Technical University of Denmark

Potential Analysis of Regulating Power from Electric Vehicle (EV) Integration in Denmark

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Potential Analysis of Regulating Power from Electric Vehicle (EV) Integration in Denmark

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***Abstract*— The potential analysis of having electric vehicles (EVs) provide regulating power has been implemented. The possible regulating power capacity from EVs and the economic return for EV users by providing regulating power are obtained. A spot price based charging schedule scenario has been used to do the day-ahead charging schedule for all EVs based on the predicted driving pattern. On top of the obtained charging schedule, the predicted EV availability and the charging schedule are used to calculate the possible regulating power capacity from EVs for both up regulating power and down regulating power. The activated regulating power and regulating power prices in the Denmark West System in 2010 have been used to calculate the economic return for EV users if all the regulating power is provided by EVs.**

***Index Terms*— Electric Vehicle (EV), Regulating Power, Driving Pattern, Spot Price, Up Regulating Power, Down Regulating Power**

I. Introduction

With more and more renewable energy integrated into power systems, it has become an attractive option to use electric vehicles (EVs) to balance the uncertainties introduced by renewable energy. At the same time, replacing conventional internal combustion engine (ICE) vehicles with EVs can help reduce the "green house" gas emission from the transport sector and the dependence of transport on petroleum.

Denmark is a unique place for renewable energy utilization and EV deployment. At this moment, the wind power penetration level in Denmark is around 20%. The Danish government has set a target of having 50% penetration of wind power in 2025 [1].The average driving distance in Denmark is 29.5 km per day [2]. It is possible to meet the driving requirement for one day with a fully charged 20 kWh battery. Therefore, from the perspectives of balancing the fluctuation introduced by renewable energy and meeting the driving requirements, it is an interesting option to implement the idea of integrating EVs into the power systems.

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The possibility of using vehicle to grid (V2G) to improve wind power integration was studied in [3]. The traffic data were used to calculate the vehicle fleet availability. It was concluded that it is possible to have EVs providing instantaneous disturbance and manual reserve to help integrate more wind power. The feasibility study of implementing V2G scenario in Denmark was done in [4]. The system constraints for integrating EVs into power systems were examined and the technical and economical viability of various possible V2G architectures were studied. It was concluded that the V2G technology can assist in realizing the Danish government goal of "50% of the total energy consumption to be met by wind power in 2025". A vehicle to grid demonstration project was implemented in AC Propulsion Inc. to evaluate the feasibility and practicality of EVs providing regulation service [5]. A test vehicle was fitted with a bi-directional grid power interface and wireless internet connectivity to carry out the demonstration. It was shown that it is feasible for EVs to provide regulation service from a technical and economical point of view.

Three types of EVs were studied in [6] to check the feasibility of V2G concept from economic perspective and the four markets were used to carry out the quantitative analysis of the economic return for EV users by providing V2G service. It was concluded that EVs should participate in the ancillary service market to be profitable by providing ancillary service. It was studied in [7] that under what conditions plug-in hybrid electric vehicles (PHEVs) can generate revenues. The actual data of four months in 2008 in Germany and Sweden were used to do the analysis.

In this paper, the potential of using EVs to provide regulating power in Denmark were investigated using the driving pattern data and the regulating power market data to obtain the regulating power capacity from EVs and the economic return for EV users.

The rest of the paper is arranged as follows. The day-ahead spot price based EV charging schedule was presented in Section II. In Section III, the regulating power capacity from EVs in Denmark East (DKEast) and Denmark West (DKWest) were calculated and presented. The regulating power requirement and price analysis and the economic return for EV users were implemented for DKWest and the results were depicted in Section IV and Section V, respectively. In the end, a brief conclusion was drawn for the study that has been done for the potential analysis of regulating power from EVs.

II. Day-Ahead EV Charging Schedule based on Spot Price

The purpose of the EV charging schedule based on spot price is to meet the charging requirements of all EVs at the minimum cost with estimated spot prices and estimated EV driving information.

