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EMPIRICAL ANALYSIS FOR DISTRIBUTED ENERGY RESOURCES' IMPACT ON FUTURE DISTRIBUTION NETWORK

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ABSTRACT

There has been a large body of statements claiming that the large scale deployment of Distributed Energy Resources (DERs) will eventually reshape the future distribution grid operation in various ways. Thus, it is interesting to introduce a platform to interpret to what extent the power system operation will be alternated. In this paper, quantitative results in terms of how the future distribution grid will be changed by the deployment of distributed generation, active demand and electric vehicles, are presented. The analysis is based on the conditions for both a radial and a meshed distribution network. The input parameters are based on the current and envisioned DER deployment scenarios proposed for Sweden.

Index Terms— distribution network, distributed energy resources, distributed generation, electric vehicle, active demand, power system losses, voltage profiles

1. NOMENCLATURE AND DEFINITIONS

DER - Distributed Energy Resource. DERs are electric components installed in the distribution grid, which participate in the power system operation, regardless of producing or consuming power. The integration of DERs in the grid reflects a paradigm shift regarding how electricity power is distributed in a power system [1][2].

A *Scenario* is a specific future plan in terms of amount of DERs, implemented within a certain distribution network during a specific period (e.g., a random weekday in spring). The DERs specifically focus on three *Dimensions*: *Active Demand* (AD), *Electric Vehicles* (EVs) and *Distributed Generation* (DG). Each scenario should pose certain technical challenges for the Distribution System Operator (DSO).

DG is defined as electric power generators connected to the medium voltage distribution grid within the scale of 1.5 MW [3]. Specifically in this paper, wind power is studied due to its increasing penetration in the Swedish power system.

From the grid operation's perspective, *EVs* are modelled as portable batteries whose behaviour and properties are determined by the vehicle type, driving patterns and availability of charging facilities.

AD is defined as residential consumers who change their load by either (i) shifting consumption according to the electricity prices on the day-ahead market, (ii) producing their own energy by installing photovoltaic (PV) panels on their roofs, or (iii) updating housewares with the purpose of improving energy efficiency. In the end, these changes will reshape the load profiles of the households.

2. INTRODUCTION

A series of environmental goals, such as [4][5][6], are proposed worldwide. The new legislation coupled with new market rules promises an increased penetration of DERs in the distribution grids [7]. Furthermore, reduced cost and the subvention of new technology create further incentives for a large scale deployment of DERs. The expansion of DG installation, especially powered by intermittent energy resources, poses new challenges to the operation and management of distribution networks. Subsequently, the DSO needs to contract more reserved capacities to mitigate the frequent mismatch between the generation and the demand from consumers [7]. Moreover, the advancement in storage and vehicle charging technology, together with dedicated support from policy makers, promise a bright future for EVs [8]. The introduction of EVs does not only increase the total consumption, but also implies a new load pattern which is time and consumer driving behaviour dependent. Finally, the new legislations, market rules and metering technologies encourage the consumers to respond on price signals from the electricity markets. Thus, an opportunity is created for the DSOs to manage, or even optimize the load patterns on the demand side [9].

2.1. Scope

As noted previously, there has been a large body of statements claiming that the large scale introduction of DERs will reshape the distribution grid operations and planning [1][7][10][11]. To provide an idea on how to foresee and

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to manage the upcoming operational changes, the purpose of this paper is to interpret changes in the power system onto different scenarios in the future European distribution network environment. This paper focus on the voltage profiles and power losses, which are the two primary concerns for the grid operation and planning. This is because it is directly relevant to the operational investments, and are sensitive to changes in the network [1][7][10][11][12]. Two reference networks are modelled in Matlab Simulink. The DGs, EVs and ADs are modelled based on Swedish conditions and prerequisites. The research outputs from the paper are quantitative analysis on the selected scenarios.

2.2. Outline of the paper

The remainder of the paper is structured as follows. Section 3 is a review of how the DER components are modelled. Section 4 presents the reference distribution network models which is the basis of the simulation platform. It is followed by section 5, which contains some simulation results and analyses. The paper is concluded in section 6.

