Residential Grid Integration of Solar Photovoltaics and Electric Vehicles

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***Abstract*—In the last few years, there is an increased penetration of solar photovoltaic (SPV) units in low voltage (LV) distribution grids. Also electric vehicles (EVs) are introduced to these LV networks. This has caused the distribution networks to be more active and complex as these local generation and load units are characterised by unpredictable and diverse operating characteristics. This paper analyses the combined effect of SPVs and EVs in LV Danish residential grids. The EVs charging needs based on typical driving patterns of passenger cars and SPV power profiles during winter/summer days are used to determine any resultant grid congestions. Simple grid reinforcement measures like modifying feeder layouts are applied in this work to verify improvements in grid bottlenecks. The results of the analyses show that the SPV and EV combination can complement each other in improving the grid voltage profiles, especially during the high demand hours in summer.**

***Index Terms*-- driving patterns, electric vehicles, low voltage residential grids, grid congestions, solar photovoltaic.**

I. Introduction

The primary distribution grids in Denmark is characterised by large penetration of dispersed generation units like wind turbines and combined heat and power units (CHPs). In the Western Danish part, more than 50% of the installed generation capacity and electricity are supplied by these units [1]. In 2011, an annual average of 29% of the Danish electricity demand is delivered from wind power [2]. Further, it is planned to achieve 50% annual wind power production by 2020 as part of the Danish energy policies [3]. As one of the major solutions to support the large integration of variable and unpredictable wind power in the electricity system, local flexible generation and demand units (SPVs, micro CHPs, EVs, heat pumps etc.) coordinated and controlled by 'smart grids' are widely promoted [4]. In 2011, the installed capacity of SPV has increased by 74% world-wide [5]. In Denmark, during the past several months, many residential consumers have installed grid-connected SPV units (6kW capacity). This is triggered by the reasonable capital costs of the SPV units and the "net-metering" provision available for solar electricity by using "grid as storage" [6]. The consumers earn 0.08 ¢€/kWh for any surplus electricity fed to the low voltage grids. On the other hand, the EVs which are representative of future clean transportation and flexible demand/storage in smart grids are likely to penetrate significantly in the LV grids. They are of sizeable loads in the range of approximately 3kW-11kW and are expected to charge during the peak and off-peak hours. These scenarios of large power infiltrations and variations is highly challenging to the local grid operation where it may become difficult to manage voltages, grid congestions and power quality.

The use of coordinative and optimal charging of EVs applied in view of future smart grid technology provides more flexibility to the EVs to deliver grid ancillary services [7]-[9]. The integration levels of EVs in existing local distribution grids are dependent on the capacity limits of the feeders and components and operating thresholds [10]-[12]. As distributed generation units, the SPV units can provide key grid support functions like voltage regulation, loss reduction etc. [13], [14]. However, the degree of support and penetration level depends on the strength and load diversity of the local grid [15]-[17]. The objective of this work is to quantify the impact assessment of integrating SPV and EV units together in detailed models of two local residential grids. The grid bottlenecks that may result from the high penetration of these units can determine the hosting capacity and ruggedness of the grids. Simple grid re-configuration measures like splitting the existing feeders is also analysed in this work to verify the resultant improved network operation.

II. Case Study

The two LV networks studied in this work are residential grids in Denmark. The full circuit model representation of the two grids is given in Appendix as Fig AI and Fig. AII[12]. There are in total 166 households, six feeders in Grid I and the total transformer capacity is 630kVA. In order to simply the network diagram, the household loads under each cable box are aggregated as a single load. The Grid I configuration is normally operated as radial. However, the feeders can be connected as ring structures by closing cables between them (tie points). Grid II has 75 household connections, five feeders and the total transformer capacity is 400kVA. The key parameters and data of the transformer and cables are provided in [12]. Each household (H) is connected to a cable box (B) in Fig. AI and Fig. AII through three phase, 35A fuse supply. The households are single residences without electric heating and the annual average demand is approximately 4,200kWh. The aggregated load profiles (transformer level) of two grids for summer and winter weeks are depicted in Fig. 1. The winter days are characterised by high power consumption compared to the summer days in Denmark. Also the average utilisation of the transformer capacity is below 20% as the trend of household demand remained more or less flat over the last two decades in Denmark [18].