In the charging schedule study, the low power charging option is considered. Three low power charging options were used to do the charging schedule which are 1 Ph 10 A charging, 1 Ph 16 A charging and 3 Ph 16 A charging. The details of the three options are listed in TABLE I.

TABLE I
Proposed EV Low Power Charging Methods

Charging Method	Charging Specification	Charging Power (kW)	Charging Time (Hours)
Method 1	1 Ph 10 A	2.3	5.65
Method 2	1 Ph 16 A	3.68	3.53
Method 3	3 Ph 16 A	11.04	1.18

In [8], it is recommended that the SOC of EV batteries should be below 20% in order have a satisfactory battery lifetime and the SOC of EV batteries is approximately 85% at the end of constant current charging. The charging times are 5.65 hours, 3.53 hours and 1.18 hours for Method 1, Method 2 and Method 3, respectively.

The personal car numbers are 1.21 million in DKWest and 0.89 million in DKEast, respectively [9]. These two numbers were used for the EV charging study.

The driving pattern analysis in Denmark has been done using the Danish National Transport Survey data and the results were presented in [2]. The availability is shown in Fig. 1. The EV availability data were used for the spot price based EV charging study and the regulating power capacity calculation.

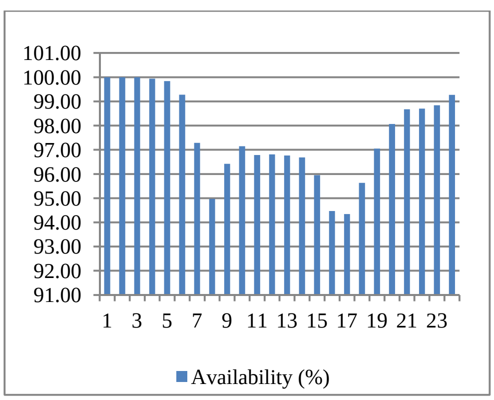

Fig. 1 EV Hourly Availability Data [2]

In order to avoid putting the EV charging load on high demand hours and increase the EV penetration level without putting extra stress on existing power systems, a spot price based charging schedule method was used. The idea is to smooth the demands as much as possible for the time periods when EVs are doing charging. The charging time periods are chosen as 00:00 am – 06:00 am and 10:00 pm to 12:00 am based on the spot price analysis. The demands for these time periods will be same for the chosen charging time periods unless the resultant demand is less than the original demand.

The system demands with and without EV charging for DKWest and DKEast for different EV penetrations are shown in Fig. 2 and Fig. 3, respectively. The system demands with the proposed spot price based EV charging schedule method show that the EV penetration level can be up to approximately 70% without putting extra stress on the existing power system.

