and the latter requires 3 buses (Fig. 1). Thus, admittance matrix size is reduced and then, computing time too.

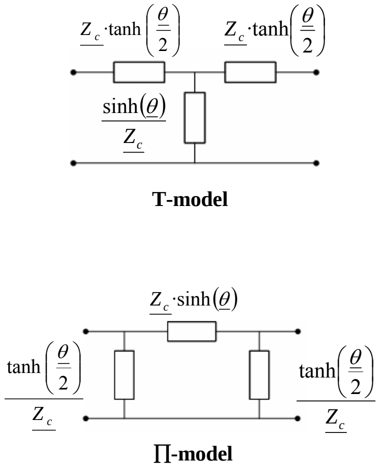


Figure 1. T and ∏-model power line model.

B. Tool description

Each new application to connect a PV generator system to the network is a study case. Before allowing its connection, the utility needs to study the impact on the system. It uses several criteria to accept or refuse the request.

The tool uses a graphical interface structured in different fields in order to get fast evaluation. Its objective is to create a final report of the study case that will help utility's planning engineers to assess the impact of a new PV generator..

The structure is the following:

- General data regards to application of new PV generator.
- Network data, including the distribution transformer and the low-voltage power lines connected to it.
- Transformer data.
- Low and peak coefficients to create the scenarios.

All this information allows the creation the matrixes that define the current global system and will use the calculation-engine:

- Buses list, their numerical code and their nominal consumption.
- Branches list, where the parameters of the power lines are defined: unit resistance (Ω/km), unit reactance (Ω/km), unit capacity (nF/km), lenght (meters) and maximum intensity (A).
- Admittance matrix [Y] has been calculated with the ∏-model parameters according to (1):

$$\underline{y}_{kk} = \sum_j \underline{y}_j$$

(j is next to the bus k)

$$\underline{y}_{kl} = -\sum_j \underline{y}_j$$

(j is between *k* and *l*) (1)

- A matrix which shows the connection between buses, called ‘electrical way’. It is similar to admittance matrix. It is created as in [5]. For example, for a radial low-voltage network like shown in Fig. [2], this matrix is (2).

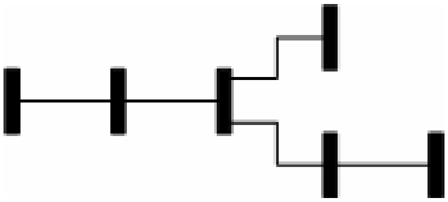


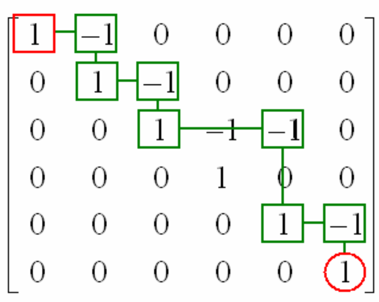
Figure 2. Example of low-voltage network.

$$[ID] = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & -1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

The tool checks that all these matrixes are properly derived before going on with the calculation. For example, for the former matrix described, the sum of each column must be zero, except for the first. Then, it is guaranteed an electrical connection between all the buses.

The process to assess that there is an electrical connection is described following (Fig. 3):

1. Set which position fills the bus-load in the ‘electrical way’ matrix. The list of buses fixes which of them have consumption.
2. Search the (-1) placed in the same column over the load.
3. Search the (1) placed at left of the previous position.
4. Repeat the process up to the first bus.



$$\begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & -1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

(6,6)-(5,6)-(5,5)-(3,5)-(3,3)-(2,3)-(2,2)-(1,2)-(1,1)

Figure 3. Electrical buses connection assesment.

The tool does not yet include a graphical representation of the grid. However, the ‘electrical way’ matrix will be useful to obtain the electrical connection, from load to transformer by this algorithm:

The new PV generator is included separately. It is needed to define its bus connection point and the new branch parameters. All this information is included in the lists of buses, branches, admittance matrix and ‘electrical way’ matrix.

C. *Load Flow*

The method used to solve the load flow problem is the Newton-Raphson algorithm, because its rapid convergence to the solution. It has been chosen its compact form, defined by equations (3), where V and θ are the module and the angle of the bus-voltage. P and Q are the active and reactive power of the loads.

$$\begin{bmatrix} H & N \\ M & L \end{bmatrix}^k \cdot \begin{bmatrix} \Delta\theta \\ \Delta V / V \end{bmatrix}^k = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}^k \quad (3)$$

Matrixes H, N, M and L are built, for i≠j according to (4).

$$\begin{aligned} H_{ij} &= L_{ij} = V_i \cdot V_j \cdot \left(G_{ij} \cdot \sin\theta_{ij} - B_{ij} \cdot \sin\theta_{ij} \right) \\ N_{ij} &= -M_{ij} = V_i \cdot V_j \cdot \left(G_{ij} \cdot \cos\theta_{ij} + B_{ij} \cdot \sin\theta_{ij} \right) \end{aligned} \quad (4)$$

