Pandapower - an Open Source Python Tool for Convenient Modeling, Analysis and Optimization of Electric Power Systems

Leon Thurner, Alexander Scheidler, Florian Schäfer, Jan-Hendrik Menke, Julian Dollichon, Friederike Meier, Steffen Meinecke and Martin Braun Senior Member, IEEE

Abstract—Pandapower is a Python based, BSD-licensed power system analysis tool aimed at automation of static and quasi-static analysis and optimization of power systems. It is a full fledged power system analysis tool that provides power flow, optimal power flow, state estimation, topological graph searches and short circuit calculations according to IEC 60909. The pandapower network model is based on electric elements, which are defined by nameplate parameters and internally processed with equivalent circuit models. The tabular data structure used to define networks is based on the Python library pandas, which allows comfortable handling of input and output parameters. The implementation in Python makes pandapower easy to use and allows comfortable extension with third-party libraries. Pandapower has been successfully applied in several grid studies and validated with real grid data.

Index Terms—Python - open source - load flow - optimal power flow - short circuit - IEC60909 - automated network analysis - power system analysis - graph search

I. INTRODUCTION

A paradigm shift in electric power systems towards distributed generation as well as an increasing degree of automation raises the complexity of power system operation, analysis and planning in future power systems. Challenges arise especially in distribution systems, where a majority of distributed energy resources are connected. The rising level of complexity calls for new tools that allow a high degree of automation, while still being easy to use. For scientific applications, open source tools provide a free and transparent alternative to commercial tools.

A. Available Open Source Tools

There are several open source power system calculation tools with different strengths and focuses available today. Matpower [2] is a widely used power system analysis tool that solves power flow and optimal power flow problems and also includes an optimal scheduling tool for market simulations [3]. There are ports of the original MATLAB based code to other languages, most notably Python's PyPower [4]. MatDyn [5] and pypower-dynamics [6] extend Matpower and PyPower respectively for dynamic analysis of electric power systems. Dynamic network evaluations and simulations are also provided by PSAT [7], which is based on MATLAB/Simulink. Dome [8] is a Python tool which was derived from PSAT, but is not available under an open source license. GridCal [9] includes a power flow, time-series and short circuit calculation methods and comes with a comprehensive GUI. The simulation and optimization library PyPSA [10] is aimed at time-series simulation of security-constrained linear optimal power flow and investment optimization. PowerGAMA [11] and pss [12] are also aimed at market optimization in electric networks. OpenDSS is a Delphi based steady-state simulation tool that allows a wide range of network analysis including unbalanced power flow calculations [13].

B. Python in Power Systems Analysis

Many of the available open source tools are based on MATLAB [2], [5], [7] or Delphi [13]. Even though the tools themselves are open source, they depend on commercial platforms. Therefore, they can neither be freely used as stand-alone software nor easily extended with other libraries. Parallelization on computational clusters is also subject to specific license agreements. The fact that Delphi is not designed to run on Linux further limits the possibility to deploy computational clusters. A free alternative to commercial platforms is the programming language Python, which is available under an open source license. Python is a scripting language with a straightforward and easy to learn syntax. Scientific libraries like numpy and scipy are internally implemented in C, so that mathematical analysis and data manipulation routines are carried out efficiently [14]. Python has gained significant popularity for open source projects, especially in scientific applications. Since a large variety of libraries are freely available in Python, Python applications can be easily extended with third-party libraries. They can also be parallelized on computational clusters without license or compatibility constraints. Consequently, many recently developed tools for power system analysis are implemented in Python [1], [4], [9], [10], [11], [12].

C. Network Models

Any electric power system analysis function, like power flow or short circuit calculation, is based on a mathematical model of the electric network. There are different approaches how power system tools allow the user to specify this model.
A commonly used approach is the bus-branch model (BBM), which defines the network as a collection of buses which are connected by generic branches. Branches are modeled with a predefined equivalent circuit and are used to model multi-pole elements like lines or transformers. Buses are attributed with power injections or shunt admittances to model single-pole elements like loads, generators or capacitor banks. Since the BBM is an accurate mathematical representation of the network, electric equations for power systems analysis can be directly derived from it. The BBM can also be freely parametrized and is not bound to specific models of electric utilities. On the other hand, the user needs to calculate the impedances for each branch and summed power injections at each bus manually from the nameplate data of the grid elements. This can be cumbersome and error-prone especially for more complex elements, like transformers with tap changers or more than two windings.