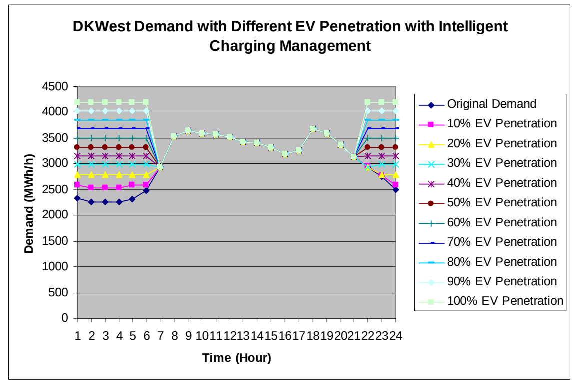

Fig. 2 DKWest System Demands with Different EV Penetrations

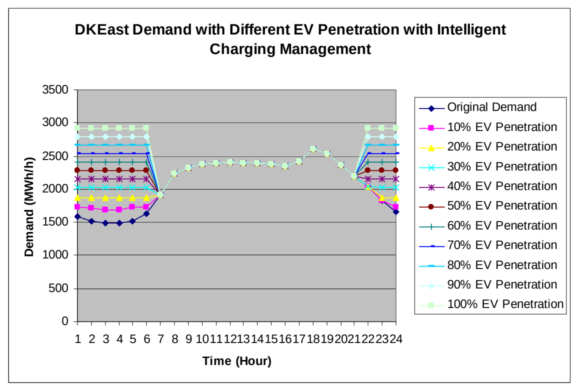

Fig. 3 DKEast System Demand with Different EV Penetration

III. Regulating Power Capacity Analysis from EVs

In the Nordic countries there is a common regulating market managed by the TSOs with a common merit order bidding list. The balance responsible parties (for demand or generation) make bids consisting of amount (MW) and price (DKK/MWh). All bids for delivering regulating power are collected in the common Nordic NOIS-list and are sorted in a list with ascending prices for up regulating power (above spot price in the same hour), and descending prices for down regulating power (below spot price in the same hour). Taking into consideration the potential congestions in the transmission system, the TSO manages the activation of the cheapest regulating power [10].

The regulating power capacity analysis is to determine the maximum possible regulating power capacity for the three charging methods with different EV penetration. In the EV charging schedule study based on spot price, the conclusion is that the EV penetration level limit is approximately 70% without putting extra stress on the existing power systems with the proposed spot price based charging schedule method. This limit was used to determine the maximum possible regulating power capacity for the three charging methods. The available regulating power capacities with lower EV penetration levels were obtained as well.

In order to calculate the available regulating power capacity from EV systems, the driving pattern analysis results were used to get the available EVs in each hour of a day.

The regulating power from EVs consists of both up regulating power and down regulating power. The up regulating power can be provided by releasing charging schedule or feeding power back to grid (V2G).

Based on the charging schedule study, the EVs which are doing charging at each hour are calculated for the spot price based charging scenario. This group of EVs can provide up regulating power by releasing charging. The EVs which do not have charging schedule can provide up regulating power by feeding power back to grid. The total up regulating power capacity is the sum of the two up regulating power from EVs.

The down regulating power can be provided by charging the EVs which do not have a charging schedule in a specific hour.

Since DKWest and DKEast are connected to different synchronizing zones, the regulating power capacity analysis was done for DKWest and DKEast separately.

A. DKEast Regulating Power Capacity from EVs

The up regulating power and down regulating power capacities from EVs in DKEast for Method 1 are shown in Fig. 4 and Fig. 5, respectively. The plots for Method 2 and Method 3 have the same pattern and are skipped in order to avoid redundancy.

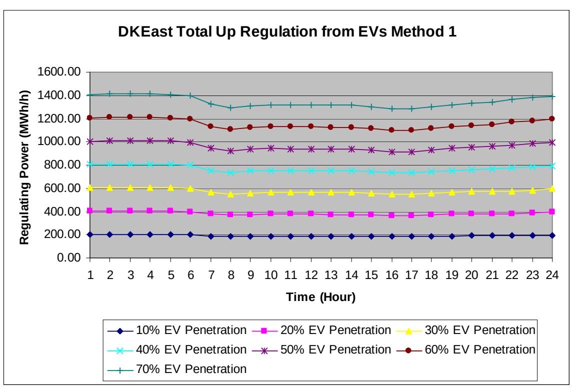

Fig. 4 DKEast Up Regulating Power from EVs Method 1

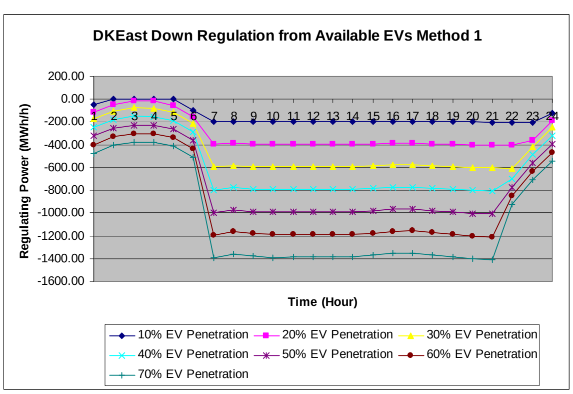

Fig. 5 DKEast Down Regulating Power from EVs Method 1

Table II
DKEAST MAXIMUM UP REGULATING POWER FOR METHODS 1, 2 AND 3

EV Penetration Level	method 1 (MWh/h)	mehtod 2 (MWh/h)	method 3 (MWh/h)
10%	204	322	944
20%	408	654	1883
30%	609	981	1883
40%	810	1276	3761
50%	1010	1593	4699
60%	1211	1910	5637
70%	1412	2227	6576

