ROSEAU LOAD FLOW: A MODERN SOFTWARE PACKAGE FOR THE MODELLING AND STEADY-STATE SIMULATION OF POWER DISTRIBUTION GRIDS

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Abstract

The concept of modelling and simulation of electricity grids, in particular for power flow and short-circuit analysis, has been around for decades. Numerous numerical methods and software tools thus have already been developed for that purpose. Nonetheless, it is still the subject of active research, driven by new needs of power grid operators and by advances in the fields of applied mathematics and software engineering. This paper introduces the result of such recent research, namely: *Roseau Load Flow*, a new tool for power distribution grid simulation that is especially suitable for the analysis of low- and medium-voltage grids. We describe its specific features and main design choices, highlighting how *Roseau Load Flow* differentiates from existing solvers and improves over the state-of-the-art in the area of modelling and simulation of power distribution grids. Then, we demonstrate its capabilities by evaluating the hosting capacity of a real low-voltage grid for distributed generators equipped with Volt-VAr and Volt-Watt regulations.

1 Introduction

Numerous free and commercial software tools are already available for addressing the modelling and steady-state simulation of electricity grids, specifically for power flow calculations and short-circuit analysis [5][6]. Historically, steady-state solvers were initially employed to analyse transmission grids; this was reflected in design choices such as relying on single-phase modelling for power flow calculations, with the underlying assumption that the grid being modelled was essentially balanced. Steady-state simulation techniques were subsequently applied to distribution grids, starting at the medium-voltage level, and progressing to the low-voltage level. As a result, design choices and modelling assumptions were adapted to reflect the distinct nature of power distribution grids, such as their more unbalanced characteristics, particularly at the low-voltage level. The adaptations also considered the specific techniques used by Distribution Grid Operators, such as Volt-VAr and/or Volt-Watt regulations [1]. Simultaneously, progress in related domains, including mathematical methods and software engineering technologies, created opportunities for improvement in power grid modelling and simulation, spurring the development of new generations of solvers.

In this paper, we introduce *Roseau Load Flow*, a new software package dedicated to the modelling and steady-state simulation of power distribution grids, and we demonstrate its capabilities by evaluating the hosting capacity of a real-world low-voltage grid for distributed generation equipped with Volt-VAr and Volt-Watt regulations. Section 2 is dedicated to the presentation of the prominent features and main design choices of the solver itself, emphasising how it differentiates from existing solvers and improves over the state-of-the-art. Section 3 introduces the problem of evaluating the hosting capacity of low-voltage grids for distributed generators, especially in the context of Volt-VAr and Volt-Watt regulations, and shows how this problem may be solved using the *Roseau Load Flow* solver. Numerical results are presented as an illustration.

2. Specific features and design choices

2.1 Individual conductor modelling

The most important phenomena that must be considered when modelling a power line in a distribution grid are usually its series impedance, the mutual inductive coupling between phases, and the coupling between conductors and the ground both in normal operation (especially the capacitive coupling between the underground cables and the ground) and in fault conditions (e.g. phase-to-ground short-circuit). These phenomena are usually captured in the form of a "lumped model" such as the one depicted in Fig 1.

The equations that characterise such a model are quite involved. Consequently, most existing approaches (especially those that were designed several decades ago when computers were much less advanced) involve some kind of approximation, such as Kron's reduction, which aim at reducing these equations to those of a simpler physical system. Such approximations make the problem easier to solve from the mathematical point of view, and thus make solvers easier to implement; however, they are by nature detrimental to the accuracy of the modelling, especially for strongly imbalanced networks. Solvers that use this technique thus provide approximate values, especially for the neutral current which must be estimated a posteriori after the neutral conductor was initially eliminated for the sake of simplification. This technique also limits the versatility of the solver, for instance by preventing the modelling of a floating neutral.

Imbalance, however, may be significant in distribution systems, especially at the low voltage level. It may have a strong effect on voltages and currents, making it crucial for a load flow solver to capture this phenomenon accurately. Being able to estimate the neutral current is particularly important to check for potential overloads, especially when using a smaller conductor for the neutral wire than for the phases. Accurately modelling coupling phenomena between the grid and the ground may also be important when analysing not only faults, but also normal operating conditions; especially when using specific techniques such as “Single-Wire, Earth-Return”.

