COMBINATION OF LINEAR POWER FLOW TOOLS FOR VOLTAGES AND POWER ESTIMATION ON MV NETWORKS

Jérôme BUIRE
L2EP – France
jerome.buire@centralelille.fr

Xavier GUILLAUD
L2EP – France
xavier.guillaud@centralelille.fr

Frédéric COLAS
L2EP – France
frederic.colas@ensam.eu

Jean-Yves DIEULOT
CRIStAL – France
jean-yves.dieulot@polytech-lille.fr

Léticia DE ALVARO
Enedis – France
leticia.de-alvaro@enedis.fr

ABSTRACT

European Grid codes define new network management rules. In order to answer these decrees, it is important to estimate accurately the voltages and powers inside distribution networks. The intermittent nature of renewable sources leads to consider stochastic variables in power flow algorithms. A review of power flow methods and their ability to comply with these requirements is done, which shows that computationally demanding nonlinear methods have to be discarded when dealing with stochastic data and considering limited calculation time. A combination of linear methods is proposed, for which average errors in power and voltage are quite low, when applied to a real-life distribution network. The validity domain of the method is also presented.

INTRODUCTION

Current distribution networks are undergoing important evolutions due to the massive connection of renewable energy along with the replacement of overhead lines by underground cables, generating reverse power flows and increasing voltage fluctuations. Recent European Grid codes decree help to address the aforementioned problems. More specifically, the Demand Connection Code (DCC) and Operational Planning and Scheduling (OPS) chapters impose constraints at the grids interfaces and require to generate operational planning tools for distribution networks. Hence, the new voltage and reactive power management algorithms should embed an estimation of voltages, power flow and reactive power reserves. A load flow tools is necessary to comply with these requirements.

The intermittent nature of renewable resources and consumers leads to consider stochastic variables in distribution networks models. The most widespread method for dealing with this type of data and generating such models is the combined use of Monte Carlo Simulation and Newton-Raphson algorithm [1]. Whereas this procedure yields accurate results, it is hampered by numerical problems and a high computational burden. Furthermore, the black-box nature of this algorithm does not give physical insight on parameter sensitivities. An alternative method should estimate accurately the power flows at the grid interface (TSO-DSO), voltage levels in MV networks (in ordered to schedule controls) and the currents in the conductors.

In the first part of this paper, a review of a wide range of candidate Power Flow methods is proposed and their ability to accurately estimate voltages and power flows is evaluated. The specific case of French radial distribution grids, which embed dedicated, consumption or mixed feeders with known parameters, will be considered.

In the second part, it is shown that the most adequate power flow method consists of a combination of linear algorithms, using an approximation of the grid voltages [2] that feeds in turn an estimate of the grid powers. However, only theoretical upper bounds are given in [2] with no assessment of the general performance of this algorithm. In this paper, the average estimation accuracy and the validity domain of the combination of linear methods are, at last, presented.

COMPARISON OF LINEAR AND NON LINEAR POWER FLOW METHODS

State of the art of power flow algorithms

The study begins with a review of candidate methods, which are presented in three families: non-linear, linear and aggregation techniques.

The two first classes of algorithms allow to determine either power flow or voltages in the network or both. The third family enables to generate a lumped model of the power flow (consumption and production).

Non-linear power flow methods use no numerical approximations, such as the classical ac power flow combined with the Newton-Raphson method [3]. Other algorithms, such as Distribution Load Flow (Distflow) [4] that estimates the state of a node with respect to its neighbour, similar to the Backward Forward Sweep (BFS) method, require that the grid has a radial structure.

Linear methods are sorted into three subclasses which have specific properties. The DC power flow [5] is mainly used to estimate the power flows however it cannot provide good voltage estimates as it assumes that all voltages are 1pu. The first-order Taylor expansion proposed by Bolognani [2] allows to compute bus voltages. But this linearization forbids the estimation of impedance power (impedance of conductors). The last studied method is the Ward [6] method, it yields an estimate of power flow and voltage bus based on a voltage/current model, the estimation of both variables at the same time is known to be poor.

Last, aggregation methods are either based on the power flow equations, such as the Power Transfer Distribution

Factor Method [7] which uses the DC power flow and allows to reorganize the network, or a voltage/current model (REI equivalent) [8]. This second aggregation method applies the superposition theorem to a voltage/current model.

