A Modular Power System Planning and Power Flow Simulation Framework for Generating and Evaluating Power Network Models

David Ciechanowicz, Dominik Pelzer, Benedikt Bartenschlager, and Alois Knoll

***Abstract*—This work presents a modular power system planning and power flow simulation framework for the generation and evaluation of power network models (PNM) using spatially resolved demand data. It targets users who want to study large-scale power grids having only limited information on the actual power system. Besides creating cost minimal PNMs, users are able to flexibly configure the framework to produce PNMs individually tailored to their specific use cases. Both greenfield and expansion planning are possible. The framework further comprises a built-in ac power flow simulation designed to simulate power flows in large-scale networks. This allows users to conduct a great variety of simulation studies on entire power systems, which would otherwise not be possible without access to comprehensive power grid data. Apart from the presentation of the methodology, this work comprises a demonstration of the power system planning process at the example of Singapore. The investigation shows that the framework is capable of generating a network that matches the topological and electrical metrics of the Singapore power grid.**

***Index Terms*—Power system planning, power distribution planning, power network model, power flow simulation.**

I. INTRODUCTION

INTERMITTENT renewable energy sources, new types of consumers with tempo-spatially variable demand such as electric vehicles, and a trend towards a more distributed power infrastructure pose new challenges to power system operators. To ensure power grid stability and high power quality, these developments require more intelligent control of consumers and generators as well as extensions of the physical infrastructure. Simulation-based approaches can provide measures to investigate the impact of these developments on the power grid and to support planners in making infrastructure development decisions. This requires frameworks allowing tempo-spatially resolved simulations of the power flow on a system scale. One crucial input for these simulations is detailed information on the power network including the location and capacities of generators, consumers, substations, and power lines. Publicly available data on these aspects are typically sparse, thus impeding the development and application of such simulation frameworks. Hence, there is a demand for a planning process which artificially generates *power network models* (PNM) that realistically emulate the actual infrastructure.

This can be achieved by an approach referred to as *power system planning* (PSP) which includes the planning of the distribution and transmission grid. The objective of this approach is to derive realistic PNMs by applying general topological and electrical power system principles to the accessible data. The literature provides a number of PSP models which share the same general problem statement of minimizing an economic cost function subject to technical and operational constraints [1]–[9]. Hereby, the location and power rating of substations and power lines are considered the design variables [9], [10]. In this context, power flow equality, substation and power line capacity limits, as well as bus angle and bus voltage limits are most commonly used as constraints [1], [11], [12]. Within the PSP the *expansion* and *greenfield* strategy may be distinguished. The former builds on an existing power grid which is incrementally expanded [7], [9] while the latter strategy conducts the planning from scratch [8], [13]. Regarding the planning period, *static single-stage* [5], [6] and *dynamic multi-stage* [3], [4], [7] approaches can be distinguished. PSP models may also differ in the voltage level they are applied to: *low voltage* (LV), *medium voltage* (MV), *high voltage* (HV), or any combination of them.

PSP is a complex mixed integer non-linear optimization problem which has been addressed in different ways in literature. Common approaches include numerical methods such as *mixed integer linear programming* [14], [15], *non-linear programming* [16], [17], or *dynamic programming* [18], [19]. Due to the *NP*-hardness of the problem, these methods, however, only show good performance for small-scale systems with a few hundred nodes and edges. Therefore, heuristics have been developed which address the problem on a larger scale. These mainly include *genetic algorithms* [2], [20], *evolutionary algorithms* [21], [22], *tabu search* [23], [24], *particle swarm optimization* [25], [26], and *simulated annealing* [27]. An excellent overview of the different approaches applied in the field of PSP is provided

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in [28]. Holistic approaches being able to generate detailed large-scale distribution grids for multiple voltage levels including geographical constraints mainly use a combination of algorithms for different sub-problems and apply iterative approaches to generate the final power grid [1], [11], [12], [29]–[31].

This paper presents a holistic modular PSP and power flow simulation framework for bottom-up generation and evaluation of PNMs. The methodology consists of a network planning approach which is capable of generating PNMs with the characteristics of real-world power systems while using minimal input data. The network planning process involves a power flow simulation which ensures the generated PNM to be able to reliably operate under the demand/supply-conditions defined by the input data. The power flow simulation itself can further be employed to conduct power flow studies on the generated PNMs. This can be used to evaluate how a network designed for a certain demand/supply profile would behave if those conditions change, e.g., by introducing a large amount of distributed energy sources or *plug-in electric vehicles* (PEV) into the system.

There are a variety of practical use cases for this framework in the context of simulation based modeling and optimization of urban infrastructures. The development of the framework is motivated by the use case of investigating the impact of road transport electrification on power grids. For this purpose, a nanoscopic, agent-based traffic simulation for modeling the traffic in an entire megacity has been developed [32]–[35]. The traffic simulation can be coupled with the power flow simulation in the proposed framework through the IEEE Standard *High Level Architecture* (HLA). This allows exploring the power grid impact of a great variety of different electrification scenarios, charging strategies, vehicle-to-grid implementations, charging behaviors, and charging station distributions. Considering both traffic and power system at the same time further allows optimizing charging infrastructures and charging strategies with regard to optimal satisfaction of charging demand and minimal power system impact.

Other possible application scenarios include the investigation of the impact of distributed energy sources or the transition towards more intelligent consumers participating in demand response schemes. Also, scenarios for expanding power networks in developing countries under fast changing conditions can be explored. The methodology is thus targeted to users who want to conduct such studies on a large-scale but only have limited information on the actual power system. While the resulting models are not an exact representation of the real-world environment, they are a powerful tool to investigate what-if scenarios to explore the large-scale impact of certain infrastructure measures on the overall system. Demonstrating the usefulness of such investigations using synthesized but close-to-reality data may further incentivize authorities to make more real-world data available or to employ such simulation frameworks for their own planning purposes.

Compared to existing approaches the presented framework has the following advantages:

1) Opposed to traditional approaches which are top-down methods, the presented framework is designed as a bottom-up process. It is therefore capable of generating PNMs based on locations and the active power demand of consumers. This allows a more realistic planning of the LV grid as tempo-spatially highly resolved data can be taken into account. This part of a power system is of particular interest as little redundancies make it vulnerable to load and supply perturbations. In addition, in cases in which only power demand data of individual consumers is available, a bottom-up approach is the only possibility for generating a PNM. This is often the case as its strategic importance prevents authorities from revealing detailed information on the power system.
2) The framework is not limited to planning a cost minimal satisfactory solution, sometimes wrongly indicated as an optimal power grid. It, in fact, can be multi-purposely parameterized according to the available input data and can therefore generate PNMs with a large variety of different characteristics. By specifying available information on existing electrical installations the user can exert influence on the automatic planning process. Besides greenfield planning, existing PNMs can also be expanded to explore optimal transition paths to meet future requirements. This provides a high flexibility in tailoring the power grid to the requirements of each individual use case. Monte Carlo simulations and ceteris paribus sensitivity analyses can be conducted to identify the impact of parameter uncertainty.
3) The planning scope is not limited to a certain amount of electrical consumers or a specific number of different voltage levels. Due to the applied network decomposition approach, computational requirements grow linearly with the number of consumers. This allows planning a city-scale power system within minutes and conducting power flow studies on that PNM within seconds.
4) To allow conducting power flow studies, the framework, besides the PSP planning module, offers the built-in possibility to simulate AC power flows on entire, possibly large-scale PNMs which none of the other frameworks is capable of. This way, users are able to plan a PNM and subsequently conduct power flow studies with the same framework without the need for exporting, modifying, and importing data to and from other tools. Those studies are not limited to one single time step but may cover arbitrary time horizons at any temporal resolution.
5) The framework uniquely implements the IEEE Standard *High Level Architecture* (HLA) [36] allowing to bi-directionally exchange information with other simulations. Possible applications are investigations on the impact of a large-scale introduction of *plug-in electric vehicles* (PEV) [37] and *vehicle-to-grid* [38], [39] on a city's power grid.