Table III
DKEAST MINIMUM UP REGULATING POWER FOR METHODS 1, 2 AND 3

EV Penetration Level	method 1 (MWh/h)	mehtod 2 (MWh/h)	method 3 (MWh/h)
10%	183	293	879
20%	366	617	1758
30%	549	925	2638
40%	733	1172	3517
50%	916	1465	4396
60%	1099	1758	5275
70%	1282	2051	6154

Table IV
DKEAST MAXIMUM DOWN REGULATING POWER FOR METHODS 1, 2 AND 3

EV Penetration Level	method 1 (MWh/h)	mehtod 2 (MWh/h)	method 3 (MWh/h)
10%	-202	-323	-970
20%	-403	-645	-1936
30%	-605	-968	-2905
40%	-807	-1291	-38726
50%	-1008	-1613	-4840
60%	-1210	-1936	-5807
70%	-1412	-2258	-6775

Table V
DKEAST MINIMUM DOWN REGULATING POWER FOR METHODS 1, 2 AND 3

EV Penetration Level	method 1 (MWh/h)	mehtod 2 (MWh/h)	method 3 (MWh/h)
10%	0	-93	-747
20%	-16	-261	-1569
30%	-76	-444	-2406
40%	-149	-640	-3256
50%	-225	-839	-4108
60%	-302	-1037	-4960
70%	-378	-1236	-5812

The maximum and minimum of up regulating power and down regulating power for Methods 1, 2 and 3 with different EV penetrations are listed in Table II and Table V. The maximum up regulating power capacities in DKEast is 6576 MWh/h with 70% EV penetration and Method 3, and the minimum up regulating power is 183 MWh/h with 10% EV penetration and Method 1. The maximum down regulating power capacities in DKEast is -6775 MWh/h with 70% EV penetration and Method 3, and the minimum up regulating power is 0 MWh/h with 10% EV penetration and Method 1.

B. DKWest Regulating Power Capacity from EVs

The up regulating power and down regulating power capacities in DKWest for Method 1 are shown in Fig. 6 and

Fig. 7, respectively. The plots for Method 2 and Method 3 have the same pattern and are skipped in order to avoid redundancy.

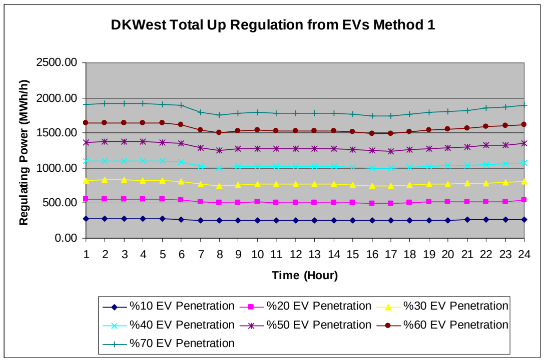

Fig. 6 DKWest Total Up Regulating Power from EVs Method 1

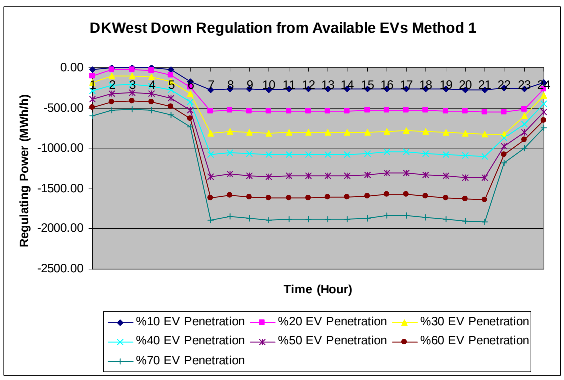

Fig. 7 DKWest Down Regulating Power from EVs Charging Method 1

Table VI

DKWest Maximum Up Regulating Power for Methods 1, 2 and 3

EV Penetration Level	method 1 (MWh/h)	mehtod 2 (MWh/h)	method 3 (MWh/h)
10%	277	438	1281
20%	554	870	2557
30%	827	1302	3832
40%	1099	1732	5106
50%	1372	2163	6380
60%	1644	2593	7654
70%	1916	3024	8928