A more user-friendly way to specify networks is to use an element-based representation. An element is either connected to one or multiple buses and is defined with characteristic parameters. Instead of a generic branch model, there are separate models for lines, two-winding, three-winding transformers etc. This allows defining the network with nameplate parameters, such as length and relative impedance for lines, or short circuit voltage and rated apparent power for transformers. Where a BBM allows only the definition of a summed power injection at each bus, single-pole elements (such as load or generation elements) can be connected to buses independently. This also allows connecting multiple elements at one bus.

The element models need to be processed with the appropriate equivalent circuits to derive a mathematical description of the network. Decoupling the element model from the electric model allows to specify different equivalent circuits for different analysis functionalities. For example, an external grid element can be modeled as slack node in the power flow calculation, but as a voltage source with internal impedance in the short circuit calculation. The element-based model also allows composite models that are internally represented by more than one branch, such as a three-winding transformer, or by a combination of bus- and branch attributes, such as ward equivalents.

D. pandapower

Even though there are many tools available today, there is no full fledged power system analysis tool focused on symmetric static evaluations, which is easy to use and well suited for automation in scientific applications. Available tools which are well suited for automation (e.g. MATPOWER) do not include the possibility to define elements with nameplate parameters because they are based on a BBM. Other tools which do include element models, have a focus on dynamic calculations (e.g. Dome, PSAT) or on energy optimization (e.g. PyPSA) or unbalanced analysis (e.g. OpenDSS). Additionally, some static evaluation methods like graph searches, state estimation and short circuit calculations according to IEC 60909 are only available in commercial tools and not in any open source tool.

To fill this gap, we introduce the open source tool pandapower in its current version 1.4.0. It is implemented in Python, guaranteeing free availability and flexible expansion with other open source libraries. Since it is developed as a cross-platform library, it can be deployed seamlessly on computational clusters and parallelized without any license constraints. The tabular data structure is based on the powerful data analysis tool pandas (see Section II). pandapower comes with an extensive library of electric elements, such as ZIP loads, lines, transformers or switches (see Section III). The pandapower power flow implementation is originally based on PYPOWER, but has been extended with several features and accelerated with just-in-time compilation (see Section IV-A). The optimal power flow allows using the interior point solver provided by PYPOWER with the pandapower element models (see Section IV-B). pandapower includes an original implementation of a weighted least squares state estimation including bad data detection (see Section IV-C). It also includes an original implementation of a short circuit calculation in accordance with IEC 60909 (see Section IV-D). On top of the electric analysis functions, a module for topological searches allows graph analysis of electric networks using the NetworkX library (see Section V). All implementations are thoroughly verified and wherever possible validated by comparing with commercial software tools. pandapower has been successfully applied in multiple grid studies [15], [16], [17], [18].
II. DATA STRUCTURE

pandapower is based on a tabular data structure, where every element type is represented by a table that holds all parameters for a specific element and a result table which contains the element specific results of the different analysis methods. The tabular data structure is based on the Python library pandas [19]. It allows storing variables of any data type, so that electrical parameters can be stored together with status variables and meta-data, such as names or descriptions. The tables can be easily expanded and customized by adding new columns without influencing the pandapower functionality. All inherent pandas methods can be used to efficiently read, write and analyze the network and results data.

A pandapower network (abbreviated as net) is a Python dictionary that holds all information about the network (see Fig. 1). Most importantly, it includes an element and a result table for each element type, such as line, transformer, switch etc. (see Section III). The element table holds all input parameters that are specified by the user, while the result table is used by power flow or optimal power flow functions to store the results. Input and output parameters are identified by the same index in both tables. The net furthermore includes dictionaries which hold standard type data (see Section VI-A) and network wide parameters like frequency, network name or rated apparent power for the per unit system.