In Section II the individual steps of generating PNMs are laid out, followed by a description of the power flow simulation process in Section III. The implemented PSP methodology is applied to the case of Singapore in Section IV. This way, the effectiveness of planning a power system with realistic topological and electrical metrics from data on the power demand of spatially distributed consumers, the number of substations, and the total power line length is demonstrated. Conclusions on the methodology and the results as well as an outlook are given in Section V.

II. POWER SYSTEM PLANNING

The goal of the PSP methodology is to create a PNM which connects the consumers of any given geographic *region* via power lines to substations of different voltage levels by fulfilling various technical and topological requirements. The planning process proceeds bottom-up requiring data of consumers, each described by a distinct pair of spatial coordinates and its active power demand. Supplementary data, e.g., the reactive power demand or matching power factors, the number and technical specification of substations and power plants, total branch length and branch resistance/reactance values, as well as substation and branch capacity buffers may optionally be provided to further customize the output. For the case of PNM expansion rather than greenfield planning, data of the initially existing PNM may also be used. Specific values of the input data are given in the demonstration of the PSP process on the example of Singapore in Section IV-A.

Throughout this paper the graph theoretical term *node* refers to the electrical engineering term *bus*. It can either be a *load bus* (PQ), e.g., a consumer or a substation acting as a consumer, or a *generator bus* (PV), e.g., a power station or a substation acting as a producer. The same applies to an *edge* and a *branch* which denote a power line. The planning process splits the region into one to many *areas*. An area is characterized by any non-zero number of PQ buses and exactly one PV bus. Each PQ bus has to be directly or indirectly connected to its area's PV bus via branches. For an area to be feasible, the criteria described in Section II-A have to be fulfilled.

In reality, power lines are typically not laid in a beeline. For reasons of simplicity, geographic factors are neglected when placing substations or laying power lines. To still emulate branched power lines and thereby realistically account for power losses, power lines are extended in length by a stretch factor. To allow for a different branching depth, this factor depends on the power line's voltage level. The specific stretch factors may be selected to produce a PNM with a total power line length similar to the target value. This way, realistic electrical properties of the generated PNM can be maintained although the spatial composition of the installations may deviate in reality.

The planning process starts at the lowest voltage level by clustering consumers into a certain number of spatial areas with a similar power demand. A PV bus is then placed at the load center of each area. A validation ensures areas to be technically feasible when directly connecting each consumer to the area's PV bus with a power line. Before applying the desired topology, an optional step recombining the network to minimize its costs may be conducted. The regular planning steps are illustrated in Fig. 1 and described in Sections II-B to II-F. A voltage level may alternatively be planned manually, either partly or entirely, as described in Section II-G. After completing the planning for one voltage level, the process is iteratively executed for all higher voltage levels. The output, consisting of a model of a power system including areas, buses, and branches characterized by their attributes, is ultimately combined to form the entire PNM as described in Section II-H.

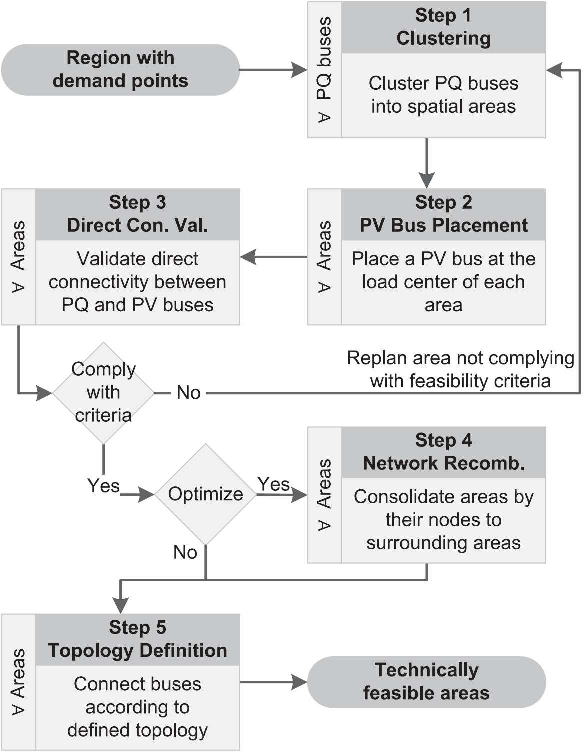

Fig. 1. Regular power system planning process for one voltage level.

A. Feasibility Criteria

For an area α to be technically feasible, various conditions need to be fulfilled. Most importantly, both *Kirchhoff's current* and *voltage law* need to be satisfied which is ensured by the employed power flow model described in Section III-A. Furthermore, the feasibility of a network is evaluated based on three additional conditions described in the following. Firstly, the aggregated power demand $P_{\mathrm{D},\alpha,i}$ of all $|N_\alpha|$ PQ buses i and the aggregated power losses $P_{\mathrm{L},\alpha,j}$ in all $|M_\alpha|$ branches j must not exceed the maximum power $P_{\mathrm{S},\alpha,\max}$ the corresponding PV bus can supply:

$$P_{\mathrm{S,max},\alpha} \geq \sum_{i=1}^{|N_\alpha|} P_{\mathrm{D},\alpha,i} + \sum_{j=1}^{|M_\alpha|} P_{\mathrm{L},\alpha,j} \tag{1}$$

Secondly, when current is flowing in a conductor, there is a voltage drop between the two ends of it. Therefore, the voltage of a PQ bus is not equal to the one at its connected PV bus. The voltage $V_{\alpha,i}$ at each PQ bus i must be within a predefined range:

$$V_{\min} \leq V_{\alpha,i} \leq V_{\max} \quad i = 1, 2, \ldots, |N_\alpha| \tag{2}$$

Finally, for each of the $|M_\alpha|$ branches j, a maximum length $L_{\max,\alpha,\mathrm{j}}$ must not be exceeded. This length depends on the targeted minimum voltage $V_{\min}$, the branches' voltage level $U_{\alpha,j}$, its resistance $R_{\alpha,j}$ and reactance $X_{\alpha,j}$, the apparent power flow $|S_{\alpha,j}|$, and the power factor $cos\left(\varphi_{\alpha,j}\right) = \frac{P}{|S_{\alpha,j}|}$ according to

$$L_{\mathrm{max},\alpha,\mathrm{j}} = \frac{1}{|S_{\alpha,j}|} \cdot \frac{(1 - V_{\mathrm{min}}) \cdot U_{\alpha,j}^2}{(R_{\alpha,j} \cdot cos\left(\varphi_{\alpha,j}\right) + X_{\alpha,j} \cdot sin\left(\varphi_{\alpha,j}\right))} \quad j = 1, 2, \ldots, M_\alpha \tag{3}$$

The same conditions have to be fulfilled for reactive power values Q. Validating those criteria is done by calculating power flow and voltage values for all branches and buses in α as described in the first step of the power flow simulation process in Section III-B1.

