NOVEL METHOD FOR IDENTIFYING MAXIMUM RENEWABLE ENERGY PENETRATION IN DISTRIBUTION GRIDS

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ABSTRACT

With more and more integration of renewable energy sources into the grid, electrical network structure is experiencing significant changes which causes existing power system study tools and algorithms need to be developed again. This paper presents a novel approach to obtain maximum power capabilities in distribution grids with high penetration of distributed generators. An algorithm is developed for calculating the maximum probabilistic hourly capability for a set of nodes inside the distribution grid, taking into account generators contingencies and MVDC (Medium Voltage Direct Current) links. For the case study presented, the MVDC increase the distributed generation penetration.

INTRODUCTION

In Europe there is clear trend towards high penetration of distributed energy sources (DES) and renewable energies into the grid, driven by both decrease technology cost and governmental subsidiaries. Such a trend poses technical and economic challenges for both transmission and distribution network operators, such as a voltage rise problems eventually resulting in curtailment of distributed generation (DG), power balance in network after any generation goes off, etc...

In Germany, the above-considered challenges, also determined by the so-called energy transition are under investigation in the Kopernikus-ENSURE project as mentioned in acknowledgement.

The paper aims to address three key drivers, sustainable generation, competitive overall cost and security of supply by proposing a novel method of planning generation capacity for the distribution grid.

A stochastic approach using Montecarlo method is proposed for the first time to obtain higher power capability range under “N-1” criteria for distributed generator in hybrid AC-DC network. The outcome may be used to explore new, potential different, installation of distributed generation inside the distribution grids.

ALGORITHM

The algorithm described in this paper is able to estimate the maximum penetration of the distributed generation, under the constraints and the load present in the distribution grid. Mainly, it is characterized by the simplicity of use and may be used as inner loop for more complex grid planning tools.

As input, it needs the grid data, in particular: the list of stations and sub-stations and the list of branches defined by overhead lines, cables and power transformers. If available, a list of generators can be also considered. According to the classic steady-state analysis, the branches are described by the PI model with longitudinal and transversal components. The stations and sub-stations are described by a simple node. The grid constraints taken into account are the current flow through the branches, the voltage deviation for the nodes and the tap position for the power transformers. Regarding the generators, their capability is defined by their maximum and minimum active and reactive power combined with their maximum apparent power. If necessary, other linear constraints between active and reactive power can be considered.

The load has an hourly definition with a span of one year; the values can be provided as simple time series or by an external loop (if the operator wants to analyse different types of scenarios).

As output, it provides the maximum probabilistic hourly capability, in terms of active and reactive power injected into the grid, for the selected nodes: these nodes must be manually selected by the operator during the input data definition. These power capabilities could be used either directly if the goal of the analysis is to define the maximum capability for the selected nodes or as input for further studies investigating the availability of renewable energy sources.

Main loop

According to the probabilistic approach, the algorithm is composed by a random number generator [1] and an

Optimal Power Flow [2], [3] linked in between. These components are sequentially called at every time step in order to create a non-sequential Montecarlo method [4] as shown in Figure 1. The random events change the active power absorbed by the loads; a time constant power factor is assumed for each node to calculate the reactive power. Furthermore, a normal distribution with a standard deviation of 10% is used [5]; failures of power lines and transformers are not considered.

The Optimal Power Flow is then used to maximise the active power injected into the grid by virtual generators installed on specific selected nodes, ensuring the supply of the load.

The system security is provided, at each time step, defining an inelastic demand values and a fixed grid constraint together with "N-1" criteria [6]. The "N-1" criteria is implemented by solving, with a single optimal power flow, a certain number of cases equal to the number of selected nodes in addition to the base case. In the base case all the virtual generators are present, while, in the other cases, the *ith-virtual-generator* is removed from the *ith-case*. It is additionally assumed that the virtual generators will provide the same amount of active and reactive power in the different cases because no power deviation is allowed. The grid interconnections are used for power balance.

At the end of each iteration, the results of the entire time horizon are saved and a verification of the variance of the output is performed in order to terminate the main loop: a threshold of 1% is used [5].