Table VII

DKWest Minimum Up Regulating Power for Methods 1, 2 and 3

EV Penetration Level	method 1 (MWh/h)	mehtod 2 (MWh/h)	method 3 (MWh/h)
10%	249	398	1194
20%	497	796	2388
30%	746	1194	3581
40%	995	1592	4775
50%	1244	1990	5969
60%	1492	2388	7163
70%	1741	2786	8357

Table VIII

DKWest Maximum Down Regulating Power for Methods 1, 2 and 3

EV Penetration Level	method 1 (MWh/h)	mehtod 2 (MWh/h)	method 3 (MWh/h)
10%	-274	-439	-1317
20%	-548	-876	-2629
30%	-822	-1315	-3944
40%	-1095	-1752	-5257
50%	-1369	-2190	-6571
60%	-1643	-2629	-7886
70%	-1917	-3067	-9200

Table IX

DKWest Minimum Down Regulating Power for Methods 1, 2 and 3

EV Penetration Level	method 1 (MWh/h)	mehtod 2 (MWh/h)	method 3 (MWh/h)
10%	0	-129	-1017
20%	-20	-353	-2129
30%	-102	-601	-3265
40%	-211	-877	-4428
50%	-314	-1146	-5586
60%	-41	-1416	-6744
70%	-520	-1686	-7901

The maximum and minimum of up regulating power and down regulating power capacities for Methods 1, 2 and 3 with different EV penetrations are listed in Table VI - Table IX. The maximum up regulating power capacities in DKEast is 8928 MWh/h with 70% EV penetration and Method 3, and the minimum up regulating power is 249 MWh/h with 10% EV penetration and Method 1. The maximum down regulating power capacities in DKEast is -9200 MWh/h with 70% EV penetration and Method 3, and the minimum up regulating power is 0 MWh/h with 10% EV penetration and Method 1.

IV. Regulating Power Requirement And Price Analysis

The intention of regulation power requirement and price analysis is to analyze the relation between the wind power production and the regulating power requirement, and the relation between the regulating power requirement and the regulating power prices.

Because the activated regulating power data of DKEast are not available on the Energinet.dk website, it is decided to choose the activated regulating power requirement of DKWest to carry out the regulating power requirement and price analysis.

In order to get the relation between wind power production and the regulating power requirement, the plots of wind power production versus up regulating power, and wind power production versus down regulating power were obtained and are illustrated in Fig. 8 and Fig. 9, respectively.

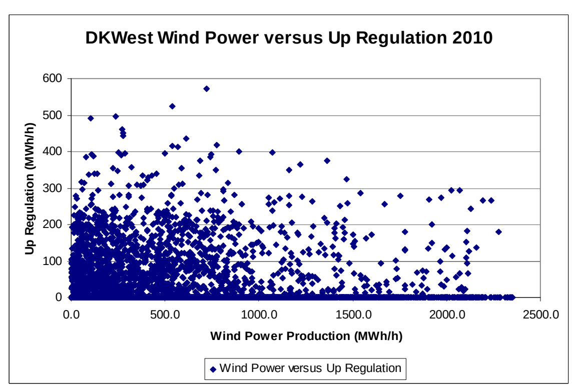

Fig. 8 DKWest Wind Power versus Up Regulating Power 2010

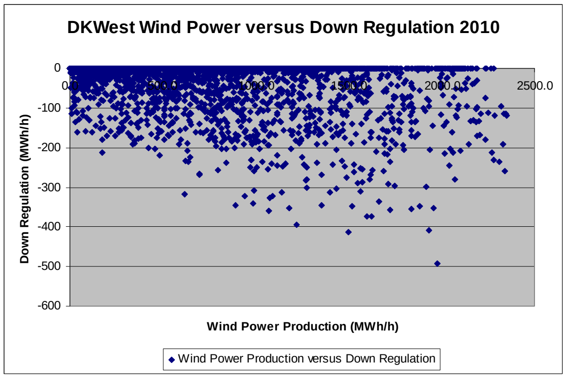

Fig. 9 DKWest Wind Power versus Down Regulating Power 2010

It is shown that the relation between the wind power production and the regulating power requirements is not very obvious. But for the economic return study purpose, it is assumed that the regulating power requirement will be doubled with the doubled wind power capacity in the situation when the regulating power requirements are high due to the wind power production prognosis errors.