B. Step 1: Clustering

The first step of generating areas from a given geographic region is grouping all $|N|$ PQ buses into K clusters with equal or similar power demand. This is achieved by employing a *k-means* [40] algorithm[1] which is extended by an option to produce clusters with equal or similar power demand. An excellent example on the functioning of same-size k-means clustering is provided by the open source project ELKI[2]. A cluster is considered the first stage of an area in which Constraint (1) is fulfilled. In a simple case, K equals the number of substations on one voltage level and may be provided by the input data. Alternatively, a minimum value can be determined from the aggregated peak power demand of all PQ buses and the operational power rating of the considered PV bus $P_{\mathrm{S,max}}$ by considering conversion losses η and an optional utilization rate μ. In this case, K is determined by

$$K = \left\lceil \frac{\sum_{n=1}^{|N|} P_{\mathrm{D},n}}{P_{\mathrm{S,max}} \cdot \eta \cdot \mu} \right\rceil \tag{4}$$

Depending on the available computational resources, the given area may first be divided into multiple non-overlapping sub-regions to reduce the number of nodes the k-means algorithm has to process at once. This can, for instance, be achieved by iteratively bisecting the region and resulting sub-regions until each sub-region holds a previously defined maximum number of nodes.

C. Step 2: Substation Placement

In the next step, a substation is placed at the location resulting in smallest power line transmission losses which is the load gravity center $\vec{r}_{\mathrm{c},\alpha}$ of each area α. According to [41], this location can be determined by weighting the geographic location $\vec{r}_{\alpha,i}$ of each PQ bus i within α with its power demand $P_{\mathrm{D},\alpha,i}$ so that

$$\vec{r}_{\mathrm{c},\alpha} = \frac{\sum_{i=1}^{|N_\alpha|} \left(P_{\mathrm{D},\alpha,i} \cdot \vec{r}_{\alpha,i}\right)}{\sum_{i=1}^{|N_\alpha|} P_{\mathrm{D},\alpha,i}} \tag{5}$$

D. Step 3: Direct Connectivity Validation

Before the buses in an area are connected according to the desired network topology, a basic feasibility test is conducted. The consumers of each area are tentatively directly connected to their area's PV bus via a power line. In case this setting already violates any of the feasibility criteria defined in Section II-A, each infeasible area is further divided into two areas of equal or similar power demand according to Sections II-B and II-C. Passing this test is a necessary yet not sufficient condition for an area's feasibility. Therefore, further feasibility checks are conducted at a later stage.

E. Step 4: Network Recombination

The preceding bisecting and a spatially inhomogeneous power demand may yield areas with a low number of PQ buses or a low utilization rate of the substation. This step therefore consolidates the number of areas. This can either be done with the objective to obtain a user-defined number of areas or to find a cost minimal solution.

An area is consolidated by trying to assign all its PQ buses to neighboring areas. If this can be achieved without violating the feasibility criteria in Section II-A, the area which remains without any PQ buses is removed. Reconnecting a PQ bus to a neighboring area includes recalculating the location of this area's PV bus as described in Section II-C followed by a validation of the specified feasibility criteria. In case a cost minimal solution is desired, the area is only consolidated if the total costs of all involved areas after reconnecting the buses are below the total initial costs. This procedure is performed for all areas in the order of their number of PQ buses, starting with the smallest area. The network recombination procedure is iteratively repeated for the entire set of areas until the desired number of areas is reached or no more areas can be consolidated.

F. Step 5: Topology Definition

Depending on the voltage level, different topologies are commonly used in power grids. The user may specify in advance the kind of topology which should be applied to each voltage level. The most common topologies in real-world power grids and the algorithmic process to generate them is described in the following:

1) **Ring networks** are typically planned for LV and MV grids. The process of planning a ring is illustrated in Fig. 2. To create such networks from the nodes of an area (Fig. 2(a)), the implemented *density-based spatial clustering of applications with noise* (DBSCAN) [42] algorithm[3] generates clusters of nodes based on a maximum allowed distance between two nodes (Fig. 2(b)). Only PQ buses are used for the clustering, the area's PV bus is excluded in this process. Each cluster serves as the basis for planning a ring. A ring with minimal total branch length is found by solving a *traveling salesmen problem* (TSP) [43] on all nodes of a cluster starting and

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[1] https://code.google.com/p/ekmeans/

[2] http://elki.dbs.ifi.lmu.de/wiki/Tutorial/SameSizeKMeans

[3] https://commons.apache.org/proper/commons-math/apidocs/org/apache/commons/math3/ml/clustering/DBSCANClusterer.html

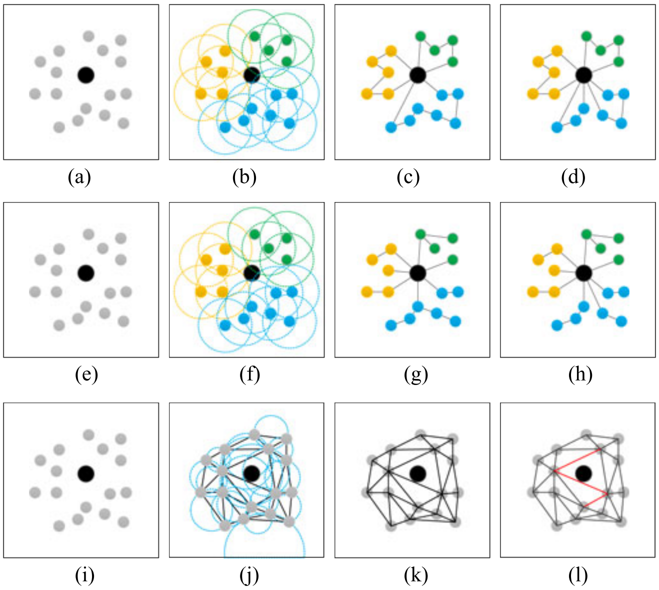

Fig. 2. Process of planning (a)–(d) ring, (e)–(h) radial, and (i)–(l) meshed networks.

ending with the area's PV bus (Fig. 2(c)). As the TSP is *NP*-hard, the heuristic TSP *2-opt* algorithm[4] is used which provides a good trade-off between accuracy and performance. In each planned ring Constraint (2) and (3) are validated for each branch and bus. In case any constraint is not satisfied, the ring is divided into two rings with an equal number of consumers (Fig. 2(d)). For each of those rings the TSP is individually solved and the mentioned constraints are again validated.