III. ELECTRIC ELEMENT MODELS

The pandapower library includes a lot of different electric models, some of which are not available in any other open source tool (see TABLE I). The electric models and equivalent circuits, representing the different elements, are described in this Section. Detailed formulas for the calculation of the electric parameters are also available in the pandapower documentation. To allow a convenient step-by-step definition of networks, there are create functions for each element.

A. Bus (bus)

Buses represent the nodes of the network. They are defined by a nominal voltage bus.vn_kv [2] which is the reference voltage for the per unit system. The rated power for the per unit system is defined system wide with the parameter net.sn_kva. The voltage magnitude res_bus.vm_pu and angle res_bus.va_degree are results of a grid analysis.

B. Load (load)

Loads are used to model electric consumption. They are defined by the active power load.p_kw and reactive power load.q_kvar. The ZIP model allows modeling loads with constant power, constant current or constant impedance. The percentage of the load which consumes a constant current is defined by the parameter load.const_i_percent, the constant impedance part is defined by the parameter load.const_z_percent. The rest of the load is assumed to be a constant power load. For constant current and constant impedance, the active power value is assumed to be the power consumption at rated voltage. All nodal powers are given from a consumer viewpoint. The load model includes a scaling factor load.scaling that allows to scale the load.

C. Static Generator (sgen)

Static generators are used to model constant power injection with active power sgen.p_kw and reactive power sgen.q_kvar. Since all nodal power is given from a consumer viewpoint, the power generation is defined to be negative. This might seem unintuitive for generator type elements, but the consistent convention makes the definition of power values unambiguous even for elements where the signing is not obvious, such as external grids, shunts or buses. The static generator model includes a scaling factor sgen.scaling equivalent to the load scaling factor.

D. Voltage Controlled Generator (gen)

Generator elements are used to model voltage controlled power generation units with a fixed active power injection gen.p_kw and a voltage magnitude set point gen.vm_pu. Adherence with the voltage magnitude in the power flow calculation is achieved by setting the generator bus as a PV node (see Section V-A). The reactive power res_gen.q_kvar is then calculated so that the voltage magnitude is equal to the set point. Reactive power limits gen.q_min_kvar and gen.q_max_kvar can be enforced in the power flow, in which case the voltage set point might not always be reached.

TABLE I

| ELEPH EN OF OPEN SOURCE ELEMENT MODEL LIBRARIES | MATPOWER 6.0 | PYPOWER 5.1.2 | PSAT 2.1.10 | OpenDSS 7.6.5 | PyPSA 0.10 | GridCol | pandapower 1.4.0 |
|-----------------------------------------------|-------------|-------------|-------------|-------------|-------------|---------|----------------|
| ZIP-load                                      | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| Line                                         | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| 2-Winding Transformer (π)                     | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| 2-Winding Transformer (T)                     | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| 3-Winding Transformer                        | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| DC Line                                      | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| Ideal Switches                               | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| Volt.-Controlled Generator                   | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| Static Load / Generation                     | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| Shunt                                        | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| Unsymmetrical Impedance                      | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| Ward Equivalents                             | ✓           | ✓           | ✓           | ✓           | ✓           | ✓       | ✓              |
| Storage Unit                                 | ✓           | ✓           |             |             |             |         | ✓              |

[2] All pandapower model parameters are notated as element.parameter in this paper, where element is the element table in the data structure and parameter the name of the parameter with which it can be accessed. By convention, all parameter names in pandapower end with the parameter unit.
E. External Grid (ext_grid)

The external grid element model represents a voltage source with a voltage magnitude ext_grid.vm_pu and the corresponding voltage angle ext_grid.va_degree. Adherence with the complex voltage set point in the power flow calculation is achieved by setting the generator bus as a slack node (see Section IV-A.). pandapower supports the connection of multiple external grids in galvanically coupled network areas.

F. Shunt (shunt)

Shunts are network elements that can be used to model a capacitor bank or a reactor. Shunts are defined by a reactive power shunt.q_kvar and an active power shunt.p_kw value, which represents the losses. The parameter shunt.step allows to model a discretely segmented shunt, such as a switchable capacitor bank.