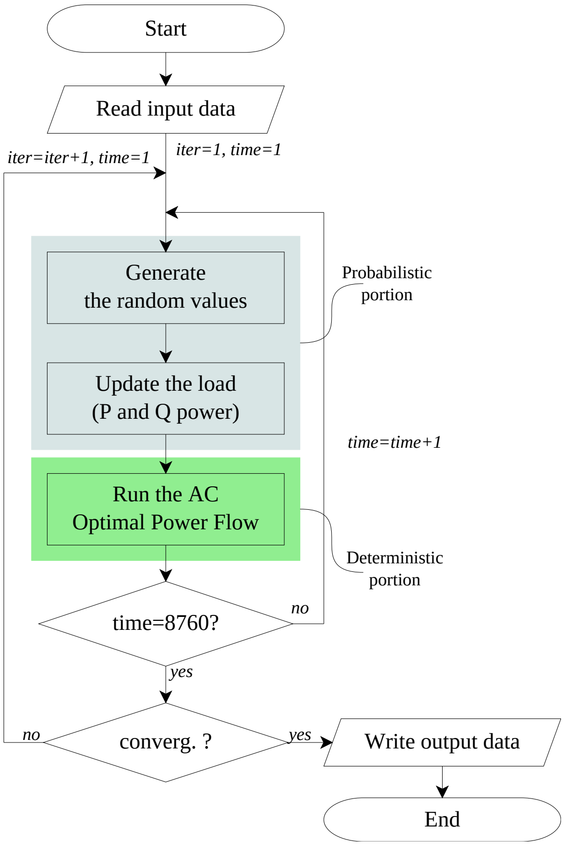

Figure 1 Main loop

It is composed by the following sections:

- Read and write data: these sections, presents at the beginning and at the end of the process, are used to get the input data and to write the output data for the post-processing analysis;
- Generate the random values: this section is used to provide the pseudo-random values used in the next session;
- Update the load values: according with the following equation:
  $$P_{n,t,i} = rP_{n,t}$$
  where r is the random value, i is the iteration number, $P_{n,t}$ is the active power for the node n at the time t which comes from the input time series;
- Run the Optimal Power Flow: in this section a new instance is performed in order to evaluate the maximum power injected into the grid.

Optimal Power Flow

The optimal power flow is implemented using the following general mathematic structure:

$$\begin{aligned} \zeta &= \min f(x) \\ h(x) &\leq 0 \\ g(x) &= 0 \end{aligned}$$

Where f is the object function, h and g are a set of non-linear inequality and equality constraints. The x vector is composed by a set of state and control variables. In particular, the state variables are the voltage magnitude and phase for each node, while the control variables are the active and reactive setpoint for the generators and the tap positioning of the power transformers.

The equality constraints are represented by the active and reactive power balance for each node while, the inequality constraints, by the current flow limits. Moreover, according to "N-1" principle, a multiple set of control, state variables and constraints are used where a maximum deviation of these variables through each case is considered.

The Optimal Power Flow routine is also able to solve a hybrid AC-DC grid, where the two network topologies are connected with two or more converters. The converter component is modelled according to the following power balance equations:

$$P_{AC} + P_{DC} + P_{LOSS} = 0$$

$$i_{AC} - \frac{\sqrt{P_{AC}^2 + Q^2}}{\sqrt{3}v_{AC}} = 0$$

$$\alpha + \beta i_{AC} + \gamma i_{AC}^2 - P_{LOSS} = 0$$

Where the first equation provides the power balance between the AC and DC side, the second and third are used to calculate the losses inside the converter using a quadratic relationship with the AC current [7].

Implementation

The algorithm has been written in C++, using Microsoft® Visual Studio™. For the Optimal Power Flow, IPOPT [8] has been used as solver for non-linear programming problem. The algorithm has been tested on Intel® Xeon® E5-2630 v2 @ 2,60GHz machine.

To speed up the Optimal Power Flow routine, the analytic form of Jacobian and Hessian matrices of object function and constraints are provided directly to the solver.