2) **Radial networks** may be used in LV and MV grids alternatively to ring networks. The process of planning a radial network is illustrated in Fig. 2. The nodes of an area (Fig. 2(e)) are clustered using the DBSCAN algorithm (Fig. 2(f)) as described for generating a ring topology. A radial network is then created by constructing a *minimum spanning tree* (MST) using *Kruskal*'s [44] algorithm[5] which ensures a minimal total length of all branches (Fig. 2(g)). In case any branch or consumer in the so-planned MST violates Constraint (2) or (3), the MST is divided into two MSTs with an equal number of buses (Fig. 2(h)).

3) **Meshed networks** show some degree of redundancy making this topology especially common for MV and HV grids. The process of planning a meshed network is illustrated in Fig. 2. Starting from the nodes of an area (Fig. 2(i)), this network type is generated by executing a *delaunay triangulation* (DT) [45]. In a DT, triangles are built so that no node is inside the circumcircle of any triangle (Fig. 2(j)), resulting in a partially connected mesh (Fig. 2(k)). If the meshed network generated by the implemented algorithm[6] shows a higher redundancy than desired, branches are iteratively removed starting with the one connecting the two nodes with the highest node degree (Fig. 2(l)). This removal is subject to Constraints (2) and (3).

G. Alternative for Step 1 to Step 5: Customized Planning

Alternatively or in addition to the regular planning process described in Sections II-B–II-F, there is also the possibility for a more customized planning than simply modifying parameter settings. It includes the user-defined placement and specification of available buses and branches. The customized planning option is especially useful when detailed input data for parts of the power system to be planned is already available and should manifest in the resulting PNM. In case data for an entire voltage level is available, the regular planning process is omitted for this voltage level and buses and branches are placed and specified as given by the data. If only parts of a voltage level should be planned manually, the regular planning process is executed considering the placement and specification of the given buses and branches. This way, available data on parts of the network can be directly integrated in the regular planning process to allow for expansion planning.

H. Step 6: Voltage Level Combination

After all areas in the lowest voltage layer have been planned, the algorithm continues at the next higher level. The set of PQ buses in this layer is given by the consumers directly connected to this voltage level and all substations from the lower level acting as consumers on this level. The power demand of those substations equals their power supply to lower voltage consumer plus their internal conversion losses. For this and all higher layers, the entire planning procedure is repeated which finally leads to the PNM.

III. POWER FLOW SIMULATION

The power flow simulation computes the capacity utilization at every branch as well as the voltage at every bus. This is on the one hand necessary during the PSP process for assessing the feasibility criteria given in Section II-A. Most importantly, on the other one, the simulation can be applied for conducting simulation studies on an already planned PNM. This allows investigating the impact of changes of the tempo-spatial load distribution on an existing PNM. In a real-world setting, these changes may result from new load types (e.g., electric vehicles) or from changed power consumption behavior (e.g., increasing use of airconditioners, use of smart loads, or deployment of demand response schemes). This step therefore does not aim at further modifying the PNM but at identifying times and locations of grid congestion and voltage drops.

The process starts at the lowest voltage level by simulating power flows on every branch. The results are then validated according to the feasibility criteria introduced in Section II-A. This process is illustrated in Fig. 3 and described in Sections III-B1 and III-B2. The outputs generated for one voltage layer are then taken as inputs for the next level as described

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[4] https://github.com/phil8192/tsp-java
[5] The algorithm was self-implemented based on the description given in [44]
[6] http://www.cs.cornell.edu/home/chew/Delaunay.html

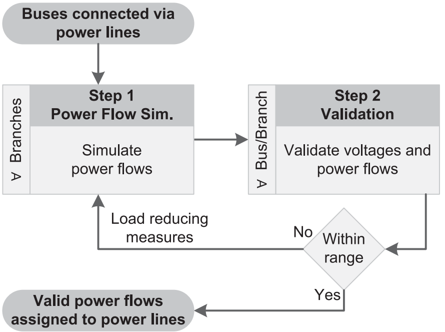

Fig. 3. Regular power flow simulation process for one independent power system part.

in Section III-B3. The outcome of the entire simulation process consists of active and reactive power values on both ends of each branch and the power losses in every branch. Additionally, the voltage for each bus is determined.

In Section III-A the implemented power flow model is introduced followed by a description of the single steps of the simulation procedure for an entire PNM with multiple voltage levels in Section III-B.

A. Power Flow Model

AC models realistically reproduce the power flow on power lines. Due to their non-linearity, finding a solution is, however, a computationally expensive task. In this work, a standard AC power flow model is taken which uses network decomposition to overcome possible performance issues when solving large-scale power flow problems. In this context, a power system is divided into independent parts which are then solved separately to reduce execution time. The implemented power flow model *JPOWER*[7], exhaustively described in [46], uses the *Newton-Raphson* [47, pp. 222] algorithm for solving AC power flow problems. In distribution networks with a high ratio of resistance to reactance values, the Newton-Raphson algorithm may require a great number of iterations or might even not converge at all [48]. In case no convergence can be achieved after a user-defined number of iterations, the power flow simulation for this part switches to the *Fast-Decoupled* algorithm [47, p. 228] and, if still no solution can be found, to the *Gauss-Seidel* [47, pp. 212] algorithm, both of which are also implemented in JPOWER. When calculating the power flow in a two-busbar system in which a power line directly connects a PV bus and a PQ bus, JPOWER usually does not find a solution with neither algorithm. In each of these cases, an own implementation of the iterative process described in [47, p. 207] which is independent of JPOWER is applied. In case a solution exists, it is always found this way. By design of the implemented algorithms, this solution obeys both of Kirchhoff's circuit laws.

B. Simulation Process

In order to reduce computational requirements, power flow calculations are performed consecutively for independent parts of the network; the smallest being a ring or tree, the largest being composed of multiple rings or trees spanning over multiple areas or even voltage levels. As a decomposition of a meshed network may go in hand with violating Kirchhoff's circuit laws, a meshed network is always treated as one single independent part. The upper boundary for the size of an independent part is only limited by the available computational resources. On an average work station, several thousand buses and branches can typically be processed in a time frame of a few minutes. To optimally use existing resources, the user can either adapt the size of an independent part or allow for parallelization when calculating power flows for the independent parts. In the following description of the simulation process an independent part is assumed to be an area as introduced in Section II.