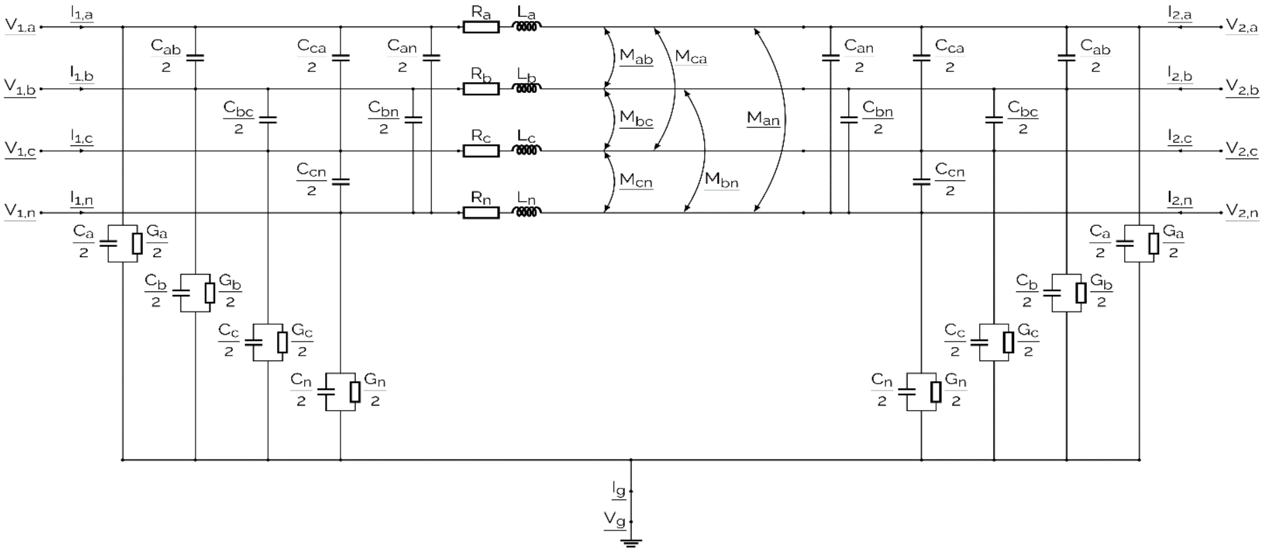

Fig. 1 Lumped line model implemented in *Roseau Load Flow*

For these reasons, we consider that using simplifying assumptions such as Kron’s reduction is undesirable when studying power distribution grids, especially at the low-voltage level. In *Roseau Load Flow*, we thus implemented the full model depicted in Fig 1, with distinct, coupled equations for each phase, for the neutral wire and for Earth currents, without resorting to Kron’s reduction or any kind of similar approximation. *Roseau Load Flow* thus provides accurate modelling as well as improved versatility, such as the ability to support floating neutrals.

2.2 Voltage dependence of loads and generators

Generally speaking, a load or generator model is an equation that determines how much current will flow through each of the conductors that are attached to that load (e.g. one phase and the neutral wire, or three phases and the neutral wire), for any value of the electrical potential of these conductors. Existing software packages for the simulation of power distribution grids usually implement a catalogue of load models such as “constant power”, “constant impedance”, etc, for single-phase or multi-phase loads. Distributed generators are usually modelled as constant power.

On some occasions however, it is important to model elements that exhibit a specific type of voltage dependence. This is typically the case when using Volt-Watt and/or Volt-VAr regulations for “flexible” distributed generators, as we will demonstrate in Section 3. Such regulations consist in modulating the active and/or reactive power output of a generator depending on the value of voltage, using functions such as those depicted in Fig 2.