3. DER MODELS

In this section, the main principles of the DER models are handled.

3.1. Distributed Generation

A cluster of wind power plants is modelled as an aggregated generation unit connected to the medium voltage distribution network. Their production profiles changes on an hourly basis, and their volumes are collected from [13]. To capture the features of wind generation, the mean values and deviations are calculated and it is assumed to follow a normal distribution [14]. The potential production of wind power is determined by the penetration level of DG, μ_{pen}^{DG}, i.e., the ratio between the installed DG capacity and the peak load. The aggregated wind generation and its size is presented in Table 1 with respect to the peak load. The unit names can be found in the topologies of network models (see Fig. 3).

Table 1. The Location and penetration level of wind power

Network	Radial network			Meshed network	
Unit Name	G1	G2	G3	G1	G2
Penetration	$\frac{2}{7}\mu_{pen}^{DG}$	$\frac{3}{7}\mu_{pen}^{DG}$	$\frac{2}{7}\mu_{pen}^{DG}$	$\frac{1}{3}\mu_{pen}^{DG}$	$\frac{2}{3}\mu_{pen}^{DG}$

3.2. Electric Vehicle

In this paper, EVs are modelled as mobile batteries, whose sizes and charging capacities are given in [8]. The driving pattern data are taken from a Swedish travelling survey [15][16]. How much, when and where the EVs are charged are dependent on: (i) driving patterns (e.g., behaviour of the commuter), (ii) the type of EV, (iii) charging availability.

There are two types of EVs studied in this paper, i.e., pure Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs). The total number of EVs is in proportion to the number of households in the studied area. It is assumed that if one EV leaves the geographic area reflecting the studied distribution network, an EV with the same features will enter. Three states for EVs are set: ”Running (0)”, ”Charging (1)”, and ”Parking (2)”. The initial states of all EVs are assumed to be at home and charging. When an EV is supposed to start and there is enough power to run the predefined trip, then the state of the EV is set ”Running”. ”Charging” will be applied when either of the aforementioned premises is not satisfied, if charging facilities are available. In cases when the EV does not have sufficient power to drive to the destination, it is either in the state of ”Charging”, if there is charging facility available on sites, or in the state of ”Parking” if not. The charging time is dependent on the remaining time before the next trip and the type of charging facilities. For observations, states, location, and State of Charge (SOC) in each time instant for every EV are recorded in matrices together with the equivalent load matrix. The SOC, power consumption duo to charge, remaining trip length and numbers of competed trips are updated after each iteration. Additional details regarding the modeling approach can be found in [17][18] and [11].

Fig.1 presents the equivalent load of a random EV fleet. Its equivalent load is dependent on its travelling routes, travelling patterns, charging patterns and SOCs. The peak load appears at around 18:00 - 22:00, while there is no consumption in the morning.

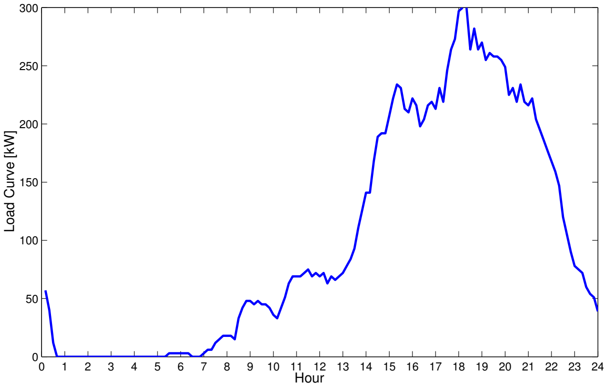


Fig. 1. Equivalent load of EVs.

3.3. Active Demand

The original residential load profiles are given by [12]. Properties, such as location (at which bus), type (apartment or house), are assumed to be random. Industrial and commercial loads are excluded from the study since they have applied flexible consumption based on their internal optimisations. Subsequently, the proportion of the demand that are insensitive to price is defined as the base load.