Form the EV users' perspective, the aim of providing regulating power is to gain as much economic return as possible. Therefore, the relation between the regulating requirements and the regulating prices was analyzed as well. The relation between up regulating power and up regulating power prices and between down regulating power and down regulating power are illustrated in Fig. 10 and Fig. 11, respectively. It is shown that the very high up regulating power prices and the very low down regulating power prices happened during high up regulating power requirement time periods and high down regulating power requirement time periods.

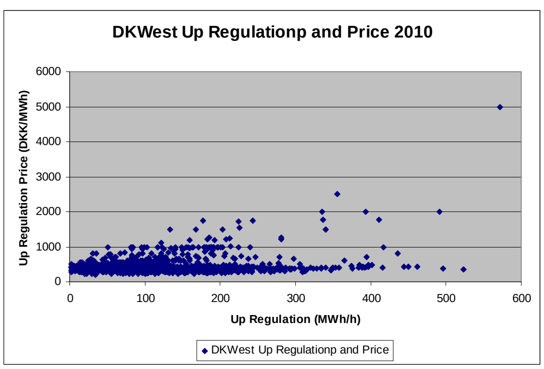

Fig. 10 DKWest Up Regulating Power versus Prices in 2010

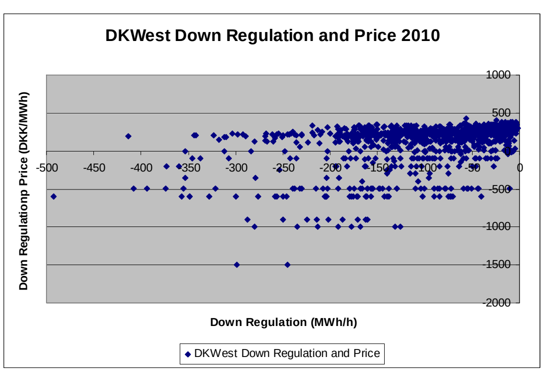

Fig. 11 DKWest Down Regulating Rower versus Prices in 2010

V. ECONOMIC RETURN FOR EV USERS BY PROVIDING REGULATING POWER

In order to investigate the economic return for EV users by providing regulation power, the days with very high up regulating power prices and very low down regulating power prices in 2010 of DKwest were selected from the extracted regulating power data from Energinet.dk. The regulating power and regulating power prices in the selected days are illustrated in Fig. 12 and Fig. 13, respectively.