III. SIMULATION SCEANRIOS

In Denmark, an average of 1,800 hours of sunshine is estimated annually with a global irradiation of 1,000kWh/m^2 [19]. Most of the sunny days are prevalent during the period from April to July. Fig. 2 shows the SPV power produced from a 6kW unit during a winter and summer week. In this paper, it is assumed that all the households in the LV grids are installed with SPV units of 6kW which follows the power profile given in Fig. 2. The SPV units are modeled as constant negative PQ loads operating at unity power factor. The EVs are considered to be charged at maximum 11kW through a three phase, 16 A charger at each household. The EVs are modeled as constant power loads opearting at unity power factor. In a previously conducted study [12], the maximum integration levels of 11kW EVs per household in the two LV grids are 6% and 27% respectively during the peak demand period. In a real scenario, the charging power of EVs depends on the connection status/period (availability based on leaving and arrival time) and need for charging (battery state-of-charge determined from the driving distances of pasenger cars). This study considers a typical weekly driving pattern and the distribution of cars [20] to determmine the charging needs of EVs. Also the EVs are assumed to start charging as soon as they arrive home. Power system steady state analysis are conducted in this study to simulate various scenarios of analysing the impact of SPVs and EVs in the two LV grids using DIgSILENT Power Factory software. The period of high and peak demand hours of electricity (15:00-20:00 hrs) are considered here for simulation studies. These hours are also characterised by the coincident period where more than 80% EVs arrive home and 60% of solar power is produced. The grid congestions and capacity violations in the two grids are analysed here for four different cases in this study a) H load (Ref.) b) SPVs + H load c) EVs (charging) + H load and d) SPVs + EVs + H load.

IV. RESULTS AND DISCUSSIONS

Fig. 3 shows the EV distribution in the two grids based on their arrival time. This has resulted from applying the Gaussian distribution with a mean of 16:00 hours and a standard deviation of 2 hours. Based on the typical Danish

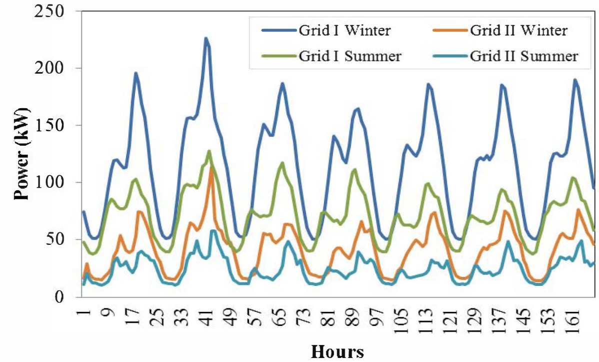

Fig. 1 Winter and summer week load demand profile of two LV grids

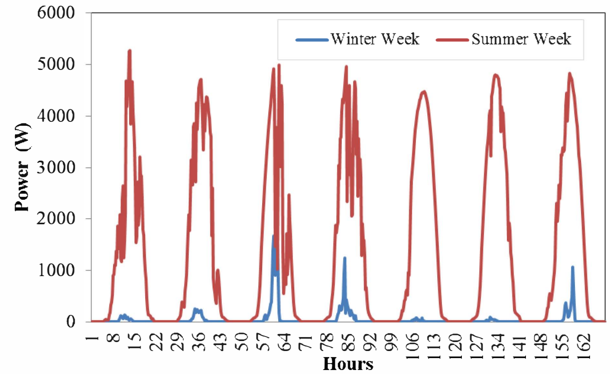

Fig. 2 SPV power profile for winter and summer week

driving distances of passenger cars in Denmark presented in [20], the average driving distance is less than 30km and 75% of the cars are driven less than 40km a day. The random charging needs of the EVs are generated by applying an uniform distribution of the driving statistics in [20] with a given driving distance resolution of 10km and a typical EV driving efficieny of 0.15kWh/km. Table I gives the charging profile of EVs calculated in the two LV grids for a weekday (day 3) and weekend day (day 7) in Fig. 2. An average of approximately 60% and 40% EVs needs charging during these two days respectively.These two days are characterised by high number of EVs that needs to be charged and higher solar power production, especially during the winter days in Fig. 2. This is relevant for analysing the combined interaction between EVs and SPVs in the grid. Applying 4 different cases as mentioned in Section III, the parameters that reflects the primary grid bottlenecks like cable box voltages, cables and transfomer loading are computed using static power system simulations. Table II shows the voltages of two cable boxes, one each from the two LV grids which are the worst affected from SPV and EV integration. The farthest cable boxes in the weak feeders of Grid I (Feeder 6 – B54) and Grid II (Feeder 4 – B27) produce the largest voltage deviations from the normal limit of ±10% (EN 50160 std.). These weak feeders are characterised by the large number of household connection and long cables as compared to other feeders. The results are presented for six hours (15:00-20:00) for the two selected days (day 3&day 7). For the winter days, the peak demand hour (17:00 hrs) provides the largest voltage drop of 0.88 pu at Grid I - B54, due to EV charging demand.