CASE STUDY

In order the verify the algorithm described above, a case study has been done. The distribution grid used is shown in the Figure 2 [9]: it is composed by 102 nodes, 142 branches (overhead lines, cables and power transformers) and three interconnections with other neighbours' grids.

Inside the grid there are all the voltage levels, from the distribution level at 6.6 kV, up to the transmission level at 275kV. The load sum for one year is equal to 3.4 TWh.

The three interconnections are simulated with virtual generators, without capability limits, but with a fixed voltage value, equal to 100% of the nominal; the voltage deviation for the remaining nodes is equal to ±2%. All low-level power transformers are equipped with tap chargers, with a range of -20% and +10% respect the nominal ratio. The loadability of the transmission/sub-transmission components is around 100MVA, while, for the distribution components (33kV), is about 20 MVA.

The investigation is divided in several parts, which are presented and described below:

- *Base*: in this case only the load is present. The load profile comes directly from the time series analysis and a simple Montecarlo is performed to have a base set of results;
- *Distributed Generator (DG)*: in this case the maximum probabilistic hourly capability is evaluated for a set of four nodes. In Figure 2, these nodes are highlighted sequentially with four virtual generators: from *G1* to *G4*. The load profile is equal to the previous case;
- *DG with "N-1" criteria*: this case is similar to the previous one but, the "N-1" criteria is enabled for the virtual generators from *G1* to *G4*;
- *DG with "N-1" criteria and MVDC*: in this case, a Medium Voltage Direct Current point to point with a capability of ±100M~~V~~W and ±100MVAr is additionally installed as shown in the Figure 2. Regarding the converter losses, a quadratic model, with a 2% of losses at the nominal power, is used.

Concerning the performance of the Optimal Power Flow routine, it needs about 300-400 millisecond to solve a single instance composed by 1500 of variables and constraints; it means that the algorithm needs about 1 hour to run a single time series of 8760 hours. The main loop needs about 100 iterations to converge but, using parallel computer techniques, it terminates in less than 4 hours.

In Figure 3, the results of the last three cases are summarized and compared. The maximum probabilistic hourly capability is calculated by adding the active power produced by the generators at each hour of the day, for each iteration and for each day of the year. The maximum probabilistic hourly capability is then illustrated as a surface defined, inferiorly by the 0% of the percentile and superiorly by the 100% of the percentile; in each case, the black line represents the average values and the distribution of the frequency can be well approximated with a Gaussian distribution shape.