3.3.1. *Price Sensitivity*

Price sensitivity is modelled as changed consumption (e.g., from heat pumps) with respect to the electricity price from the day-ahead market. We assume that consumers are price sensitive, and proper metering technology and market contracts are available.

Stochastic hourly prices are generated based on the electricity price data from Nordic energy day-ahead market (Nordpool), for the time period 01.2009 to 10.2011 [19]. The electricity price is modelled as a normal distribution and is dependent on the price of the previous hour. These two factors are assumed to have an equal effect on the price setting. The price sensitivity strategy is defined by a piecewise function by shifting or shedding consumption of prioritized residential appliances based on customers' preferences [20][21]. For example, when the electricity price reaches 10% above the average price, the tasks of tumble dryers, supposed to start at this particular instant, will be postponed for 6 hour when a lower electricity price can be expected. Thus, the cost of electricity is reduced. A summary of the patterns of different house appliances is presented in Table 2.

Table 2. Price sensitivity strategy for appliances [20][21]

Appliances	Strategy			
	priority	control	price	limit
Dish Washer	1	postpone for 6h	105%	–
Tumble Dryer	2	postpone for 6h	110%	–
Washing Machine	3	postpone for 6h	115%	–
Heating	4	postpone for 1h cut 30% off	120% - 500%	1h
Kitchen Appliance	5	postpone for 1h	500%	1h

3.3.2. *Small scale production*

Consumers with small scale production connected to their households (a.k.a. prosumers) are studied. It is important to mention that these generators are connected to the low voltage network (e.g., 400 V), and are modelled as load reduction rather than pure production (as in the case of DG). We assume that all the customers who are price sensitive, own PV panels as well. PV energy production are estimated by applying historical irradiation data from NASA [22].

3.3.3. *Energy efficiency action*

Energy efficiency actions aim to save energy by implementing solutions to reduce the demand of the households (e.g., improving the insulation of the house, updating house appliances, etc). The efforts of energy efficiency actions can significantly reduce the total consumption in households. An optimistic study shows that the consumption can be reduced by 80% [23]. η_{eff} denotes the improved energy efficiency, and is defined as:

$$\eta_{eff} = \frac{\text{new residential load} - \text{small scale production}}{\text{original residential load}} \quad (1)$$

3.4. Modelling result

Fig.2 is an example of consumption and DG production on an hourly basis. In this case, the installed capacity of DG is about half of the peak load in the network, and the actual generation is just around 30%. The consumption peak occurs at around 20:00 when the base load reaches its maximum and meanwhile there is a minor contribution from the EVs. The injected power of every bus can be derived from the difference between the DG production and the consumption as shown in the example. Given the injected power in the system, we can calculate the power flow afterwards.