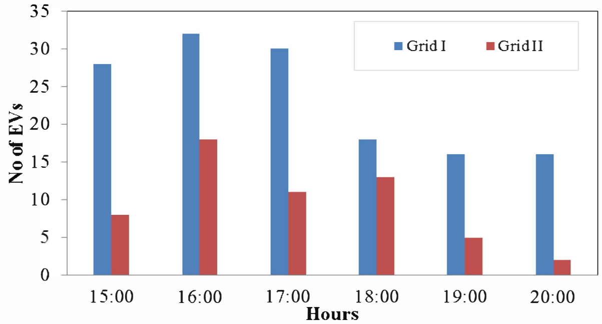

Fig. 3 EV distribution based on arrival times in the two LV grids

The summer days which are characterised by high SPV power production and low household demand (15:00 hrs) results in highest voltage rise of 1.13 pu at Grid I – B54. The voltage drops during some hours of the winter days (15:00hrs - WWD & WWE and 16:00 hrs – WWD) for the case with EV charging are reduced when the SPV units produces power. As the remaining hours does not have enough solar power production, the voltage drops for SPV+EV combination remains the same as the EV case. For most of the summer hours considered in this study, the voltage rise from SPV simulation cases are reduced from combining EV charging and SPV power production in the grids. These improvements in voltage profiles during summer hours and some winter hours display the complementary effect of EVs and SPV units operating together in the distribution grids.

Simple grid reinforcement steps like splitting weak feeders in the two LV grids are performed. In Grid 1, a new cable is connected from the transformer secondary to B48 of the existing feeder 6 and cable C48 is opened to act as an open tie point. Similarly in Grid 2, the cable box B21 is split into two, where a new cable box B21x has a new cable connected from the transformer secondary. This cable connects the households (16 Nos.) under cable boxes, B23 to B27. The voltage profiles of the peak demand hour (17:00 hrs) for the winter days and the hour with high SPV power production (15:00 hrs) for the summer days, after splitting the feeders are given in Table III. Comparing the voltages of these specific hours in Table II, the grid reconfigurations has improved the voltages for all the cases of EV and SPV integration and all voltages are within the standard operating thresholds. The results of active power losses are multiplied for the increased penetration of EV and SPV units when compared to the reference case. However the average percentage losses of these grids with these new units lies around 2-3% which is reasonable based on the higher grid capacity utilisation. The cable loadings in both grids for all the simulation cases are within the thermal ratings. An average maximum loading of 80% has resulted in some of grids cables for the cases with integration of SPV units and combined SPV and EV units. The transformer loading for the winter peak demand hour (17:00 hrs) and high solar power production hour (15:00 hrs) are depicted in Fig. 4. The transformer is loaded the same for both the reference and SPV case for the winter days, as there are no solar power produced during those hours.

TABLE I
DISTRIBUTION OF EV CHARGING DEMAND IN THE TWO LV GRIDS

EV charging demand kWh	**No. of EVs**			
	Grid – I Weekday	***Grid – I Weekend***	***Grid – II Weekday***	***Grid – II Weekend***
0	61	91	30	47
1.5	15	20	12	4
3	16	9	9	5
4.5	21	9	5	4
6	8	6	2	3
7.5	9	6	3	3
9	7	4	4	1
10.5	8	2	1	1
12	5	0	1	1
13.5	1	0	0	1
15	7	4	1	1
22.5	3	6	2	1
30	3	3	3	1
37.5	2	2	1	1
45	0	4	1	1

The additional demand from EV charging results in the increasing transformer loading for the EV simulation case. For the summer hours, as the SPV units produce more than 80% of the rated power, the transformers are loaded closer to its ratings.This is reduced when the EVs are charged in the grids consuming the power produced locally from the SPVs. However, the solar power production during these hours are in excess after meeting the local grid demand which are fed to the external grid. Some of the other simple and advanced solutions to mitigate the voltage violations, transformer loading and reverse power include transformer on-load tap changers, voltage regulators along feeders, preemptive control and coordination of generation and demand using real-time communication etc. The findings in this study provides a measure of the present grid capability to handle high penetration of new units like SPVs, EVs etc. and to take corrective actions to ensure the power quality and reliability of the grid supply.