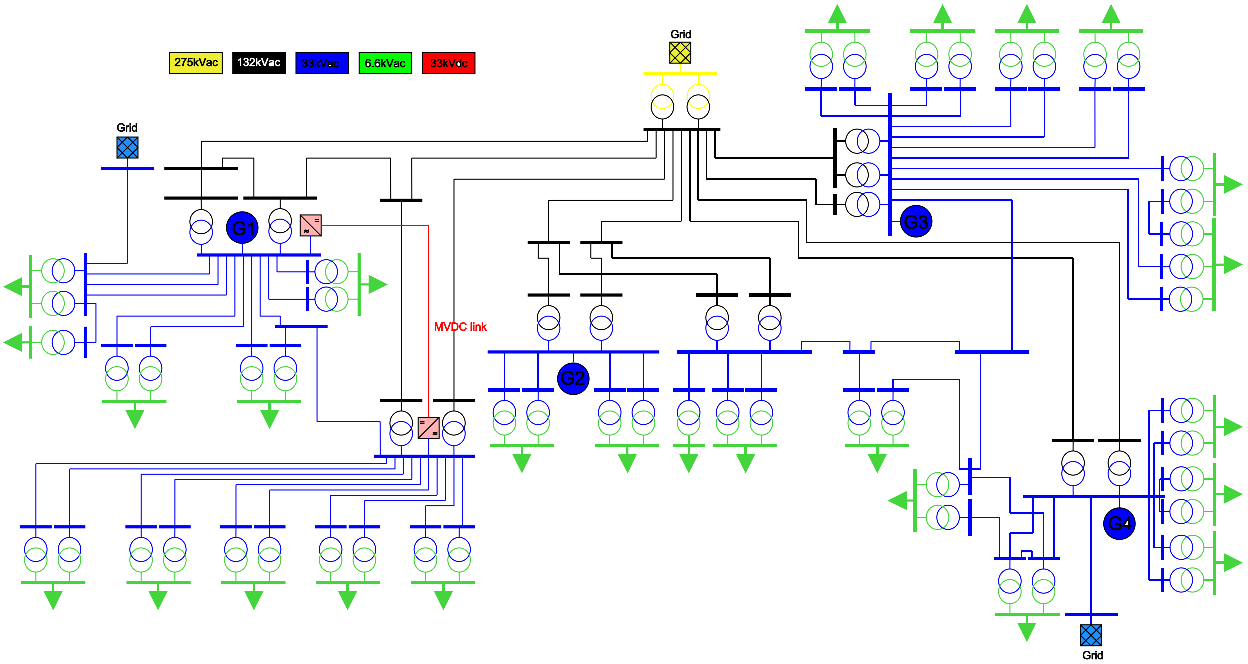

Figure 2 Schematic of investigating distribution network topology [9]

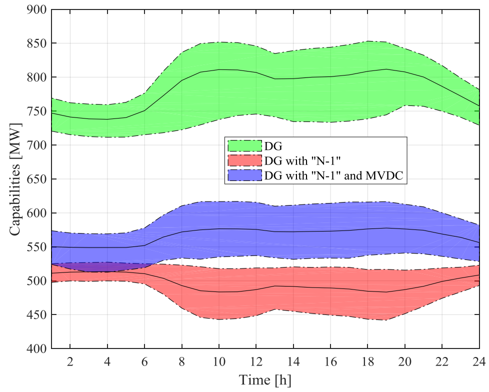

Figure 3 Maximum probabilistic hourly capability for different cases (hourly average of the year)

In the considered grid and for the three case studies, the installed virtual generators are always capable of producing an active power lower than the inferior bound, without violating the defined grid constraints. On the other hand, the probability of exceeding the limit defined by the upper bound without violating the same constraints is zero. The active power defined by each point of the shaded areas can be produced only with a certain probability, which could be additionally calculated taking into account the hourly capability of renewable energy sources. As expected the “N-1” criteria reduces the capability curve; in this case, the reduction is about 250MW. In the last case, the introduction of the *MVDC* point-to-point system increases the capability of about 70MW thanks to the direct connection between the production and demand side. In Figure 4, the voltage distributions are reported for the node where the virtual generator *G2* is installed.

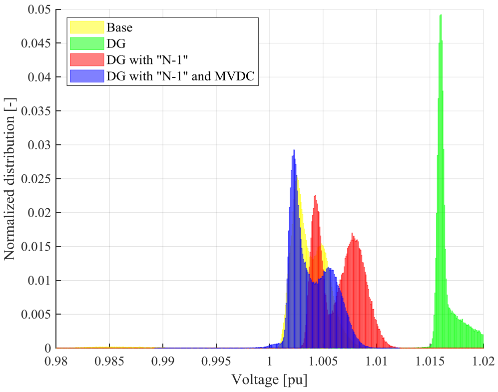

Figure 4 Voltage distribution for G2 node

In the *DG* case (green shape) the voltage distribution is close the to the limit of 102%, with a small range of deviation: from 1.015 to 1.02 with a peak on 1.016. The *DG with “N-1”* distribution (red shape) is closer than the previous-one to the nominal value but, only in the last case (with *MVDC*, blue shape) the voltage distribution is similar to the *BASE* case (yellow shape). Some negligible points are present inside the range of 0.98-0.99.

CONCLUSIONS

This paper presents a framework for the evaluation of the maximum distributed generation penetration in a distribution grid. The result shows a significant reduction of possible active power infeed when considering the “N-1” criteria for the virtual generators. In addition, a suitable connection of *MVDC* link between load and generation nodes increases the distributed generation penetration thanks the flexible active and reactive management. More studies can be performed to take into account the availability of renewable energy source and the active demand.

ACKNOWLEDGEMENT

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