Choice of comparison criteria

The following criteria have been chosen in order to compare the capacities or qualities of the methods in accordance with the requirements presented in the introduction:

- "Aggregated model"

This first criterion allows to show the capacity of methods to interpret the power consumption under an aggregated form.

- "Power estimation"

This second criterion highlights the ability of methods to estimate the power consumption of the distribution network.

- "Load sensitivity"

This criterion discriminates methods which can use load sensitivities.

- "PQ diagram"

This criterion allows to show methods which can use PQ diagrams, which is important when considering generator constraints.

- "Voltage estimation"

This criterion evaluates the accuracy of voltage estimation.

- "Stochastic"

This criterion illustrates the capacity of methods to use stochastic variables (that is, to use stochastic inputs and to produce stochastic outputs).

Whenever a method does not fulfil at all one of these criteria, it cannot be used directly, either it should be discarded as a candidate method or it has to be modified to fulfil at this criterion.

Evaluation method

The comparison is done either using a qualitative appraisal of the criterion or by undertaking numerical evaluations. The accuracy of power and voltage estimations are obtained by comparing estimations of each method to the reference method when applied to a real distribution network, and converted in turn into a qualitative mark. A maximum error lower than 1 % (voltages or powers) deserves a mark above average.

Other criteria are evaluated in a qualitative way. Each method has been implemented in MATLAB software, allowing not only to compare the accuracy, but also the qualitative ease of use and coding under the same conditions.

The proposed scale has 5 levels ranging from 0 to 5. Receiving a score of 5 means that the method fully answers the requirements. An average evaluation means that the method is not entirely fit, showing technical difficulties, weak accuracy, etc. A 0 mark means that the method is inappropriate.

The network which is illustrated in the figure 1, has 2500 nodes, 900 loads, 120 km of underground cable, 600 km of overhead lines and 3 wind farms. The quantitative study uses this network and allows to evaluate load flow results.

The results are compared with that provided by an AC power flow combined with the Newton-Raphson's method, which are considered as reference data.

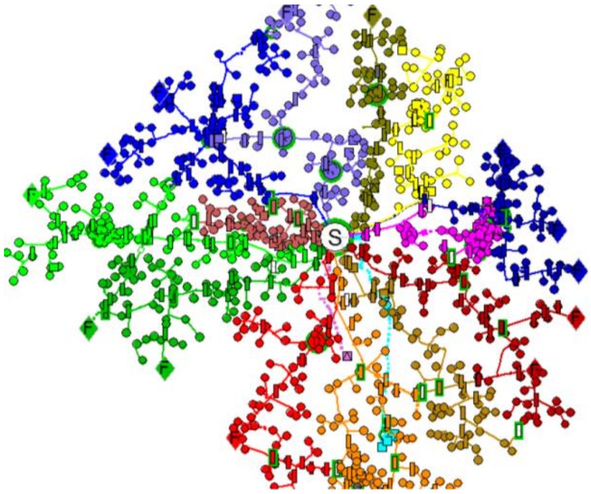

Figure 1. Distribution network used

Comparison results

Figures 2, 3 and 4 represent the results of the comparison, radar diagrams are used to display marks.

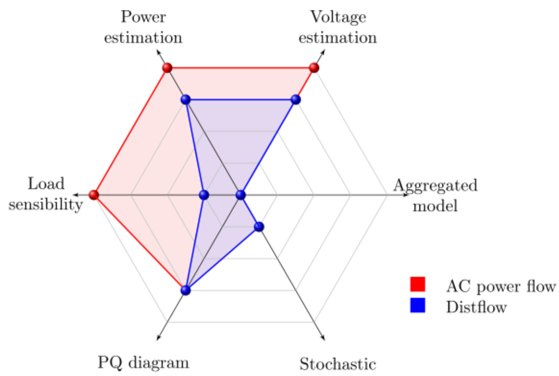

Figure 2. Comparison of non-linear methods

Figure 2 displays non-linear methods features; one can notice that they enjoy good estimation performances. However, it is worthy of note that these methods suffer from numerical problems, the computation can be long for large networks, which is detrimental to their industrial use. Moreover, as the algorithm is quite complex, understanding the influence of stochastic variables and generating an aggregated model is not straightforward or even inappropriate.

Figure 3 focuses on linear methods, which are suitable for the use of stochastic variables because it is possible to handle linear combinations of probability distributions. However, the accuracy of these methods is limited, because the algorithms should start with an initial guess (often for voltage values) which the final solution depends on. One can note that the three subclasses (Ward, Bolognani and DC power flow methods) yield results which are consistent with several objectives and hypotheses of this study. Neither of them, however, is a good candidate method, and often more than one criterion is not achieved. Any of these methods cannot be used as is, it is necessary to propose modifications and/or combinations with other methods.