V. CONCLUSIONS

The LV distributions grids are increasingly penetrated with large number of units like SPVs, EVs etc. which have variable and diverse operating characteristics. This paper investigates the combined effect of SPVs and EVs in two detailed models of LV residential grids. The typical driving characteristics of EVs, winter and summer power profiles of SPVs are used in this study. The two grids are characterised by a few number of weak feeders where the voltage limit violations are minimised due to the balancing effect of SPV power generation and EV charging, particularly during peak demand hours of summer days. Simple measures of splitting the weak feeders in the grids have improved the voltage profiles. These impact assessment studies enable the system utilities to understand and implement remedial actions and additional grid reinforcement measures. The additional investments and the level of smart technologies that is required to control and coordinate such distributed local resources are relevant for effective planning and operation of future smart distribution systems.

TABLE II
VOLTAGES AT CRITICAL CABLE BOXES IN GRID I AND GRID II

Hours	Grid I – Feeder 6 (B54)								Grid II – Feeder 4 (B27)							
	Ref	*EV*	*SPV*	*EV + SPV*	*Ref*	*EV*	*SPV*	*EV + SPV*	*Ref*	*EV*	*SPV*	*EV + SPV*	*Ref*	*EV*	*SPV*	*EV + SPV*
Day 3	*Winter weekday (WWD)*				*Summer weekday (SWD)*				*Winter weekday (WWD)*				*Summer weekday (SWD)*			
15:00	0.94	0.9	0.95	0.92	0.96	0.92	1.12	1.09	0.97	0.96	0.97	0.97	0.99	0.97	1.12	1.10
16:00	0.94	0.92	0.95	0.94	0.96	0.94	1.11	1.09	0.97	0.94	0.97	0.94	0.98	0.97	1.06	1.04
17:00	0.94	0.88	0.94	0.88	0.96	0.89	1.07	1.01	0.96	0.92	0.96	0.92	0.97	0.95	1.05	1.03
18:00	0.95	0.88	0.95	0.88	0.97	0.88	1.05	0.98	0.96	0.94	0.96	0.94	0.97	0.95	1.06	1.04
19:00	0.95	0.9	0.95	0.9	0.97	0.92	1.03	0.99	0.96	0.96	0.96	0.96	0.97	0.97	1.02	1.01
20:00	0.96	0.94	0.96	0.94	0.97	0.95	0.99	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	0.99
Day 7	*Winter weekend day (WWE)*				*Summer weekend day (SWE)*				*Winter weekend day (WWE)*				*Summer weekend day (SWE)*			
15:00	0.96	0.94	0.96	0.96	0.97	0.96	1.13	1.12	0.98	0.96	0.98	0.97	0.98	0.96	1.09	1.07
16:00	0.94	0.92	0.94	0.92	0.97	0.95	1.08	1.07	0.97	0.96	0.97	0.96	0.99	0.97	1.08	1.06
17:00	0.93	0.89	0.93	0.89	0.97	0.93	1.08	1.05	0.97	0.93	0.97	0.93	0.98	0.94	1.01	0.97
18:00	0.94	0.91	0.94	0.91	0.97	0.94	1.09	1.07	0.96	0.95	0.96	0.95	0.98	0.97	1.04	1.03
19:00	0.94	0.92	0.94	0.92	0.97	0.95	1.03	1.02	0.96	0.96	0.96	0.96	0.97	0.97	1.02	1.01
20:00	0.95	0.93	0.95	0.93	0.97	0.96	0.99	0.97	0.96	0.97	0.96	0.97	0.98	0.98	0.99	0.99