1) Step 1: Power Flow Simulation: The simulation is initialized by defining all consumers or substations acting as consumers to be PQ buses, all power stations or substations acting as producers to be PV buses, and one of the PV buses as the *slack bus*. Buses are initialized as described in [47, p. 219]. The power flow simulation starts by determining the active and reactive power on both ends of each branch j and the voltage V_i at every bus i using the power flow model described in Section III-A. The power difference between both ends of a branch is thus the active and reactive power loss, $P_{\mathrm{L},j}$ and $Q_{\mathrm{L},j}$. The power supply of each PV bus can be determined by the sum of power flows on all directly connected branches with outgoing power flows. The total active and reactive power the PV buses have to supply are then calculated as

$$P_{\mathrm{S},\alpha} = \sum_{i=1}^{N_\alpha} P_{\mathrm{D},\alpha,i} + \sum_{j=1}^{M_\alpha} P_{\mathrm{L},\alpha,j} \tag{6}$$

$$Q_{\mathrm{S},\alpha} = \sum_{i=1}^{N_\alpha} Q_{\mathrm{D},\alpha,j} + \sum_{j=1}^{M_\alpha} Q_{\mathrm{L},\alpha,j} \tag{7}$$

2) Step 2: Validation: Finding a feasible solution to the power flow problem is a necessary yet not sufficient condition for the validity of the power flows in the context of this simulation process. While a feasible solution guarantees adherence to Kirchhoff's laws, the conditions provided in Section II-A have additionally to be met. If at any PQ bus the voltage violates Condition (2), the initial voltage at the PV buses is increased using a binary search until either the condition is met or the maximum threshold for the value is reached. In the latter case or if at any bus Condition (1) or at any branch Condition (3) cannot be hold, this particular part of the network needs to be considered overloaded. This overload may only happen when the power demand at any PQ bus is higher than the one used to originally plan the PNM. This case can occur in the presence of additional loads which were not considered for the planning of the PNM. An example for this case can be found in [37] where the impact of PEV charging is investigated for a PNM which was initially not designed to accommodate PEVs. In a real-world setting, this overload would require load reducing measures by the *power system operator* (PSO) as, for instance, implemented through congestion pricing or more complex schemes such as demand-response mechanisms. As a primary target, the

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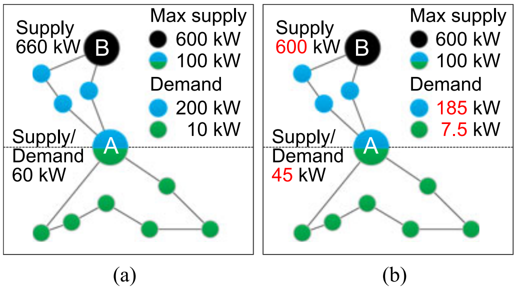
[7] https://github.com/rwl/JPOWER/



(a) (b)

Fig. 4. Exemplified results of (a) the regular upward simulation process determining each PV bus' power supply and (b) its downward counterpart determining each PQ bus' maximum power demand in case of a PV bus' overload. The horizontal line divides the network into two different voltage levels.

framework identifies times and locations of grid congestion and voltage drops. The simulation therefore assumes that an appropriate load reducing measure is taken in an overloaded part of the grid by decreasing the power demand at the PQ buses. As a default setting which treats all consumers equally, the power demand for PQ buses is curtailed proportionally to their power demand compared to other PQ buses. Load curtailments are documented both temporally and spatially to allow analyzing them after conducting a power flow study. More sophisticated measures such as smart loads or distributed battery energy storage participating in demand-response schemes or peak shaving may be implemented by the user. It is in fact one of the purposes of the presented framework to support the development and testing of such measures with regard to the entire power system.

3) Step 3: Voltage Level Combination: After calculating power flows in all branches within one voltage layer, the process continues at the next higher level. For this purpose, substations which on the lower voltage level are defined as PV buses are on the current level defined as PQ buses. The same substation therefore serves as a generator on a lower voltage level while it acts as a load on a higher level. P_D and Q_D at each of these PQ buses are set to the values of P_S and Q_S of its corresponding PV bus. This shifting of power between the two windings of a substation is done upwards for all voltage levels. It is assumed that voltage regulators, such as *on-load tap changers* or *series regulators*, are installed at each PV bus justifying initialization values for V of 1.0 pu for each voltage level. Shunt compensation is currently not considered.

In case the power demand of any substation acting as a consumer has been decreased due to a violation of any of the Conditions (1) to (3), the demand of all PQ buses directly or indirectly affected by this decrease also has to be curtailed. This process is illustrated on an example in Fig. 4. This example includes 2 PV buses and 9 PQ buses being connected in a ring topology over 2 voltage levels. For simplicity reasons, power losses are neglected in this example. In the regular upward simulation process as shown in Fig. 4(a), the power supply of substations acting as producers is determined by the power demand of connected consumers (blue: 200 kW each, green: 10 kW each). In the example, this results in Substation A supplying 60 kW and Substation B supplying 660 kW. As the demand exceeds the maximum rating of 600 kW of Substation B, this setting is considered infeasible. This network is therefore simulated again by setting the supply of Substation B to its maximum rating of 600 kW. The simulation proceeds downwards to determine the maximum possible power demand of the directly connected PQ buses as shown in Fig. 4(b). According to the description in Section III-B2 the demand of each blue colored consumer is reduced from 200 kW to 185 kW. At the same time the demand of Substation A is decreased from 60 kW to 45 kW. As Substation A can now only consume 45 kW, all green consumers together are not allowed to consume more than this value. This requires curtailing the total power demand of all green colored PQ buses from 60 kW to 45 kW resulting in reducing each PQ bus' power demand from 10 kW to 7.5 kW.

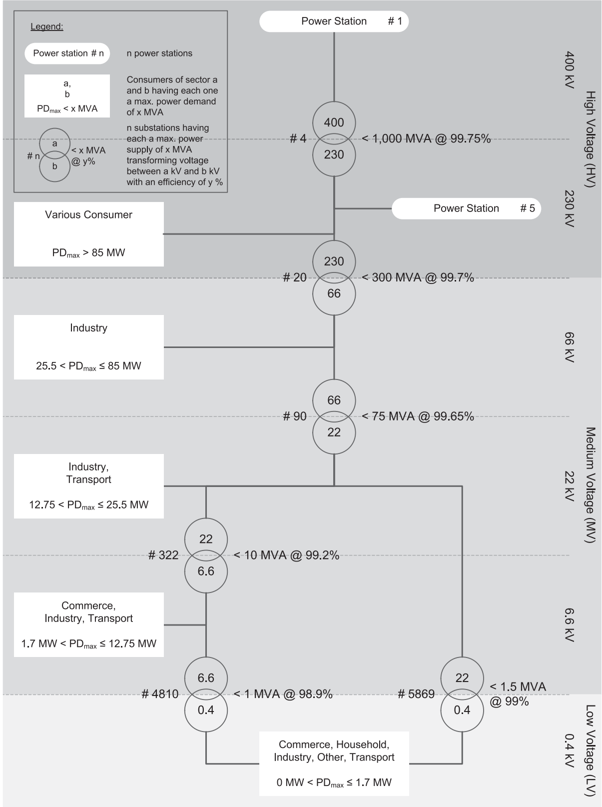


Fig. 5. Characteristics of the Singapore power grid.

IV. METHODOLOGY DEMONSTRATION ON THE EXAMPLE OF SINGAPORE

As an illustration of the functionality of the proposed methodology, the framework is applied to input data from Singapore as described in Section IV-A. In Section IV-B, a PNM along with its most important topological and electrical metrics is presented and discussed in the context of known properties of the real Singapore power grid.