G. Line (line)

Lines are modeled with a π-equivalent circuit [20]. The electric parameters of a line are specified relative to the length of the line line.length_km. The longitudinal impedance is defined by the resistance line.r_ohm_per_km and reactance line.x_ohm_per_km. The shunt admittance is defined by the capacity line.c_nf_per_km. The line current res_line.i_ka is calculated as the maximum current at both ends of the line. The line loading res_line.loading_percent can be calculated as a ratio of line current res_line.i_ka to the maximum thermal line current line.max_i_ka. A derating factor line.df can be defined to consider the fact that some lines might not be utilized to their full thermal capacity. The model also provides a parameter line.parallel to define the number of parallel lines.

H. Two-Winding Transformer (trafo)

Two-winding transformers are commonly modeled with a T-equivalent circuit [20]. However, for the sake of completeness, pandapower also includes a π-transformer model. The longitudinal impedance is defined by the short circuit voltage trafo3w.vsc_hv_percent and its real part trafo3w.vscr_hv_percent. The real part of the transformer impedance represents the copper losses in the transformer windings. The shunt admittance represents the losses in the iron core of the transformer. The open loop current trafo.10_percent defines the overall open loop losses and an active power loss trafo.pfe_kw defines the iron losses. The rated transformer voltages for the high voltage side trafo.vn_hv_kv and the low voltage side trafo.vn_lv_kv define the nominal transformer ratio and do not necessarily have to be equal to the rated voltages of the connected buses. If an angle shift trafo.shift_percent is defined, the ratio becomes complex and the voltage angle between high and low voltage side is shifted. The transformer ratio can also be influenced by defining a tap changer and its current position trafo.tp_pos. With every step the tap position trafo.tp_pos diverges from its medium position trafo.tp_mid, the transformer ratio changes by a percentage defined by trafo.tp_st_percent. It is also possible to define an angle shift per step trafo.tp_degree_percent to model phase shifting transformers. The tap changer can be located at the low voltage or the high voltage side of the transformer which is defined by the parameter trafo.tp_side. The loading res_trafo.loading_percent is calculated of the maximum loading at high and low voltage side. It can either be calculated in reference to the nominal power trafo.sn_kva or to the nominal current. Just as for lines, there is a parameter trafo.parallel which allows the definition of multiple parallel transformers in one element.

I. Three-Winding Transformer (trafo3w)

Three-winding transformers can be modeled by three two-winding transformers in wye connection [20]. The three-winding transformer model in pandapower carries out this conversion internally. The open loop losses defined by trafo3w.i0_percent and trafo3w.pfe_kw are considered in the high voltage side transformer. The short circuit voltages of the two-winding transformers are calculated with a wye-delta conversion from the short circuit voltages trafo3w.vsc_hv_percent and their respective real parts trafo3w.vscr_hv_percent and trafo3w.vscr_mv_percent. The equivalent circuit impedances for the three two-winding transformers are then calculated from the nameplate parameters according to the two-winding transformer model. The loading res_trafo3w.loading_percent is calculated as the maximum loading of the three two-winding transformers. The loading of the equivalent two-winding transformers is calculated either relative to the rated apparent powers trafo3w.sn_lv_kva, trafo3w.sn_mv_kva and trafo3w.sn_hv_kva or relative to the respective rated current as described in Section III-H.

J. Switch (switch)

The switch element allows modeling of ideal switches. A switch element connects a bus switch.bus with an element switch.element. The element type is defined by the parameter switch.et and can either be a second bus, a line or a transformer. The switch.closed parameter signals if the switch is open or closed. A closed bus-bus switch galvanically couples two buses without a voltage drop. In network calculation tools without an explicit switch model, bus-bus switches can only be modeled as a small impedance between two buses (see TABLE I). This can however lead to unwanted voltage drops and convergence problems in the power flow. The pandapower switch model avoids this problem by internally fusing buses that are connected by closed bus-bus switches as shown in TABLE I. Branches that are connected to a bus through an open switch are often
modeled by neglection or disabling the branch element (see TABLE II). This however means that the information about the switch position is lost and the open loop current of the branch element is neglected. pandapower instead internally switches the branch over to an auxiliary bus so that the branch is disconnected from the bus but the loading current is still considered.

