Analyses of Smart Grid Technologies and Solutions from a System Perspective

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Abstract—This paper consolidates the data, analysis and observations from a case study conducted in cooperation with the Smart Grid Gotland project. The analysis identifies how electrical power consumption interacts with distributed electricity generation such as wind and solar power and presents how it correlates to weather data and smart grid solutions. The analysis model developed based on the Gotland network is generic and hence can be functional in investigating other power networks of different size, voltage level and structures. The key observations from the study of smart grid solutions such as dynamic load capacity and energy storage solutions are specified. Based on the project, an overview of future risks and opportunities of smart grid systems is presented.

***Index Terms*-- dynamic rating, distributed generation, energy storage, smart grid, solar power generation, transfer limits, weather correlations, wind power generation**

I. Introduction

The Swedish government in cooperation with industry partners has established several smart grid development projects. Currently, three smart grid demonstration projects are executed on national level in Sweden: the Royal Seaport, Hyllie, and Smart Grid Gotland. All projects involve different parties that evaluate aspects of smart grids. In 2012, the Swedish Government appointed the Swedish Coordination Council for Smart Grids (SCCSG) to coordinate and encourage cooperation, knowledge transfer and discussions among all stakeholders. This created an action plan for the period from 2015 to 2030 [1].

The paper is a result of a study that was executed at the KTH, The Royal Institute of Technology in Stockholm, in close cooperation with the Smart Grid Gotland project. Gotland is an island in the Baltic Sea 90 km away from the Swedish mainland. It is connected with a HVDC link, the worldwide first installation of HVDC light technology, to the rest of the Swedish power system. The geographical location of Gotland is particularly suitable for wind power, which made Gotland to an early adopter of wind power generation. The distributed electricity generation in combination with the island system creates a unique surrounding for installing and evaluating new smart power system techniques and solutions.

The results presented in this paper are based on a study, which was commissioned by SCCSG to analyse smart grid solutions and techniques from a system perspective [2]. This analysis includes how electrical consumption interacts with distributed electricity generation in form of wind power and solar power plants and presents how it correlates to weather data and smart grid solutions.

II. Smart Grid Gotland

A. Power System

The selection of Gotland as a Smart Grid demonstration project has several advantages [3]: It is a naturally isolated power system, it provides a comprehensive overview, and still has a reasonable size so that challenges and synergies can be illustrated [4]. Gotland as an isolated system with the HVDC link to the mainland and the wind power generation at the south coast is pictured in Fig. 1. The wind power generation has reached the critical limit where the existing traditional power system infrastructure can handle the amount of wind power. In 2011, the total installed wind power was 170 MW and with the introduction of smart grid technologies Gotland

Fig. 1. Overview of Gotland, its HVDC links and electric power systems from a smart grid perspective [5] [6]

is expected to increase the capacity to 195 MW while using the current infrastructure. The wind power production was 340 GWh in 2011, which equals 38% of Gotland's electricity consumption. However, wind power production and electricity consumption are unevenly spread over the year, which could cause import and export peaks and capacity challenges of the HVDC link.

The two main electricity customers are industrial customers and the tourism sector during the summer [2].

B. *Project*

The Smart Grid Gotland project was established in 2011 to investigate possibilities of the modernization of an existing power system. Especially, the integration of increasing renewable power sources and challenges of improving the power quality are major goals [3, 7]. The project has led to photovoltaic installations (2013), implementation of smart meters (2013) and new control and monitoring systems (2014) were installed. The project can be further divided into nine sub-projects: 1) Market tests, 2) Integration of wind power, 3) Power Quality with distributed generation, 4) Market installations, 5) Smart meters, 6) Smart secondary sub-stations and rural networks, 7) Communication technology, 8) Energy storage, and 9) Smart SCADA. More information is available in [3, 7, 8].

III. DATA AND DESCRIPTIONS

The utilization data is mainly from two sources. Gotland's distribution system operator Gotland Energi AB provided the electrical consumption and wind power production data, on hourly basis [9]. The hourly weather data was recorded at the Visby Airport from 1970 to 2003 and is openly accessible from the Swedish Meteorological and Hydrological Institute [10]. Furthermore, weather data with a shorter timeframe has been gathered from Huborg at the south coast where the most wind turbines are installed.

A. *Electric consumption*

The electric consumption, electricity production from wind power, and imported power as a function of the temperature are illustrated in Fig. 2. The average values for different temperature ranges were calculated from the hourly data for one year. Fig. 3 plots percentage of year's maximum electricity consumption per hour as a function of temperature and the mean value is included. Assuming a normal distribution, maximum and minimum values are evaluated as the standard deviations from the mean and the extreme values are validated against actual observations. It is observable that the electricity consumption has an almost linear relationship with the temperature during the interval -10°C and +10°C but the average value of electricity consumption remains even outside that temperature range.

Due to the strong variation of consumption and wind power production there are periods of the year with low/high production and high/low consumption. This leads to high import and export peaks. However, the consumption is usually higher than the production and energy needs to be imported.