A. Input Data

The Singapore power grid as shown in Fig. 5 is divided into the LV grid (0.4 kV), the MV grid (6.6 kV, 22 kV, 66 kV), and the HV grid (230 kV and 400 kV). For each of the six voltage levels, the data specifies the maximum power of each substation[8], the number of substations[9], and the number of power stations with capacities greater than 100 MW[10]. Furthermore, the resistance/reactance of the 26 500 km of laid underground cables[11] are taken into account. The bottom-up planning of the power grid requires data on the number[12], locations[13], and power demand[14] of consumers connected to the various voltage levels. The raw data reveals a total peak power demand of 6 340 MW[15] for 117 852 geographically distributed consumers. Each of these consumers can be assigned to one of the sectors *industry* (44% of total power demand)*, commerce* (36%), *household* (14%), *transport* (5%), and *other* (1%).

Before clustering nodes in the provided region, the region is iteratively geographically bisected until each sub-region contains no more than 5000 nodes. The k-means algorithm is executed for every sub-region with 16 iterations each to achieve convergence. The LV (MV) grid is planned with a radial (ring) topology while the HV grid is to some extent planned manually as a partial mesh. The permitted range of the bus voltage V_i at each consumer i is set to be between 0.95 pu and 1.05 pu in accordance with [49]. The maximum distance between two nodes of a cluster using the DBSCAN algorithm is set to be twice the average branch length of their voltage level when only planning direct connections between PQ and PV buses. To account for overcapacities, a maximum substation and power line utilization of 80% is not exceeded in the LV and MV grid. In the presented planning process, branches connect buses geographically via straight lines. As in reality buses are typically not connected via a shortest path, stretch factors of 3.2 (LV), 2.6 (MV), and 1.5 (HV) are applied to extend the length of each power line and to realistically account for power losses. The factors are selected to produce a PNM with total power line length similar to the Singapore power grid.

Depending on the voltage level, substation costs of 10 700 \$/MW for the 0.4 kV level up to 24 000 \$/MW for the 400 kV level are assumed while power line costs range between 750 \$/MW/km for the 0.4 kV level up to 6 650 \$/MW/km for the 400 kV level[16].

TABLE I
PROPERTIES OF THE PNM

Property	LV	MV	HV
Topological			
# Nodes, consuming	116 613	1 239	0
# Nodes, supplying	10 679	513	4
# Edges	116 613	13 004	100
# Rings/Trees	40 270	611	0
# Nodes per ring/tree, average	3.77	21.23	—
Edge length, total [km]	17 076	8 701	864
Average path length[1] [m]	131	519	6 717
Clustering coefficient[2]	0	0.0013	0.0711
Mean degree[3]	1.83	2.09	4.35
Physical			
Power demand[4] [MW]	2 404	6 386	6 557
Power supply [MW]	2 449	6 557	6 602
Power loss [%]	1.85	2.61	0.68
Utilization, edge, average [%]	10	4	4
Utilization, substation, average [%]	20	61	18
Economical			
Costs [\$$\cdot 10^6$]	148	6 956	31 983

[1] The *average path length* is defined according to [50] as the mean geographical shortest path distance between any pair of nodes measured along a flat surface of the earth.

[2] The *clustering coefficient* is defined according to [50] as average redundancy, meaning the average number of edges from a neighbor of a node to other neighbors of this node, being scaled to the interval $[0, 1]$.

[3] The *mean degree* is defined according to [50] as the average number of edges connected to each node.

[4] The value indicates the total power demand of the respective voltage level including power losses occurring in lower voltage levels.

B. Power Network Model

The PNM generated by the PSP process contains about 130 000 nodes and approximately the same amount of edges which are distributed over 6 voltage levels. Those nodes and edges include both real-world data regarding consumers, substations, power stations, and branches available for Singapore and the ones planned by the PSP process. On an Intel Core i5-2520M, planning the entire PNM takes about 10 minutes. The same machine requires 15 seconds to simulate all power flows on that PNM for one time step. The PNM's electrical and topological properties are given in Table I. The following observations can be made:

1) The total peak demand of 6 340 MW is satisfied by supplying 6 602 MW. This implies an overall power loss of 3.96% on a total power line length of 26 643 km. This is within the reference range between 1.6% and 5.3% which is given for Singapore[17][18].
2) The average clustering coefficient for all voltage levels is within the range found in [51].
3) The mean degree of 1.83 (2.09) for the LV (MV) grid matches the values found for smaller sample power grids in [52]. With 4.35 of the HV grid the degree is at the upper bound of power grids investigated in [53].
4) The number of substations in the MV grid is about 19% above the value given in the reference data. This may have several reasons including incomplete information on the real number of substations, an inaccurate allocation of consumers to different voltage levels, or too unspecific resistance/reactance values for the laid power lines.
5) Substations in the LV (MV) grid show a very low average utilization of 20% (61%). A similar observation is made for power lines with a utilization rate of 10% (4%).

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[8] Singapore Power, Annual Report 2012 and Major Procurement Items: http://www.singaporepower.com.sg

[9] Singapore Power, Facts and Figures: http://www.singaporepower.com.sg

[10] EMA, Licensed Generation Capacity by Generation Company: http://www.ema.gov.sg/Statistics.aspx

[11] NEXANS, Power Cables 1-30 kV and High Voltage Cables for Power Transmission: http://www.nexans.de

[12] http://www.streetdirectory.com

[13] http://www.onemap.sg

[14] EMA, Monthly Electricity Consumption by Sector and Half-hourly System Demand Data: http://www.ema.gov.sg/Statistics.aspx

[15] Peak power demand on 12th January 2014.

[16] http://iea-etsap.org/web/Highlights%20PDF/E12_el-t&d_KV_Apr2014_GSOK%201.pdf

[17] http://data.worldbank.org/

[18] http://www.tradingeconomics.com/

There are several reasons that may lead to these low utilization rates. First, there may be a considerable optimization potential regarding the number of substations and quality of power lines in the Singapore network. Second, the allocation of consumers to the different voltage levels conducted for the planning process is inaccurate. And third, the nominal power rating of substations and the quality of power lines is more inhomogenous than assumed for the planning process where the values were only differentiated by voltage level.

6) By design, the total power line length and the number of substations in the LV grid match the target value.

In addition to the PNM presented above, a cost minimal PNM is planned. The planning process builds on the same input data but the network recombination step is executed until no more areas can be consolidated. As cost factors the number of substations and the total power line length are taken into account. Compared to the previously discussed PNM, the number of substations for the LV (MV) grid can be reduced by 39% (20%) while the total power line length grows at the same time by 35% (13%). This results in an overall cost reduction of 38% (27%) for the LV (MV) grid. The total costs of the power grid can be reduced from $37\,991 \cdot 10^6$ \$ to $35\,350 \cdot 10^6$ \$.

V. Conclusion and Outlook

In this paper, a modular PSP and power flow simulation framework for generating and evaluating large-scale PNMs is presented and demonstrated on the example of Singapore. The methodology iteratively employs a combination of algorithms allowing to create PNMs with a great variety of different characteristics from minimal input data. First in literature, PNMs can be generated bottom-up using consumer location and power demand data to particularly allow for a more realistic planning of the LV grid. The PSP framework comprises an AC power flow simulation which is used to ensure that the generated power grid is functional. Furthermore, it can be used to conduct studies simulating power flows under arbitrary tempo-spatial load profiles. The simulation calculates the capacity utilization at every bus and branch as well as the voltage at each consumer and substation which allows identifying times and locations of grid congestion and voltage drops. With its versatility and ability to flexibly tailor the power grid to individual use cases, the framework overcomes the common problem of limited available information on real-world power systems.