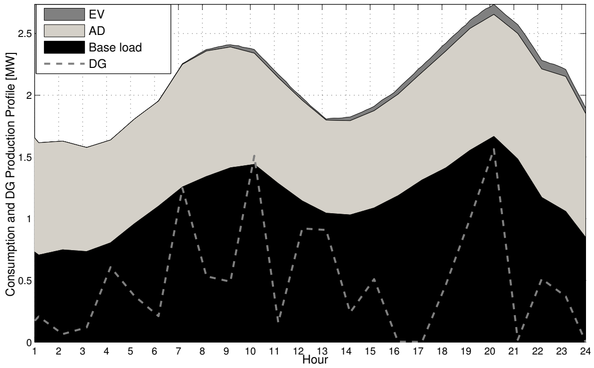
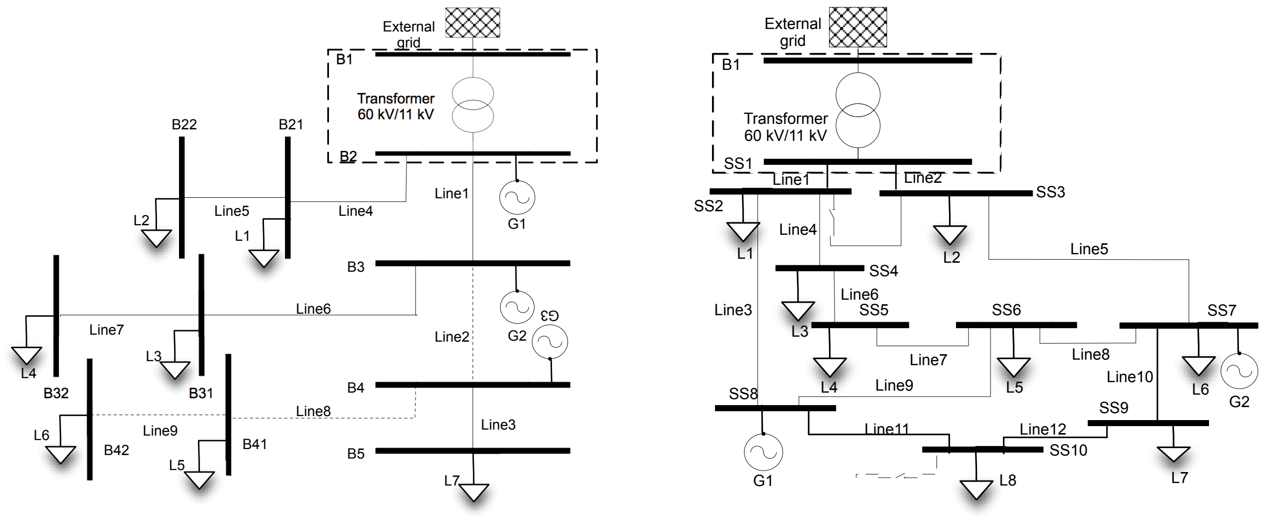


Fig. 2. Consumption and DG generation profiles on an hourly basis from SS_7 (Scenario 2050, meshed, spring).

4. NETWORK MODELS AND SCENARIOS

Distribution grids are the last stage of electricity delivery, directly connecting the end users. Their topology and sizes are different among areas depending on the operation concepts. In a power system research consortium, there exist several standardized test network models [24][25][26][27]. However, a majority of them are designed for reliability studies. This indicates an insufficient level of details needed for our research approach. Additionally, there are some network models for power flow analysis, but their sizes are too large to be implemented in Matlab Simulink. Given our problem statement,



(a) Radial network example[24]

(b) Meshed network example [25]

Fig. 3. Reference network topologies

we choose two typical European distribution network models at a medium voltage level (i.e., 10 kV). The first one is a radial network model from a Swedish test system [26], and the other one is a meshed network model from Germany [25]. The network parameters are provided in the Appendix.

The studied reference scenario, is based on Swedish data for the year 2010, i.e., there is no significant penetration of DERs. We also study two envisioned scenarios, the year 2020 and 2050, where the integration of DERs is noteworthy [4][28]. Table 3 is a summary of the studied scenarios (the penetration of DG is dependent on the peak load while that of the other two dimensions is dependent on the number of households in the studied area). Every scenario have 8 sub-cases, i.e., each scenario is performed in two different test networks and in four seasons.

Table 3. Simulation Scenarios

Scenario	Integration of different DERs
2010	$\mu_{pen}^{DG} = 10\%, \mu_{pen}^{EV} = \mu_{pen}^{AD} = 0\%$
2020	$\mu_{pen}^{DG} = 30\%, \mu_{pen}^{EV} = 20\%, \mu_{pen}^{AD} = 20\%$
2050	$\mu_{pen}^{DG} = 50\%, \mu_{pen}^{EV} = 50\%, \mu_{pen}^{AD} = 50\%,$ $\eta_{eff} = 20\%$