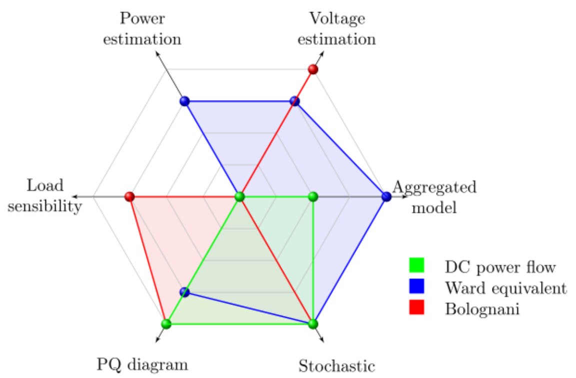

Figure 3. Comparison of linear methods

Figure 4 is dedicated to aggregation methods, which allow to simplify the resolution of a power flow. While these methods span the whole diagram, their lack of accuracy makes them unsuitable.

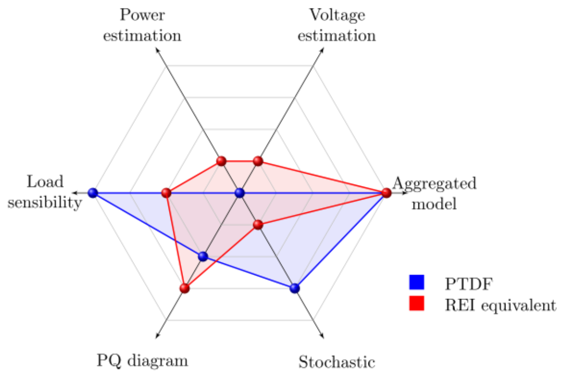

Figure 4. Comparison of aggregation methods

SELECTED TECHNIQUE

A combination of linear methods

One of the main objectives being to apply power flow methods on big, real networks, numerical difficulties to integrate stochastic variables forbid the use of nonlinear methods. The choice of linear methods is advocated. In this category, there is no method which answers well all criteria. It is necessary to combine complimentary methods.

The Bolognani method provides a good estimation of voltages without a priori. Its accuracy is sufficient to fulfill the objectives of this study [2]. However, it does not estimate lines losses, and one cannot derive the currents. The Ward method yields a good estimation of the powers, when a good a priori estimation of the voltages is fed to the algorithm, and, additionally, provides an aggregated form.

Hence, it is proposed to combine the Bolognani and Ward methods in the following sequence:

- First, the Bolognani method is used to estimate voltages
- Next, the Ward method based on impedance models yields estimates of the currents within the network
- A first order approximation is used to estimate the power due to admittances and impedances of the network.

The aggregated form is obtained by lumping the power of loads, of admittances (which depend on voltages) and of impedances (which depend on currents).

The combination is represented in figure 5. Overall, this combination yields an accurate linear power flow method.

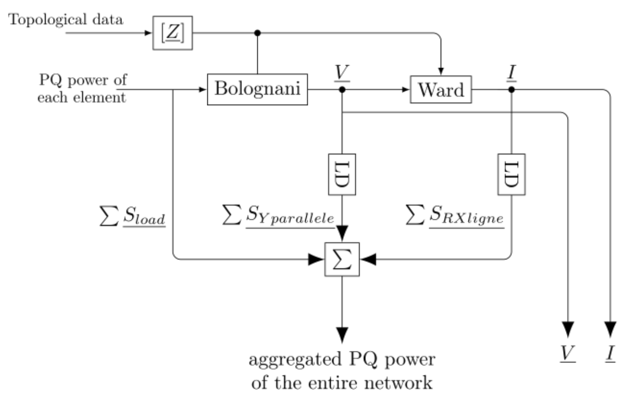

Figure 5. Combination of methods

Evaluation of average power flow accuracy

Bolognani [2] derives a peak error for voltage estimation (by bounding the residual of the approximations), but a more precise assessment of the mean and maximum accuracy of the technique has to be done, and the relevance of the combination with the Ward method has to be confirmed (using study hypotheses). Network voltages and power consumption (total consumption of the grid) are estimated.