The generated PNMs show realistic topological and electrical properties of real-world power grids. There are, however, several limitations when comparing a PNM with a real-world power system. The first aspect is concerning the historic evolution of a power system which does not necessarily follow an optimal development path. This aspect can partially be considered using expansion planning. This, however, requires sufficiently detailed information on the evolution of the existing power system. In case of scarce data, notable discrepancies between the PNM and the real counterpart may exist. The second limitation when planning large-scale PNMs with any PSP framework is that cost minimal planning cannot be expected to yield a global optimum. This is due to the large parameter space which requires a heuristic approach. Results, however, show that the presented network recombination heuristic is able to exploit the optimization potential to a large extent independently of the specific network. The third limitation is that the framework does not yet consider geographical constraints when laying power lines or placing stations.

Above all, the lack of data on the evolution of real-world power systems restrain PSP frameworks from producing more realistic PNMs. To account for this evolutionary development process, future work will comprise the development of an upgrade planning module. In contrast to the already implemented expansion planning which extends the network by adding power lines or substations, upgrade planning will also consider the possibility of modifying existing parts of the network. An example for this is to increase the maximum power rating of a substation instead of planning a new one in case this is the economically preferred option. Future work will further include geographic constraints for placing substations or branches which will make the resulting networks more realistic. Finally, the consideration of redundancies to increase the reliability of the system will be included in the PSP process up to a complexity that AC power flow simulations can handle in a reasonable time. A performance comparison of the presented method with existing top-down approaches would be desirable. This, however, requires considerable efforts in acquiring the necessary data required by both bottom-up and top-down approaches for the same region, thus leaving this subject to future work. From an application perspective, in a next step the presented framework will be employed to extend previous work on simulation-based planning of charging infrastructures for PEVs as conducted in [34]. This will allow optimizing charging station distributions, charging strategies, and PEV demand response schemes with regard to optimally satisfying charging demand while imposing minimal impact on the power system.

References

[1] C. Domingo, T. Román, A. Sánchez-Miralles, J. González, and A. Martiánez, "A reference network model for large-scale distribution planning with automatic street map generation," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 190–197, Feb. 2011.

[2] J. E. Mendoza, M. E. López, S. C. Fingerhuth, H. E. Peña, and C. A. Salinas, "Low voltage distribution planning considering micro distributed generation," *Elect. Power Syst. Res.*, vol. 103, pp. 233–240, 2013.

[3] M. Sedghi, M. Aliakbar-Golkar, and M.-R. Haghifam, "Distribution network expansion considering distributed generation and storage units using modified pso algorithm," *Int. J. Elect. Power Energy Syst.*, vol. 52, pp. 221–230, 2013.

[4] A. S. B. Humayd and K. Bhattacharya, "Comprehensive multi-year distribution system planning using back-propagation approach," *IET Gener., Transm. Distrib.*, vol. 7, no. 12, pp. 1415–1425, 2013.

[5] D. Kumar, S. Samantaray, and G. Joos, "A reliability assessment based graph theoretical approach for feeder routing in power distribution networks including distributed generations," *Int. J. Elect. Power Energy Syst.*, vol. 57, pp. 11–30, 2014.

[6] Ž. Popović, V. D. Kerleta, and D. Popović, "Hybrid simulated annealing and mixed integer linear programming algorithm for optimal planning of radial distribution networks with distributed generation," *Elect. Power Syst. Res.*, vol. 108, pp. 211–222, 2014.

[7] B. Zeng, J. Zhang, X. Yang, J. Wang, J. Dong, and Y. Zhang, "Integrated planning for transition to low-carbon distribution system with renewable energy generation and demand response," *IEEE Trans. Power Syst.*, vol. 29, no. 3, pp. 1153–1165, May 2014.

[8] N. Koutsoukis, P. Georgilakis, and N. D. Hatziargyriou, "A tabu search method for distribution network planning considering distributed generation and uncertainties," in *Proc. Int. Conf. Probab. Methods Appl. Power Syst.*, 2014, pp. 1–6.

[9] X. Lin, J. Sun, S. Ai, X. Xiong, Y. Wan, and D. Yang, "Distribution network planning integrating charging stations of electric vehicle with v2g," *Int. J. Elect. Power Energy Syst.*, vol. 63, pp. 507–512, 2014.

[10] W. Yao *et al.*, "A multi-objective collaborative planning strategy for integrated power distribution and electric vehicle charging systems," *IEEE Trans. Power Syst.*, vol. 29, no. 4, pp. 1811–1821, Jul. 2014.

[11] T. Gomez, C. Mateo, A. Sanchez, P. Frias, and R. Cossent, "Reference network models: A computational tool for planning and designing large-scale smart electricity distribution grids," in *High Performance Computing in Power and Energy Systems (ser. Power Systems)*, S. K. Khaitan and A. Gupta, Eds. Berlin, Germany: Springer, 2013, pp. 247–279. [Online]. Available: http://dx.doi.org/10.1007/978-3-642-32683-7_9

[12] L. González-Sotres, C. Mateo Domingo, A. Sánchez-Miralles, and M. Alvar Miró, "Large-scale MV/LV Ttransformer substation planning considering network costs and flexible area decomposition," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 2245–2253, Oct. 2013.

[13] D. Kumar and S. Samantaray, "Design of an advanced electric power distribution systems using seeker optimization algorithm," *Int. J. Elect. Power Energy Syst.*, vol. 63, pp. 196–217, 2014.

[14] S. Haffner, L. F. A. Pereira, L. A. Pereira, and L. S. Barreto, "Multistage model for distribution expansion planning with distributed generation—Part I: Problem formulation," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 915–923, Apr. 2008.

[15] R. C. Lotero and J. Contreras, "Distribution system planning with reliability," *IEEE Trans. Power Del.*, vol. 26, no. 4, pp. 2552–2562, Oct. 2011.

[16] R. H. Fletcher and K. Strunz, "Optimal distribution system horizon planning—Part I: Formulation," *IEEE Trans. Power Syst.*, vol. 22, no. 2, pp. 791–799, May 2007.

[17] H. Khodr, Z. A. Vale, and C. Ramos, "A benders decomposition and fuzzy multicriteria approach for distribution networks remuneration considering DG," *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 1091–1101, May 2009.

[18] Ž. Popović and D. Popović, "Graph theory based formulation of multi-period distribution expansion problems," *Elect. Power Syst. Res.*, vol. 80, no. 10, pp. 1256–1266, 2010.

[19] S. Ganguly, N. Sahoo, and D. Das, "Multi-objective planning of electrical distribution systems using dynamic programming," *Int. J. Elect. Power Energy Syst.*, vol. 46, pp. 65–78, 2013.

[20] T.-H. Chen, E.-H. Lin, N.-C. Yang, and T.-Y. Hsieh, "Multi-objective optimization for upgrading primary feeders with distributed generators from normally closed loop to mesh arrangement," *Int. J. Elect. Power Energy Syst.*, vol. 45, no. 1, pp. 413–419, 2013.