And for i=j, these matrixes are built according to (5):

$$\begin{aligned} H_{ii} &= -Q_i - B_{ii} \cdot V_i^2 \\ L_{ii} &= Q_i - B_{ii} \cdot V_i^2 \\ N_{ii} &= P_i + G_{ii} \cdot V_i^2 \\ M_{ii} &= P_i - G_{ii} \cdot V_i^2 \end{aligned} \quad (5)$$

Before each iteration, the vectors of modules and angles are actualized to start the next iteration as (6) shown.

$$\begin{bmatrix} \theta \\ V \end{bmatrix}^{k+1} = \begin{bmatrix} \theta \\ V \end{bmatrix}^k + \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix}^k \quad (6)$$

And vectors of ΔP and ΔQ are calculated as (7) shown.

$$\Delta P_i = P_i^{esp} - V_i \cdot \sum_{j=1}^{n} V_j \cdot \left(G_{ij} \cdot \cos\theta_{ij} + B_{ij} \cdot \sin\theta_{ij} \right)$$
$$\Delta Q_i = Q_i^{esp} - V_i \cdot \sum_{j=1}^{n} V_j \cdot \left(G_{ij} \cdot \sin\theta_{ij} - B_{ij} \cdot \cos\theta_{ij} \right) \quad (7)$$

This iterative process is done for the four scenarios previously quoted. And outcomes are processed to asses the fulfillment of defined connection criteria.

D. Shortcircuit power

In order to calculated short-circuit capacity at desired buses, first short-circuit impedances are calculated according to (8), (9) and (10).

- Short-circuit impedance of medium-voltage grid:

$$\underline{Z}_{th} = j \cdot \frac{V_{1n}^2}{S_{sc(MV)}} \quad (8)$$

- Short-circuit impedance of the transformer:

$$X_{sc}^{transformer} = \varepsilon_{sc} \cdot \frac{V_{2n}^2}{S_{nom}} \quad (9)$$

- Short-circuit impedance of the network:

$$X_{sc}^{network} = \sum_{i=1}^{n} X_{i(\Omega/km)} \cdot l \quad (10)$$

  It is calculated taking into account only the direct branches from the transformer to the PV-generator, using 'electrical way' matrix.

Then, short-circuit current is calculated. And finally, the short-circuit power is obtained.

E. Connection criteria assessment

The evaluation of these criteria is done processing the data obtained from the load flow for each of the four stated scenarios. They mainly match with the issues already depicted in section II.

The integration of the PV systems depends on several criteria, according to Spanish regulation [4] and utility's operation procedures. These criteria defined by [4] to accept or refuse the request are described next.

- Voltage variation: The voltage variation must be lower than 5% at the connection point between with and without PV for both low and peak demand.
- Reverse power flow: The sum of the power generated by PV generators in the network can not be higher than the 50% of the nominal power of the transformer.
- Increased short-circuit capacity: PV power must be lower than 5% of the network short-circuit capacity at the connection point.
- The intensity through power lines must be lower than 50% of the maximum intensity when connecting the new PV generator.

And the stated utility criteria defined whether to accept or refuse the request are next:

- Reverse power flow: The sum of power of all PV units in the network can not be higher than the low load.
- Increased short-circuit capacity: The sum of all PV power in the network must be lower than 5% at the bus where the nearest PV unit is connected to the transformer.

IV. CONCLUSIONS AND FURTHER WORK

This paper has shown the construction of a tool for assessing PV impact. It has been described the matrixes and the algorithms and methods employed. The solution of the load flow is the first step to improve a former version with some other complements which will make this tool not only mathematical, but more electro-technical and graphical, than this one.

On the one hand, this tool will be improved in the future by adding graphical results, as for example, a scheme of the network. The programming software (MATLAB) includes a powerful library of graphical functions, which will help to develop more visual options, like the voltage profile from the header to the bus desired, and also a scheme of branch saturation.

On the other, PV-generator technology carries, inherent to it, the harmonic problem with inverters. So it is necessary to establish, perhaps, a new criterion for harmonic injections. The evaluation of these criterions would, directly, mean that harmonic load flow should be developed. Real harmonic models of loads are needed. Reliable results depend on the reliability of the models used in the simulation.

By another side, it is known that one of the implicit conditions of the simulation is considered a balanced three-phase system. Spanish legislation allows to connect just up to 5 kW in the single-phase system, and the tool it has been introduced admits this option, but multiplying the power by the coefficient $2 \cdot \sqrt{3}$. The significance of power increases, and it is easy to think that in some systems the premise of a balanced system is not true. It would interessant to consider, as further work, the study of unbalanced systems. There exist some algorithms to solve this case, but, like in the case of harmonics, is also needed reliable data, which should include the consumption at each phase.

Further work could be summarized in: graphical tools, harmonic case and unbalanced systems.

ACKNOWLEDGMENT

This tool has been developed under the Endesa Red's Chair in Energy Innovation support.

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