K. DC Transmission Line (dcline)

A DC transmission line transmits active power between two buses. The transmitted active power dcline.p_kw is reduced by absolute transformation losses dcline.p_loss_kw and relative transmission losses dcline.p_loss_percent at the destination bus. A DC line is modeled with two generators at both buses, where the voltage control with reactive power works just as described for the generator model in Section III.D

L. Impedance (impedance)

An impedance element connects two buses with a per unit impedance in relation to the rated power impedance.sn_kva. The impedance does not have to be symmetrical, in which case the nodal point admittance matrix becomes asymmetrical. The forward impedance \( z_{ft} \) is defined by impedance.rft_pu and impedance.xft_pu, the backward impedance \( z_{bt} \) by impedance.rft_pu and impedance.xft_pu. Unsymmetrical impedances are used as equivalent elements in network reduction.

M. Ward Equivalents (ward / xward)

The ward equivalent is a combination of a constant apparent power consumption and a constant impedance load [21]. The constant impedance load is given as active and reactive power consumption ward.pz_kw and ward.qz_kvar at the rated voltage of the bus. The constant active and reactive power is given by ward.ps_kw and ward.qs_kvar. The extended ward equivalent includes an additional voltage source with internal impedance [21]. The voltage source is modeled as a generator with zero active power and a voltage set point defined by the parameter xward.vm_pu. The internal impedance is defined by the parameters xward.r_ohm and xward.x_ohm.

IV. Electric Network Analysis

With the possibility to conduct power flow, optimal power flow, state estimation and short circuit calculations, pandapower provides all of the most commonly used static network analysis features. As outlined in Section II, the pandapower data structure contains common nameplate parameters for convenient parametrization. To carry out electric network analysis, all element models have to be translated into their equivalent representation. This translation is done by converting the element-based data structure internally into a BBM as shown in Fig. 2. The internal BBM model has a similar structure as a PYPOWER casefile, but has been extended to include parameters like unsymmetrical impedances or constant current load. The correlation between pandapower elements and the BBM is not trivial for multiple reasons. First, some pandapower elements translate into multiple buses and branches (e.g. three-winding transformers, extended ward equivalents). Second, multiple elements (e.g. loads, shunts, generators or ward elements) can be connected to the same bus in pandapower, so that properties in the BBM for a bus can possibly originate from different pandapower element tables. Third, to dissolve switches as shown in TABLE II it is necessary to create new auxiliary buses, reconnect branches and merge multiple pandapower buses into one BBM bus. And fourth, areas which have no galvanic connection to any slack bus are identified and disabled in the BBM, so that some elements might be enabled in pandapower but disabled in the BBM. To keep track of the complex relationship between the pandapower elements and their representations in the BBM, several mappings are created during the conversion process. After the electric analysis is conducted on the basis of the BBM, the obtained results are allocated to the elements on the basis of these mappings. In this way, the results can also be set in relation to the input parameters, for example to calculate line loadings as a ratio of the maximal thermal current and the actual current resulting from the power flow.

A. Power Flow

The pandapower power flow solver is based on the newton-raphson method [22]. The implementation is originally based on PYPOWER, but has been improved with respect to robustness, runtime and usability.

Internal power flow parameters, such as node type for the power flow calculation (slack, PV or PQ node) or per unit
Optimal Power Flow

Short Circuit Calculation

Identify and disable disconnected network areas

Reconfigure BBM to reflect switch positions

Calculate summed power injections for all buses

Convert element parameters of lines, transformers etc. as BBM models

Fig. 2. Electric Power System Analysis in pandapower

Conversions, are carried out automatically by pandapower. This improves user convenience and reduces the risk of incoherent input data. pandapower offers three different methods to initialize the complex voltage vector for the AC power flow calculation. It can either be the result of a previous power flow calculation, the solution of a DC power flow or a flat start. Initializing with a DC power flow is recommended in meshed networks, where large voltage angle differences between the buses might lead to non-convergence in case of a flat start. In radial distribution grids on the other hand, the reference voltage angle is dictated by the external grid so that relative voltage angle shifts of transformers have no impact on the power flow result. That is why pandapower provides the option to neglect the voltage angles to allow faster and more robust convergence in radial distribution grids. The additional conversion step that is necessary to convert the pandapower model to a BBM and map back the results afterwards causes an additional overhead compared to programs that operate directly on the BBM, like MATPOWER or PYPOWER. On the other hand, some parts of the pandapower solver have been accelerated using the just-in-time (jit) compiler numba [23].