[21] I. Ramirez-Rosado and J. Bernal-Agustin, "Reliability and costs optimization for distribution networks expansion using an evolutionary algorithm," *IEEE Trans. Power Syst.*, vol. 16, no. 1, pp. 111–118, Feb. 2001.

[22] E. Diaz-Dorado, J. Pidre, and E. Garcia, "Planning of large rural low-voltage networks using evolution strategies," *IEEE Trans. Power Syst.*, vol. 18, no. 4, pp. 1594–1600, Nov. 2003.

[23] I. Ramirez-Rosado and J. Dominguez-Navarro, "New multiobjective tabu search algorithm for fuzzy optimal planning of power distribution systems," *IEEE Trans. Power Syst.*, vol. 21, no. 1, pp. 224–233, Feb. 2006.

[24] A. M. Cossi, R. Romero, and J. R. S. Mantovani, "Planning and projects of secondary electric power distribution systems," *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1599–1608, Aug. 2009.

[25] I. Ziari, "Planning of distribution network for medium voltage and low voltage," Ph.D. dissertation, Queensland Univ. Technol., Brisbane, Australia, 2011.

[26] I. Ziari, G. Ledwich, and A. Ghosh, "Optimal integrated planning of MV-LV distribution systems using DPSO," *Elect. Power Syst. Res.*, vol. 81, no. 10, pp. 1905–1914, 2011. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378779611001271

[27] J. Nahman and D. Peric, "Optimal planning of radial distribution networks by simulated annealing technique," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 790–795, May 2008.

[28] P. S. Georgilakis and N. D. Hatziargyriou, "A review of power distribution planning in the modern power systems era: Models, methods and future research," *Elect. Power Syst. Res.*, vol. 121, pp. 89–100, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378779614004490

[29] A. Navarro and H. Rudnick, "Large-scale distribution planning—Part II: Macro-optimization with Voronoi's diagram and tabu search," *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 752–758, May 2009.

[30] J. Conejo, G. Bartolome, A. Exposito, and M. Montanes, "ANETO: A system for the automatic generation of theoretical network models," in *Proc. 9th Int. Conf. Elect. Power Quality Utilisation*, Oct. 2007, pp. 1–6.

[31] A. Navarro and H. Rudnick, "Large-scale distribution planning—Part I: Simultaneous network and transformer optimization," *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 744–751, May 2009.

[32] Y. Xu, H. Aydt, and M. Lees, "SEMSim: A distributed architecture for multi-scale traffic simulation," in *Proc. ACM/IEEE/SCS 26th Workshop Principles Adv. Distrib. Simul.*, Jul. 2012, pp. 178–180.

[33] D. Pelzer, J. Xiao, D. Zehe, M. Lees, A. Knoll, and H. Aydt, "A partition-based match making algorithm for dynamic ridesharing," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 5, pp. 2587–2598, Oct. 2015.

[34] V. Viswanathan, D. Zehe, J. Ivanchev, D. Pelzer, A. Knoll, and H. Aydt, "Simulation-assisted exploration of charging infrastructure requirements for electric vehicles in urban environments," *J. Comput. Sci.*, vol. 12, pp. 1–10, 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S187775031530034X

[35] D. Zehe, A. Knoll, W. Cai, and H. Aydt, "{SEMSim} cloud service: Large-scale urban systems simulation in the cloud," *Simul. Model. Practice Theory, vol. 58, Part 2 (special issue on Cloud Simulation)*, pp. 157–171, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1569190X15000805

[36] *IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA)—Framework and Rules, IEEE Std. 1516–2010 (Revision IEEE Std 1516-2000)*, Aug. 2010, pp. 1–38.

[37] D. Ciechanowicz, D. Pelzer, and A. Knoll, "Simulation-based approach for investigating the impact of electric vehicles on power grids," in *Proc. IEEE PES Asia-Pacific Power Energy Eng. Conf.*, 2015, pp. 1–5.

[38] D. Pelzer, D. Ciechanowicz, H. Aydt, and A. Knoll, "A price-responsive dispatching strategy for vehicle-to-grid: An economic evaluation applied to the case of Singapore," *J. Power Sources*, vol. 256, pp. 345–353, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378775314001001

[39] D. Ciechanowicz, A. Knoll, P. Osswald, and D. Pelzer, "Towards a business case for vehicle-to-grid—Maximizing profits in ancillary service markets," in *Plug In Electric Vehicles in Smart Grids*. New York, NY, USA: Springer, 2015.

[40] J. Wu, *Advances in K-means Clustering: A Data Mining Thinking*. New York, NY, USA: Springer, 2012.

[41] W. Lin, M. Tsay, and S. Wu, "Application of geographic information system for substation and feeder planning," *Int. J. Elect. Power Energy Syst.*, vol. 18, no. 3, pp. 175–183, 1996. [Online]. Available: http://www.sciencedirect.com/science/article/pii/0142061595000542

[42] M. Ester, H. P. Kriegel, J. Sander, and X. Xu, "A density-based algorithm for discovering clusters in large spatial databases with noise," in *Proc. 2nd Int. Conf. Knowl. Discovery Data Mining*, 1996, pp. 226–231.

[43] W. J. Cook, *In Pursuit of the Traveling Salesman: Mathematics at the Limits of Computation*. Princeton, NJ, USA: Princeton Univ. Press, 2014.

[44] J. B. Kruskal, "On the shortest spanning subtree of a graph and the traveling salesman problem," *Proc. Amer. Math. Soc.*, vol. 7, no. 1, pp. 48–50, Feb. 1956. [Online]. Available: http://www.jstor.org/stable/2033241

[45] F. Aurenhammer, R. Klein, and D.T. Lee, *Voronoi Diagrams and Delaunay Triangulations*. Singapore: World Scientific, 2013.

[46] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, "MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 12–19, Feb. 2011.

[47] B. M. Weedy, B. J. Cory, N. Jenkins, J. B. Ekanayake, and G. Strbac, *Electric Power Systems*. Hoboken, NJ, USA: Wiley, 2012. [Online]. Available: http://books.google.com.sg/books?id=qGxQNDbMh_YC

[48] T. Tingting, L. Yang, L. Ying, and J. Tong, "The analysis of the convergence of Newton-Raphson method based on the current injection in distribution network case," *Int. J. Comput. Elect. Eng.*, vol. 5, no. 3, p. 288, 2013.

[49] *Low-Voltage Electrical Installations—Part 5–52: Selection and Erection of Electrical Equipment—Wiring Systems, IEC 60364*, 2009.

[50] M. Newman, *Networks: An Introduction*. New York, NY, USA: Oxford Univ. Press, 2010.

[51] G. A. Pagani and M. Aiello, "Power grid network evolutions for local energy trading," *arXiv preprint arXiv:1201.0962*, 2012.

[52] G. A. Pagani and M. Aiello, "Towards decentralization: A topological investigation of the medium and low voltage grids," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 538–547, Sep. 2011.

[53] G. A. Pagani and M. Aiello, "The power grid as a complex network: A survey," *Phys. A, Statist. Mech. Appl.*, vol. 392, no. 11, pp. 2688–2700, 2013.

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