TABLE III
VOLTAGES AT CRITICAL CABLE BOXES AFTER SPLITTING FEEDERS

Hours	Grid I – cable box B54				Grid II – cable box B27			
	Ref	*EV*	*SPV*	*EV+ SPV*	*Ref*	*EV*	*SPV*	*EV+ SPV*
WWD_ 17:00	0.95	0.91	0.95	0.91	0.98	0.96	0.98	0.96
WWE _17:00	0.94	0.92	0.94	0.92	0.98	0.95	0.98	0.95
SWD _15:00	0.97	0.93	1.08	1.06	0.99	0.99	1.08	1.06
SWE _15:00	0.98	0.97	1.1	1.08	0.99	0.97	1.05	1.03

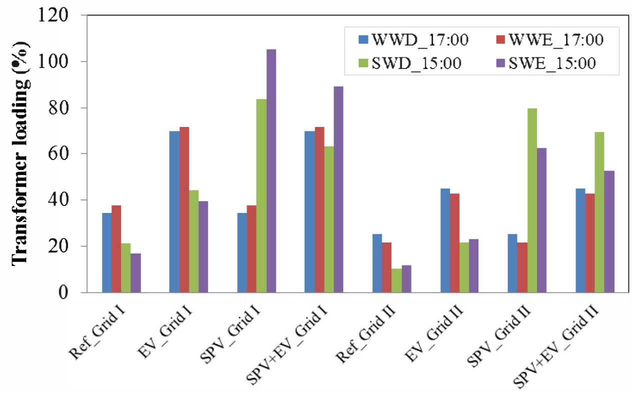

Fig. 4 Loading of Transformer in the two LV grids for different simulation cases and selected hours

VI. APPENDIX

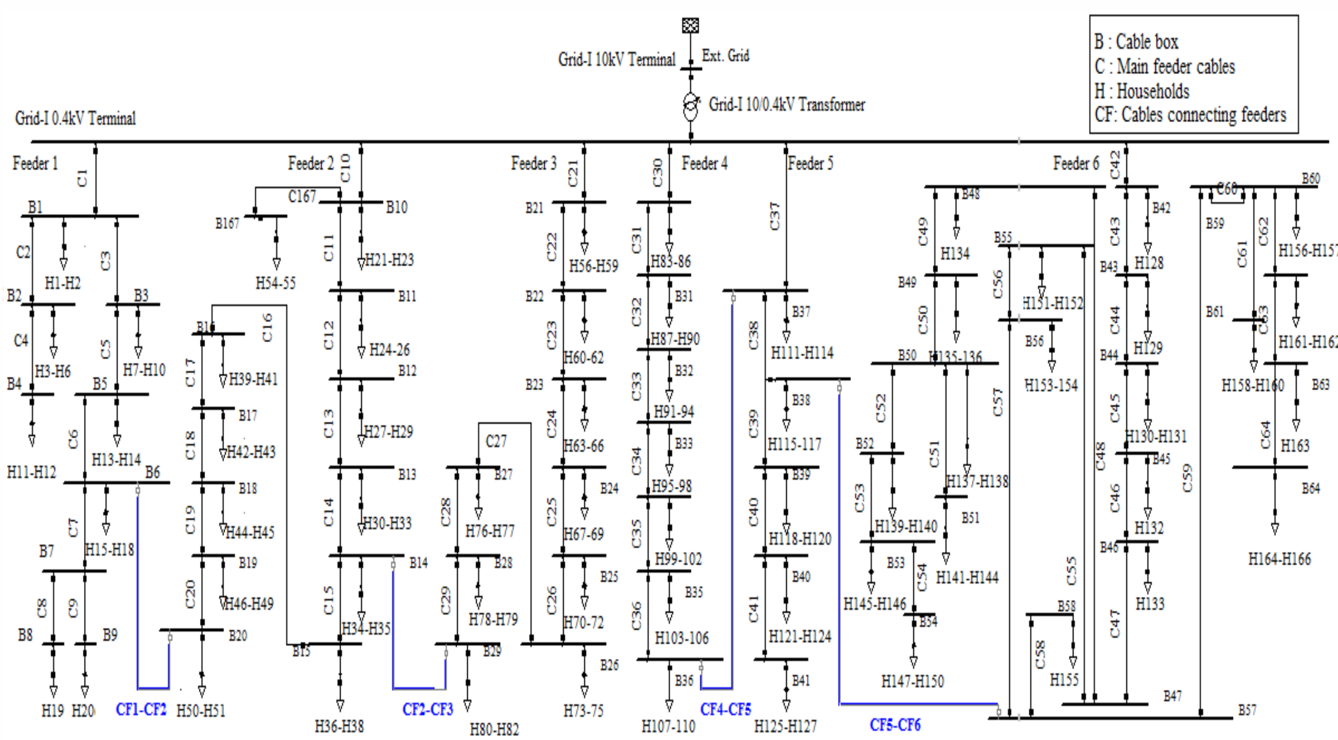

Fig AI. Grid I - Residential grid model [12]