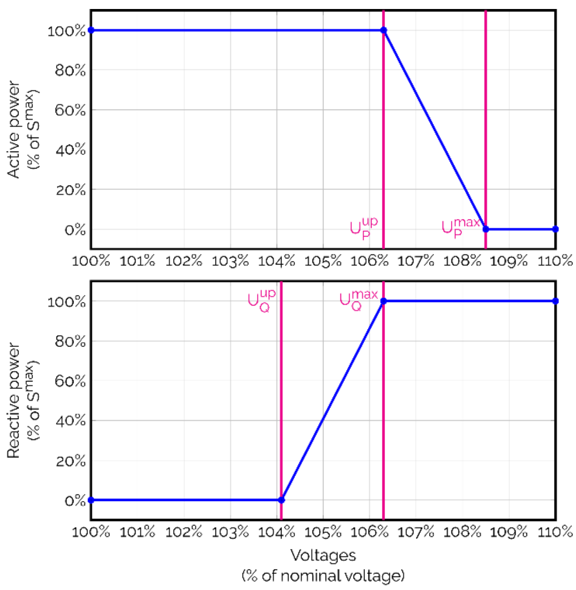

Fig. 2 The Volt-VAr and Volt-Watt regulations implemented in *Roseau Load Flow*

Introducing such regulations in a system adds new equations to the problem, which complexifies the solving process. Therefore, existing solvers usually rely on the following three-steps approach:

Algorithm 1

A. Start from some assumption on voltage, such as "voltage is equal to its nominal value everywhere in the grid"; then repeat B-C until convergence.
B. Based on the current estimate of voltages, compute the active and reactive power output of flexible generators using their regulation functions (Fig 2).
C. Assume that the generator is now "constant power", and solve the associated standard power flow equations, which updates the voltage estimate. Then go back to Step B.

The benefit of this method is that it makes it possible to introduce specific forms of voltage dependence, such as the one depicted in Fig 2, without having to heavily modify the code that solves the (standard) power flow equations. The drawback is that the solving process is now doubly iterative, with e.g. a Newton loop (assuming that the standard power flow equations are solved using the Newton algorithm) nested within a fixed-point algorithm. This approach is thus generally expected to be computationally less efficient and less stable than the alternative, which consists in directly embedding the equations of the voltage-dependent load or generator inside the main Newton loop. *Roseau Load Flow* was designed to embed any type of load model directly inside the main Newton loop, making the solving process fast and numerically stable.

2.3 Capabilities of flexible generators and interactions between regulations

Using regulation functions, such as depicted in Fig 2, raises the possibility that the generator may not have the capability to reach the setpoint required by the regulation. For instance, suppose that a generator whose nominal inverter power is 9 kVA is currently producing active power at its maximum output of 9 kW. In addition, suppose that this generator is equipped with Volt-VAr regulation; and that the voltage is high enough for this regulation to activate, requiring the inverter to consume e.g. 3 kVAr of reactive power. This setpoint cannot be reached in practice because the inverter is already at full capacity. Therefore, we must either renounce our Volt-VAr regulation and keep producing 9 kW of active power without any reactive power; or forcefully implement our 3 kVAr setpoint while curtailing sufficient active power to regenerate inverter margins; or anything in between, as a compromise between the two conflicting objectives. When using several types of regulations simultaneously, typically Volt-VAr and Volt-Watt regulations, this problem becomes even more involved.

A power flow solver aiming at modelling and simulating flexible generators must capture this phenomenon. The first aspect, which is a modelling consideration, is to offer the user the ability to choose between several precedence rules to solve regulation conflicts: prioritising active power (while renouncing Volt-VAr regulation), prioritizing reactive power (while curtailing active power), or compromising. The second aspect, which is a simulation consideration, boils down to the same issue that was raised above when discussing the implementation of the regulation functions themselves: either the rule that was chosen to resolve regulation conflicts is not implemented in the load flow solver per se, but implemented in an outer loop such as Algorithm 1; or it is integrated into the set of power flow equations and solved directly by the main Newton loop, without having to resort to a doubly iterative algorithm.

In *Roseau Load Flow*, we opted for the second of these two options: three rules are proposed to the user for solving regulation conflicts, all of which are embedded directly inside the main set of equations and solved directly inside the main Newton loop. These three precedence rules are depicted in Fig 3 below.