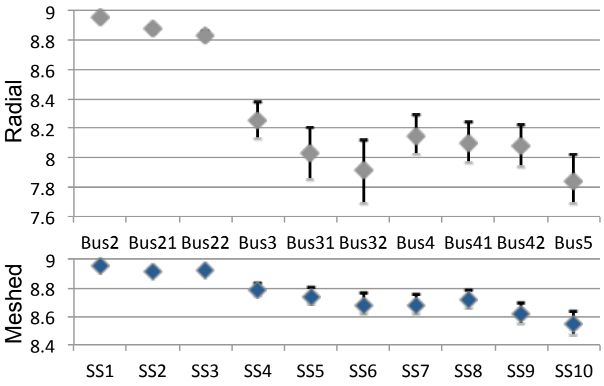


Fig. 4. Voltage profiles of Scenario 2010, winter [kV]

5. SIMULATION RESULTS

Simulations in the test networks are performed on the aforementioned models. Three different examples of voltage profiles are presented in Fig.4, Fig.5, and Fig.6. Specifically, they correspond to the winter cases for scenario 2010, 2020, and 2050. The reason to choose cases representing winter is that Sweden usually has cold winters, where there are relatively small wind production and large consumption for heating purposes. In these figures, it is observed that the voltage profile in Bus$_2$ (the radial network) and in SS$_1$ (the meshed network) have insignificant voltage drops and variations, while those on Bus$_5$ and SS$_{10}$ are of worse condition. The reason to this is a long electrical distance to these points from the external grid. The comparison of the voltage profiles on Bus$_5$ and SS$_{10}$ are summed up in Table 4. Another noticeable phenomenon is that in the radial network, Bus$_{42}$ has little voltage drop. It is because Bus$_{42}$ is connected to Bus$_3$ with a cable where the voltage drop can be compensated by the reactive power. In Table 4, V_{av} is the average value of the voltage in p.u. The nominal value is set as the average value in scenario 2010. V_{ex} is the maximal deviation from V_{av} in each case. To maintain the voltage quality, investments must

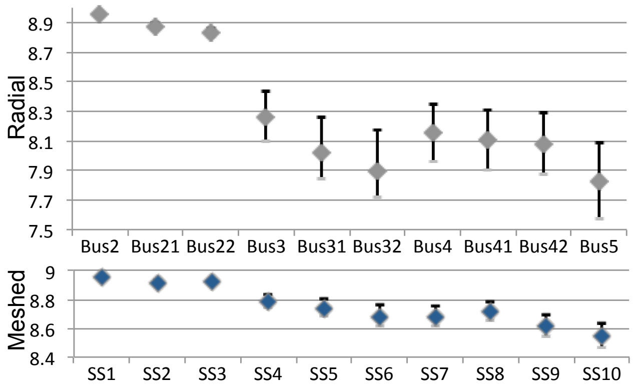


Fig. 5. Voltage profiles of Scenario 2020, winter [kV]

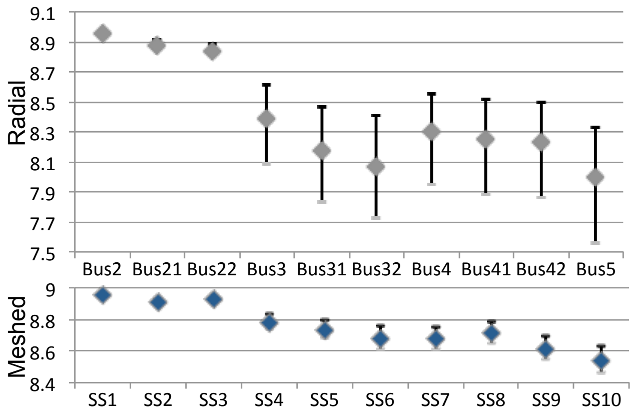


Fig. 6. Voltage profiles of Scenario 2050, winter [kV]