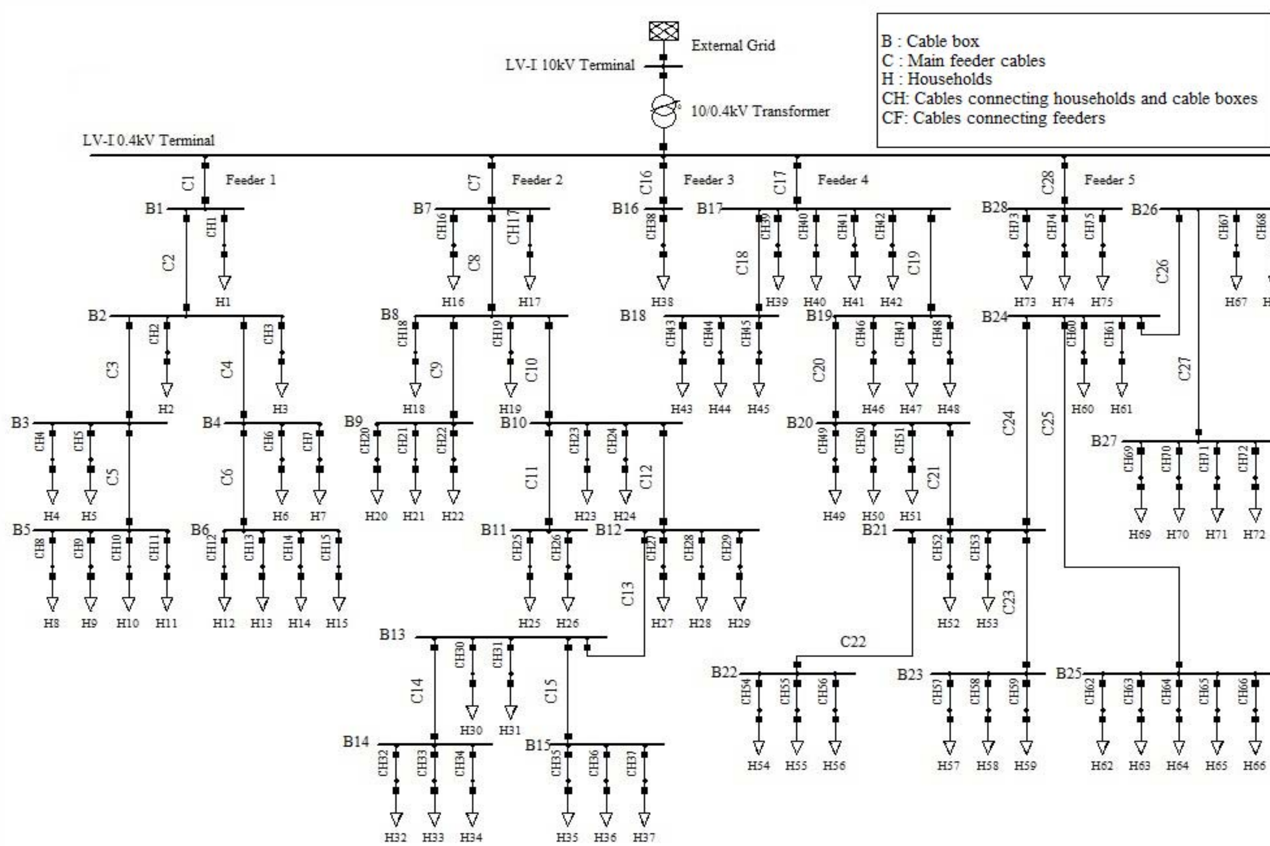

Fig. AII Grid II - residential grid model [12]

REFERNCES

[1] P. Lund, "The Danish Cell Project - Part 1: Background and General Approach", *Proc. IEEE PES General Meeting*, Tampa, USA, June 2007.