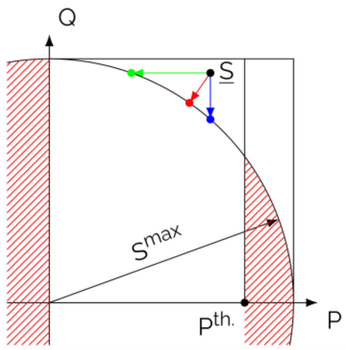

Fig. 3 The precedence rules for projecting infeasible power solutions into the feasibility domain of the inverter: "Keep P" (blue), "Keep Q" (green), and Euclidean (red)

2.3 Other notable features

Roseau Load Flow also offers some notable features such as: being able to handle radial or meshed networks; using only usual physical quantities (not "per unit" quantities), with user-chosen units (metric or imperial, kW or MW, etc) for convenience, and with consistency checks to protect against unit-related errors; a modular and generic design that allows easy integration of additional models in the future; an intuitive object-oriented modelling environment in the Python programming language; extensive documentation; and a predefined dataset of distribution grid models. Lastly, *Roseau Load Flow* is provided for free for non-commercial use, such as research and teaching activities.

3 Application to hosting capacity evaluation

3.1 Context, objectives, and methodology

In this section, we use the *Roseau Load Flow* software to estimate the hosting capacity of a low-voltage grid for flexible generation. We consider both Volt-VAr and Volt-Watt regulations simultaneously, recognizing that these regulations may conflict when used independently. The goal is to compare the performance of three projection rules that *Roseau Load Flow* provides to solve conflicts, as described in Fig 3.

Numerical simulations are carried out using one of the grid models readily provided with *Roseau Load Flow*. We add a PV generator with a capacity of 72kWp that is connected relatively far from the MV/LV transformer. Load profiles are randomly generated using *pyLPG* [3], and PV power profiles are generated using the Photovoltaic Geographical Information System (PVGIS) [4]. Without curtailment, the total energy produced by the generator is 89.98 MWh. Based on this data, we run a one-year time series simulation for each projection rule under study[1].

Fig. 4 The low-voltage network under study

[1]The code, input data, and results are publicly available at: https://github.com/RoseauTechnologies/2024_CIRED.

3.2 Results

Table 1 shows the aggregate simulation results, that demonstrates that the "Keep P" projection rule yields much better results than the other two in terms of minimising generation curtailment: it sheds only 1.6% of the annual energy of ~90 MWh, compared to 4.4% with the Euclidean projection and 6.9% with the "Keep Q" projection. This better performance does not come at the expense of reducing the performance in terms of avoiding grid constraints: all methods do contain voltage below the chosen 250 V limit, and yield similar values for total energy losses, maximum current, and VUF (voltage imbalance factor).

Table 1 Results from a one-year timeseries simulation with the three projection rules

Projection	Euclidean	Keep P	Keep Q
Generation curtailment	4.4 %	1.6 %	6.9 %
Max voltage	246.4 V	246.8 V	244.7 V
Max line current	130.0 A	131.3 A	128.1 A
Total losses	12.0 MWh	12.0 MWh	12.0 MWh
Max VUF	1.7 %	1.7 %	1.8 %

The French law [2] dictates that a non-firm connection shall not exceed 5% energy curtailment per year. Under this regulation, connecting the 72kWp generator using the "Keep P" or "Euclidean" projection rules would be acceptable, whereas using the "Keep Q" projection method would violate the 5% limit. In other words, the choice of a precedence rule greatly affects the hosting capacity of the network.

4 Conclusion

In this paper, we introduced the *Roseau Load Flow* solver dedicated to the detailed modelling and simulation of power distribution grids, and showcased how it may be used to analyse the hosting capacity of a low-voltage grid for flexible generation. The results demonstrate that the "Keep P" precedence rule offers substantially better performance in terms of minimising energy curtailment, without sacrificing the performance in terms of mitigating grid congestion.

5 References

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