Table 4. Summary of voltage profiles

Scenario		Radial			Meshed	
		$V_{av[p.u.]}$	V_{ex}	Out ±5%	$V_{av[p.u.]}$	V_{ex}
2010	Spring	1	2%	0	1	1%
	Summer	1.023	4%	0	1.005	1%
	Fall	0.997	-2%	0	0.999	1%
	Winter	0.938	-9%	82%	0.984	1%
2020	Spring	1.004	3%	0	1.006	2%
	Summer	1.022	5%	0	1.006	1%
	Fall	1.002	4%	0	1.006	2%
	Winter	0.937	-9%	77%	0.987	1%
2050	Spring	1.017	6%	8%	1.015	3%
	Summer	1.024	6%	8%	1.009	2%
	Fall	1.015	7%	1%	1.015	3%
	Winter	0.957	-9%	36%	0.996	2%

Table 5. Summary of Average Power Losses

Scenario		P_{av} [kW]		Energy Loss [MWh/d]	
		Radial	Meshed	Radial	Meshed
2010	Spring	217	543	29.42	54.86
	Summer	118	514		
	Fall	232	549		
	Winter	658	678		
2020	Spring	202	512	29.19	52.32
	Summer	125	504		
	Fall	218	520		
	Winter	671	645		
2050	Spring	161	493	22.99	49.84
	Summer	120	492		
	Fall	175	509		
	Winter	502	582		

be made in additional regulating devices (such as tap changers). Hence, the probability of the voltage being beyond the range of ±5% is presented, to demonstrate the potential threat of voltage variation and how serious it is. It is concluded from the results that: (i) the voltage profiles tend to be more robust in the meshed network, comparing to its radial counterparts when DERs are deployed; (ii) there is a large chance for voltages going beyond ±5% during the winter in Sweden, which indicates that special attention must be paid to the period when the mismatch between consumption and generation is the most severe; (iii) the increased deployment of DERs reduces the voltage drop in general, whereas the trend of enlarged voltage variations may be a potential risk for the system operation.

Table 5 summarizes the power losses (P_{av} indicates the average power loss) in the different cases. The results highlight the inspiring trend that the introduction of the DERs significantly reduces the total energy losses of the studied scenarios. However, the exception occurs in the case of **Scenario 2020, radial, winter**. The underlying reason is that the increased wind production could not match the load growth introduced by EVs. This is more obvious for the meshed network due to their higher demand compared to its counterpart in the radial network. In this case, the meshed network tends to import more power from the transmission grid inevitably leading to the power losses. Besides, there is an apparent seasonal effect on power losses. In the winter season, large amount of power needs to be transmitted from the external grids to cover the unbalance between the local production and consumption.

6. CONCLUSION

This paper presents quantitative analysis of the potential changes brought by large scale deployment of DERs in European distribution networks. The contribution are two folded: First of all, we created models for DG, EV and AD for the condition and prerequisites of Sweden. Secondly, we performed quantitative simulations of different DER deployment in two different network models. The output of the simulations reflected the voltage variations and power losses incurred by the DERs. In general, the introduction of DER could reduce the power losses and voltage drop by limiting power transferred from the centralized and remote sites.

However, it must be noted that the opposite results can happen, due to the uncertain characteristics of the DERs. It is tempting to apply our models and methodology to study other DER development scenarios in the future. The research output could potentially be used to foresee the potential benefits and challenges for the upcoming smart grid business cases (e.g., the Aggregator role [29][30]) related to the deployment of DERs.

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8. APPENDIX

Table 6. Network Data

Parameter		Value
Power factor		0.9
Overhead line	R	0.63[Ω/km]
	L	1.3[mH/km]
	C	10[nF/km]
Underground cable	R	0.16[Ω/km]
	L	3.2[mH/km]
	C	3.0[μF/km]
Cable/Line		1/3
Transformer	Type	Yg-D11
	HV	60[kV]
	MV	10[kV]
	P_{rate}	50[MVA]
	P_{loss}	265[W]
	R_s	0.01[p.u.]
	X_{sc}	0.06[p.u.]
External grid	Cap.	100MVA
	X/R	10

Network	Radial	Mesh
Peak load	13MVA	22MVA
Load points	7	8
Gen. points	3	2
Households	3800	1800