To outline the difference in computational time, Fig. 3 shows the calculation time for different standard MATPOWER case files. The timings are the shortest of 100 loops of a power flow with flat start. The pandapower timings distinguish between power flow solver and conversion overhead, which includes BBM conversion as well as result extraction. It can be seen that pandapower is faster than PYPOWER in all cases due to the jit accelerated building of the jacobian matrix and other aspects of the newton-raphson solver. It can also be seen that while the conversion overhead takes up more than half of the calculation time for small networks, its share decreases significantly for larger networks. While pandapower is slower than MATPOWER for small networks, it is faster for medium sized and large networks, even including the conversion overhead for the BBM. By default, the BBM conversion is carried out before every power flow. However, if multiple subsequent power flows are performed for the same network that only differ in the nodal power injections, the conversion into a BBM becomes redundant. For this reason, pandapower offers the possibility to reuse the BBM and the nodal point admittance matrix from previous power flow calculations. This feature can speed up applications like quasi-static time series simulations or heuristic power set point optimizations. In addition to the Newton-Raphson solver, pandapower also provides an implementation of a backward/forward sweep [24]. It is also possible to use the fast decoupled as well as the Gauss-Seidel power flow algorithms through an interface to PYPOWER.

B. Optimal Power Flow

pandapower allows solving AC and DC optimal power flow (OPF) problems through interfacing PYPOWER. The interior point solver [25], [26] provided by PYPOWER is used to solve the problem, while costs, flexibilities and constraints are configured through the element-based pandapower data structure. This allows all electric element models provided by pandapower to be used in the OPF. Branch constraints are given as maximum loading for transformers and lines, instead of absolute limits for power flows. Bus constraints include maximum and minimum voltage magnitude. Active and reactive power limits can be defined for PV/slack-elements like external grids and generators, but also for PQ-elements, such as loads and static generators. This allows flexible consideration of static generators in dispatch optimizations as well as the consideration of load shedding. The cost function for each power injection or load can either be defined by a piecewise linear or a n-polynomial cost function of the active and reactive power output of the respective elements.

C. State Estimation

pandapower includes a state estimation that allows to estimate the electrical state of a network by dealing with inaccuracies and errors from measurement data. The weighted-least-squares optimization algorithm minimizes the weighted

Fig. 3. Speed comparison of pandapower, PYPOWER and MATPOWER for MATPOWER casefiles
squared differences between measured values and the corresponding power flow equations [27].

**pandapower** supports bus, line and transformer measurements. Bus measurements can be given for voltage magnitude or active and reactive power injections. Measurements at lines or transformers can be given for current magnitude or active and reactive power flows at either end of the branch.

The state estimation may not converge if measurements include bad data. Therefore, it is necessary to remove bad data prior to the estimation process. This problem is solved in **pandapower** with a $\chi^2$ test and a normalized residual test [27]. A $\chi^2$ test is able to identify the probability that bad measurements exist in the measurement set or if the network topology does not fit the measurement data. A normalized residuals test can take information of the $\chi^2$ test, compute the normalized residuals and remove the measurement with the highest residual. The cycle is repeated until the bad data check passes or no measurements can be removed any more.

**D. Short Circuit Calculation according to IEC 60909**

While short circuit currents are an inherently transient phenomenon, they can be approximated based on a static network model. The IEC 60909 standard [28] defines rules to calculate certain characteristic values of the short circuit, such as the initial short circuit current $I'_k$, peak short circuit current $i_p$ or long term SC current $I_k$. The calculation of initial sub-transient short circuit currents for symmetrical three-phase short circuits as well as two-phase short circuits is implemented in **pandapower**. The necessary correction factors are implemented in **pandapower** according to the standard and are automatically applied in the conversion to the BBM. Additional input parameters, which are necessary to calculate internal impedances of external grids or synchronous generators, are defined in the element tables, together with the default parameters. The implementation allows modeling power converter elements, such as PV plants or wind parks, as constant current sources according to the 2016 revision of the standard [28].