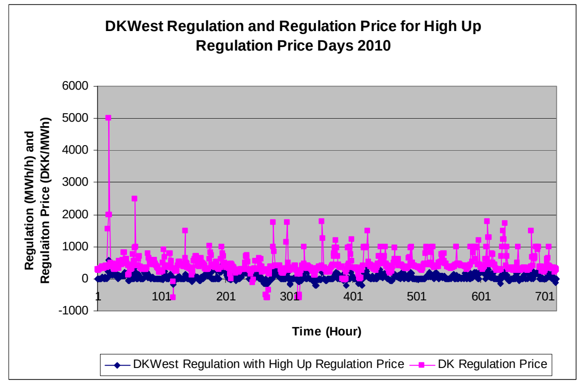

Fig. 12 DKWest Days with Very High Up Regulating Power Prices 2010

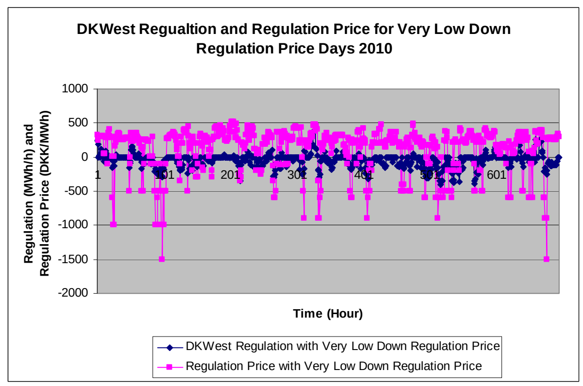

Fig. 13 DKWest Days with Very Low Down Regulating Power Prices 2010

The economic return of regulating power provision by EVs was calculated for the three charging methods with different EV penetration. The results are illustrated in Fig. 14 - Fig. 16. The maximum economic returns with different EV penetration for the three charging methods are listed in Table X.

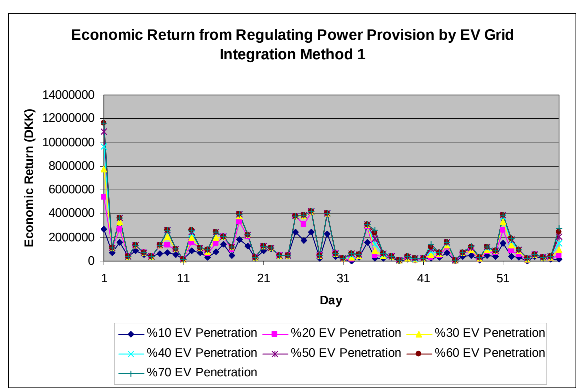

Fig. 14 Economic Return by Providing Regulating Power Method 1

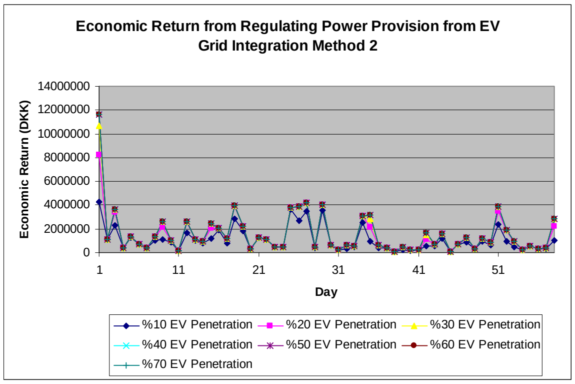

Fig. 15 Economic Return by Providing Regulating Power Method 2

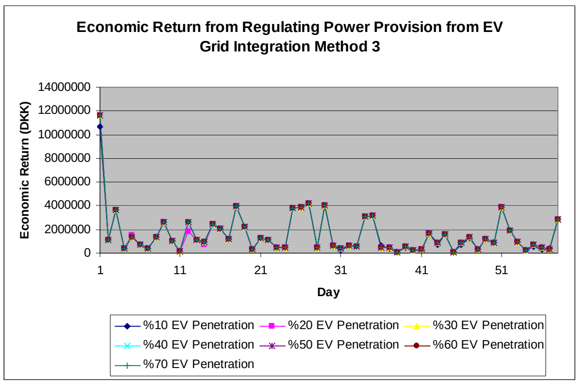

Fig. 16 Economic Return by Providing Regulating Power Method 3

Table X
MAXIMUM ECONOMIC RETURN FOR EV USERS BY PROVIDING REGULATING POWER

EV Penetration	Economic Return (million DKK)		
	Method 1	Method 2	Method 3
%10 EV Penetraion	2.69	4.30	1.07
%20 EV Penetraion	5.37	8.23	1.17
%30 EV Penetraion	7.77	1.07	1.17
%40 EV Penetraion	9.63	1.17	1.17
%50 EV Penetraion	1.09	1.17	1.17
%60 EV Penetraion	1.17	1.17	1.17
%70 EV Penetraion	1.17	1.17	1.17

The economic return to the EV users by providing regulating power is not very high considering the EV numbers.

VI. CONCLUSIONS

The potential analysis of regulating power from EV grid integration in Denmark was done in order to get the possible regulating power capacities for the proposed three charging methods and the economic returns for EV users.