The network presented in the figure 1 is considered. Loads and generators are represented by PQ models. Power references are known for each load and generator. They are used to weight the load rate and determinate the power consumption of each load. The maximal consumption of loads is 44.1 MW with a power factor f = 0.93. The nominal power of all generators is 17.2 MW with a power factor f = 1. In order to assess the performances for several network states, a wide range of load/generation rates are considered (increments of 1 %):

- 20% to 110% for load
- 0% to 100% for generator.

This range of values is equivalent to say that the network consume an active power ranging from -8.4MW (more production than consumption) to 48.5MW (high consumption without production).

As the consumption of the network can be close to zero, the absolute value of error is given (the relative error may turn to be infinite). The results are compared to the reference (Newton-Raphson) nonlinear method.

Figures 6, 7 and 8 give respectively the error in the voltages, the total active power error and the total reactive power error. These figures show their probability density functions in blue, allowing to spot the highest probable errors. The cumulative distribution functions are represented in red and give the probability that, considering the set of all load and generation conditions, the error lies below some prescribed value.

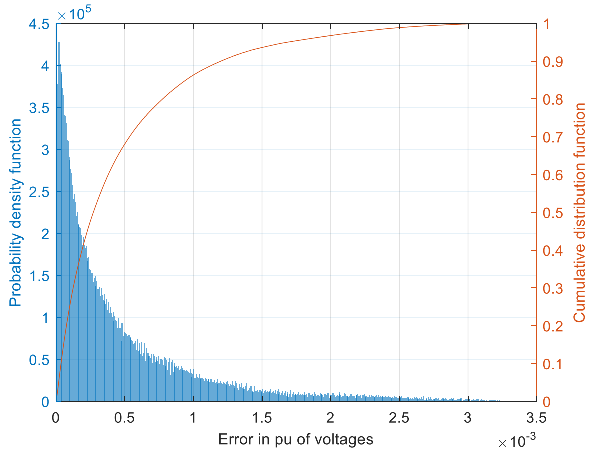

Figure 6. Voltage error

The figure 6 gives the error of all voltages within the network. The error is less than $1x10^{-3}$ pu for 86 % of configurations. The maximum error is $3.5x10^{-3}$ pu. This diagram shows that the mean error is far below the maximum error, and, hence, the practical relevance to use the Bolognani method is enlightened.

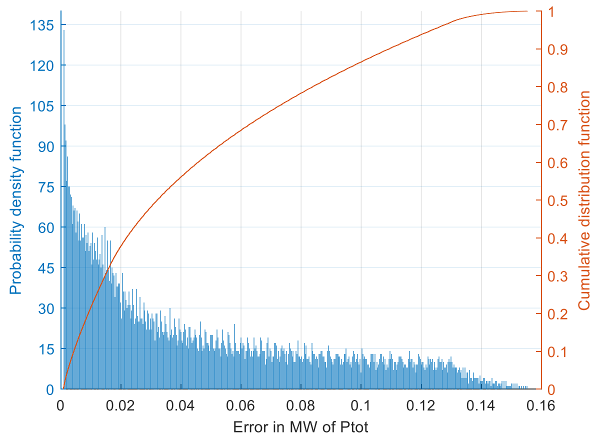

Figure 7. Total active power error

Figure 7 gives the error of the active power consumption of the entire network. 87 % of situations give an error less than 0.1 MW. The maximum error amounts to 0.16 MW, which is considered as small and, hence, is not discarding.

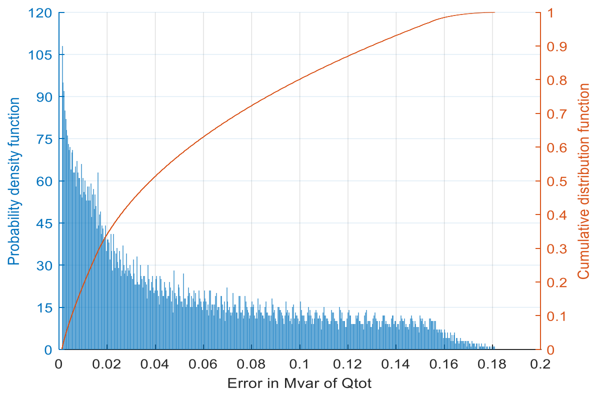

Figure 8. Total reactive power error

Figure 8 gives the error of the reactive power consumption of the entire network. 80% of situations yield an error below 0.1 MVAr. The maximum error is 0.2 MVAr.