[2] Energinet.dk. (2012, Dec.). [Online]. Available: http://www.energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx

[3] Energinet.dk. (2011, Dec.). System Plan 2011. [Online]. Available: http://energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/Om%20os/Systemplan_2011_gb.pdf

[4] Energinet.dk. (2010.). Smart grid in Denmark. [Online]. Available: http://www.energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/Forskning/Smart%20Grid%20in%20Denmark.pdf

[5] REN 21. (2012.). Renewables 2012 Global Status Report. [Online]. Available: http://www.map.ren21.net/GSR/GSR2012_low.pdf

[6] Energinet.dk. (2012, Dec.). [Online]. Available: http://www.energinet.dk/DA/El/Solceller-og-andre-VE-anlaeg/Privat/Sider/default.aspx

[7] K. Clement-Nyns, E. Haesen, J. Driesen, "The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid," *IEEE Trans. on Power Systems*, vol. 25, pp.371-380, Feb. 2010

[8] N. Rotering and M. Ilic, "Optimal Charge Control of Plug-In Hybrid Electric Vehicles in Deregulated Electricity Markets," *IEEE Trans. Power Systems*, vol.26, pp.1021-1029, Aug. 2011

[9] J. R. Pillai and B. Bak-Jensen, "Integration of vehicle-to-grid in the Western Danish power system," *IEEE Trans. Sustainable Energy*, vol.2, no. 1, pp. 12–19, Jan. 2011.

[10] L. P. Fernández; T. Román, R. Cossent, C. M. Domingo, and P.Frías, "Assessment of the Impact of Plug-in Electric Vehicles on Distribution Networks," *IEEE Trans. Power Systems*, vol. 26, pp. 206-213, Feb. 2011.

[11] P. Richardson, D. Flynn, and A. Keane, "Optimal Charging of Electric Vehicles in Low-Voltage Distribution Systems", *IEEE Trans. Power Systems*, vol. 27, No. 1, pp. 269-279, Feb. 2012.

[12] J. R. Pillai, P. Thøgersen, J. Møller, B. Bak-Jensen, "Integration of electric vehicles on low voltage Danish residential grids," in *Proc. IEEE PES General Meeting*, San Diego, Jul. 2012.

[13] T. Hoff and D.S. Shugar, "The value of grid-support photovoltaics in reducing distribution system losses," *IEEE Trans. on Energy Conversion*, vol. 10, pp. 569 - 576, Sep 1995

[14] B.H. Chowdhury and A.W. Sawab, "Evaluating the value of distributed photovoltaic generations in radial distribution systems," *IEEE Trans. on Energy Conversion*, vol. 11, pp. 595 - 600, Sep 1996

[15] R.Tonkoski, D. Turcotte, T.H.M. El-Fouly, "Impact of High PV Penetration on Voltage Profiles in Residential Neighborhoods," *IEEE Trans. on Sustainable Energy*, vol. 3, pp. 518 - 527, July 2012

[16] P.R. Caroselli, A.M. Dinkel, J.Q. Liu, R.N. Sackey, N.R. Vadhar, "Integrating Solar Generation on the Electric Distribution Grid," *IEEE Trans. on Smart Grid*, vol. 3, pp. 878 - 886, June 2012

[17] E. Demirok, D. Sera, R. Teodorescu, "Estimation of Maximum Allowable PV Power Connection to Low Voltage Residential Networks: A Case Study of Braedstrup," 1st International Workshop on the Integration of Solar Power into Power Systems Aarhus, Denmark, 24 October 2011.

[18] Danish Energy Agency. (2011, Nov.). Energy Statistics 2010. [Online]. Available: http://www.ens.dk/en-US/Info/FactsAndFigures/Energy_statistics_and_indicators/Annual%20Statistics/Documents/Energy%20Statistics%202010.pdf

[19] SolEnergicentret. (2012, Dec.). [Online]. Available: http://www.solenergi.dk/SEC/visTekst.asp?id=62

[20] W. Qiuwei, A.H. Nielsen, J.Østergaard, T. C. Seung, F. Marra, Chen Y, and C. Træholt, "Driving Pattern Analysis for Electric Vehicle (EV) Grid Integration Study," *in Proc. 2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe),* Gothenburg, Oct. 2010.