The results of the regulating power capacity study show that the regulating power capacity from EV grid integration are quite promising to meet the regulating power requirements in future power systems with high renewable energy penetration. In order to get more accurate results of regulating power capacities, the transmission and distribution grid constraints have to be considered in the future work.

The economic return study results show that the economic return for EV users is not so attractive. The regulating power price may increase if the regulating power capacity needs are increased and the regulating power prices are good enough to attract EV users to provide regulating power.

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VIII. BIOGRAPHIES

Qiuwei Wu (M' 09) obtained his B. Eng. and M. Eng. from Nanjing University of Science and Technology, Nanjing, P. R. China, in 2000 and 2003, respectively, both in Power System and Automation. He obtained his PhD degree from Nanyang Technological University, Singapore in 2009 in Power System Engineering.

He worked as a senior R&D engineer in Vestas Technology R&D Singapore Pte. Ltd. from Mar. 2008 to Oct. 23 2009. He joined Centre for Electric Technology (CET), Technical University of Denmark (DTU) as PostDoc in Nov. 2009 and has been an assistant professor with the same center since Nov. 2010.

His research interests are integration of electrical vehicles to grid for high penetration of wind power, integration study for wind farms and reliability improvement and price volatility reduction of restructured power systems using demand response programs.

Arne Hejde Nielsen obtained his MSc in Electric Power Engineering from Technical University of Denmark (DTU) in 1978.

He worked as a research assistant in DTU from 1978-1980. Afterwards, he joined central research and development department, ASEA (now ABB), Sweden. He became an assistant professor in DTU in 1982 and has been an associate professor in the same university since 1986.

His research interests cover integration of renewable energy and distributed energy resources, methods for early warning and early prevention of voltage instability, wide area monitoring system (WAMS), overvoltage and protection of offshore wind power grids, etc.

Jacob Østergaard (M'95-SM' 09) obtained his MSc in Electrical Engineering from Technical University of Denmark (DTU) in 1995.

He was with Research Institute of Danish Electric Utilities for 10 years where he did research within power system transmission and distribution and was responsible for developing industrial-academic collaboration. Since 2005 he has been Professor and Head of Centre for Electric Technology (CET), DTU. His research interests cover SmartGrids with focus on system integration of renewable energy and distributed energy resources, control architecture for future power system, and flexible demand.

Prof. Østergaard is serving in several professional organizations, boards and steering committees. He is head of the Danish experimental platform for electric power and energy, PowerLabDK, and he has been member of the EU SmartGrids advisory council. In 2009 he received the IBM Faculty Award.

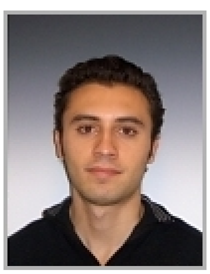
Seung Tae, Cha has a B.S degree in Electrical Engineering from Illinois Institute of Technology, Chicago in 1992, and a M.S degree in Electrical Engineering from Yonsei University, Korea in 1997. Upon graduation, he joined Korea Electric Power Research Institute where he was actively engaged in the development of KEPS, a fully digital real-time simulator, other various research projects.

He is a Ph.D candidate at Technical University of Denmark and his present interest includes real-time simulation of power systems, model development, studies involving load flow, system planning & operation.

Preben Nyeng obtained the M.Sc. degree in industrial electrical engineering from Technical University of Denmark (DTU), Lyngby, Denmark in 2000.

He was with Logos Design A/S from 2000 to 2006, developing embedded hardware and software systems, and related database and communications systems. Since 2006 he has been with the Centre for Electric Technology at DTU, as a PhD student in the field of intelligent energy systems, and related information and communication technology.

Mr. Nyeng is a member of CIGRE, the International Council on Large Electric Systems.



Francesco Marra was born in Italy. He received the degree in electronics engineering from Politecnico di Torino in 2006, the master degree in mechatronics engineering from Politecnico di Torino, Italy, in 2008.

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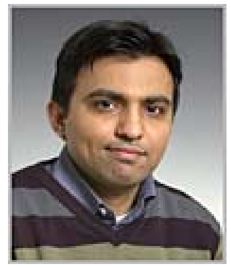

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