Take for example a full load rate (100% load and 100% generator). The load consumption is 44 MW and 17.7 MVAr. The production is 17.2 MW. First, Bolognani's method gives the voltage estimation. All voltages are compared with the reference method (Newton Raphson method), the maximum voltage relative error is 0.28 %. Then this estimation is used in order to estimate the power produced by admittance (mainly capacitor of cables). They produce 4.8 MVAr, the selected method provides an active power relative error of only 0.30 % (the network consumes 27.95 MW). The reactive power relative error is 0.75 % (the network consumes 14.0 MVAr). That is to say the relative errors of estimations are low, in accordance with specifications.

Validity domain of the proposed method

Analyzing the error characteristics shows which element will bring the main contribution to the error and under which conditions this error will be high. One can notice that the voltage error is high whenever the voltage is far away 1pu (the extremums 0.95 pu or 1.05 pu are close to 1pu). The validation procedure has shown that, in practice, this error remains negligible.

The reactive power produced by parallel admittances (mainly capacitors of underground cables) is calculated by a first order expansion. This linearization is good because it is easy to check that voltages remain near 1 pu. Then, the currents are determined by the voltages and impedance models. The results, which depend on the quality of the voltage estimation and known impedance model, show to be quite good.

Theoretically, an important part of the power error consists of the conductor impedance power mismatch. Indeed, it is difficult to give an initial guess of the currents in order to perform the linearization. Although the relative error of this contribution is high, in practice, it has little impact on the total power error which remains low. This is explained by the fact that the contribution of the conductor impedance to the total power is small (typically less than 5%).

This study confirms that the validity domain is large and states of real distribution network are included in the domains.

CONCLUSION

In order to comply with voltage and power estimation requirements and today distribution network configurations, a power flow method must provide a good power and voltage accuracy. Moreover, such a method should be able to handle load sensitivities, PQ diagrams, stochastic variables (intermittent productions and consumptions) and yield an aggregated vision of the power consumption. In the first part of the paper, a qualitative evaluation of the main power flow methods has been given.

The computation time discards the standard nonlinear power flow methods, which are precise enough but uneasy to handle. As linear methods do not provide accurate estimates, a combination of two complimentary methods was proposed.

Peak errors are given in the literature for those methods, but an evaluation of their average behavior was still missing. A case study, considering a real distribution network, has shown that this average error is far lower than the theoretical bounds, and, hence, the difference with an estimation by nonlinear methods is very small.

Future work will focus on the use of this model for optimization and control purposes. As an example of potential applications, the model described in [2] has already been used to generate a model which is embedded into an optimization algorithm which minimizes PV curtailment [9].

REFERENCES

[1] A. Alqurashi, A. H. Etemadi and A. Khodaei, 2016, "Treatment of uncertainty for next generation power systems: State-of-the-art in stochastic optimization", *Electric Power Systems Research.* vol. 141, 233-245.

[2] S. Bolognani and S. Zampieri, 2016, "On the Existence and Linear Approximation of the Power Flow Solution in Power Distribution Networks", *IEEE Transactions on Power Systems*, vol. 31, no. 1, 163-172.

[3] D. I. Sun, B. Ashley, B. Brewer, A. Hughes and W. F. Tinney, 1984, "Optimal Power Flow By Newton Approach", *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, no. 10, 2864-2880

[4] M.E. Baran and F.F. Wu, 1989, "Optimal sizing of capacitors placed on a radial distribution system", *IEEE Transactions on Power Delivery* vol. 4, no. 1, 735-743.

[5] B. Stott, J. Jardim and O. Alsac, 2009, "DC Power Flow Revisited", *IEEE Transactions on Power Systems*, vol. 24, no. 3, 1290-1300.

[6] Y. Juan, Z. Mian, L. Wenyuan, Y. Wei and Z. Xia, 2015, "Sufficient and necessary condition of sensitivity consistency in static equivalent methods", *IET Generation, Transmission Distribution* vol. 9, no. 7, 603-608.

[7] X. Cheng and T.J. Overbye, 2005, "PTDF-based power system equivalents", *IEEE Transactions on Power Systems*, vol. 20, no. 4, 1868-1876.

[8] P.Dimo, 1975, *Nodal analysis of power systems*, Abacus, Kent, England.

[9] K. Baker, E. Dall'Anese and T. Summers, 2016, "Distribution-agnostic stochastic optimal power flow for distribution grids", *2016 North American Power Symposium (NAPS)*, Denver, 1-6.