**V. Topological Network Analysis**

**pandapower** provides the possibility of graph searches using the Python library NetworkX [29] by providing a possibility to translate **pandapower** networks into NetworkX graphs. Once a network is translated into an abstract graph, all graph searches implemented in the NetworkX library can be used to analyze the network structure. It is then possible for example to find connected components or cycles in the graph and transfer the results back to **pandapower**. The line length can be translated as edge weight in the graph so that it is possible to find the shortest path between two buses or measure distances between buses in the network. The translation of the network into a graph can also be configured depending on the use case. For example, lines with open switches are not transferred as edges into the graph by default, since there is no electric connection between those nodes. If a graph search is however aimed at the physical, rather than the electrical, structure, it might be desired to include those branches into the translation as well. Additionally, **pandapower** also provides some predefined search algorithms to tackle common graph search problems in electric networks, such as finding all unsupplied buses, finding galvanically connected buses or identifying buses on main or secondary network feeders.

**VI. FURTHER FUNCTIONALITY**

1) **Standard Type Libraries:** Lines and transformers have two different categories of parameters: parameters that depend on the specific element (e.g. the length of a line or the bus to which a transformer is connected to) and parameters that only depend on the type of line or transformer which is used (e.g. the rated power of a transformer or the resistance per kilometer line). **pandapower** includes a standard type library that allows the creation of lines and transformers using predefined basic standard type parameters. The user can either define individual standard types or use the predefined **pandapower** basic standard types for convenient definition of networks.

2) **Predefined Networks:** In addition to creating networks through the API, over 70 predefined networks can be directly accessed through **pandapower**. These include the well-known IEEE power system test cases [2], benchmark networks from CIGRE [30] as well as generic medium and low voltage networks.

3) **Plotting:** **pandapower** comes with extensive plotting features using the matplotlib library [31]. All **pandapower** elements can be translated into different matplotlib collections that can be customized with respect to shape, size and color to allow highlighting and create individual network plots. It is also possible to use colormaps to codify information, like the loading of lines or the voltage at buses. An example plot of a generic **pandapower** MV network is shown in Fig. 4.
In addition, networks plots through plotly [32] are also supported, which allows interactive features, such as element selection or displaying hovering information.

VII. CONCLUSION

This paper introduces the open source power systems analysis tool pandapower, which is aimed at automation of static and quasi-static analysis and optimization in power systems. pandapower comes with static equivalent circuit models for electric elements that can be defined with common nameplate parameters. This makes it easy for the user to automate the creation of networks, which allows a convenient import of network data from different formats. The tabular data structure allows to easily access and analyze input and output parameters. For power flow studies, pandapower uses an enhanced and accelerated version of the PYPOWER Newton-Raphson solver. pandapower is the first open source power systems analysis tool to include a state estimation as well as short circuit calculation according to IEC 60909. Furthermore, an interface for topological searches allows the user to carry out customized graph searches on the electric network. This exclusive network analysis functionality, in combination with the extensive model library, makes pandapower a valuable and innovative contribution to existing open source tools. An extensive suite of unit and regression tests ensures the soundness and integrity of the implementation. A detailed documentation and interactive tutorials make pandapower easy to learn. pandapower is under continuous development on github and additional features such as an unbalanced power flow, unbalanced short circuit calculations and a graphical user interface are planned to be added in the future.

ACKNOWLEDGMENT

The development of pandapower was supported by the German Federal Ministry for Economic Affairs and Energy and the Projektträger Jülich GmbH (PTJ) within the framework of the projects Smart Grid Models (FKZ: 0325616), OpSimEval (FKZ 0325782A). We acknowledge the feedback and contributions of all users that have helped to improve pandapower. We especially thank Jakov Krstulović Opara for contributing the ZIP load model, backward/forward sweep power flow and plotly interface.

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