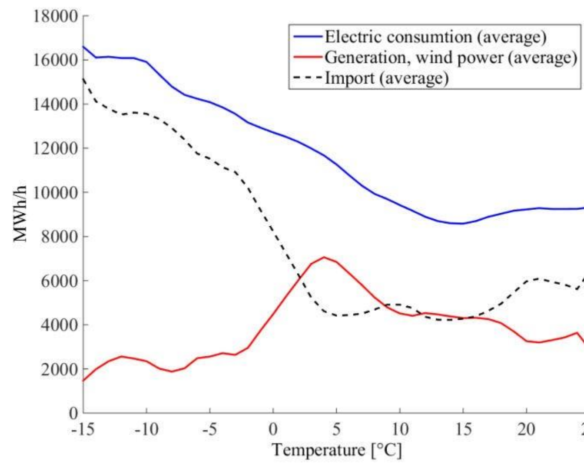

Fig. 2 Gotland's average electricity consumption, wind power generation and import as a function of outdoor temperature

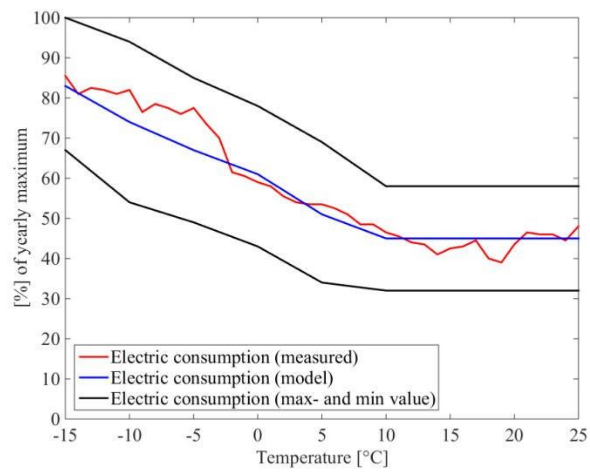

Fig. 3 Illustration of Smart Grid Gotland electricity consumption model as a function of temperature including comparison with the average of the measured electricity consumption at different temperatures

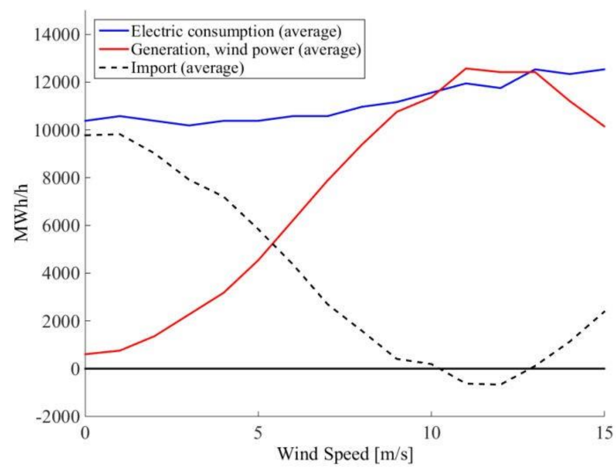

Fig. 4. Smart Grid Gotland's average electricity consumption, wind power generation and import as a function of as a function of wind speed

TABLE I
EXEMPLIFIED ILLUSTRATION OF MAXIMUM VALUES OF WIND POWER PRODUCTION DEPENDED ON THE WIND SPEED [2]

Wind [m/s]	**Days**	**Time related to total days**	**Max electricity consump.**[1]	**Min electricity consump.**[1]	**Max wind power generation.**[2]	**Min wind power generation.**[2]	**Max import**[3]	**Max export**[4]
0	89	1,01 %	84 %	27 %	34 %	0 %	87 %	-
1	607	6,91 %	95 %	19 %	69 %	0 %	98 %	38 %
2	1070	12,18 %	93 %	7 %	72 %	0 %	92 %	26 %
3	1096	12,48 %	97 %	28 %	81 %	0 %	100 %	31 %
4	1424	16,21 %	100 %	24 %	87 %	0 %	97 %	31 %
5	1006	11,45 %	95 %	7 %	86 %	0 %	82 %	51 %
6	1059	12,06 %	90 %	29 %	94 %	1 %	81 %	53 %
7	834	9,49 %	89 %	22 %	97 %	2 %	77 %	68 %
8	517	5,89 %	87 %	34 %	96 %	6 %	61 %	79 %
9	488	5,56 %	86 %	31 %	98 %	11 %	53 %	100 %
10	214	2,44 %	80 %	34 %	97 %	18 %	39 %	92 %
11	162	1,84 %	78 %	35 %	100 %	28 %	48 %	79 %
12	93	1,06 %	80 %	39 %	100 %	31 %	30 %	99 %
13	53	0,60 %	78 %	42 %	97 %	35 %	43 %	94 %
14	41	0,47 %	81 %	42 %	95 %	27 %	48 %	49 %
≥15	31	0,35 %	79 %	42 %	94 %	25 %	48 %	29 %

1 Electricity consumption: maximum in a year = index 100 % is equivalent to 195900 kWh/h

2 Electricity generation of wind power: maximum in a year = index 100 % is equivalent to 151500 kWh/h

3 Net import: max per year = index 100 % is equivalent to 187100 kWh/h

4 Net export: max per year = index 100 % is equivalent to 68700 kWh/h

B. Distributed generation

1) Wind power generation

The maximal wind speeds were measured with 18 m/s at Visby Airport and 20.7 m/s in Huborg. Fig. 4 illustrates the impact of high wind production on the import/export of energy. The small generation at 0 m/s is because the wind speed is measured at Visby Airport and the production is an average for Gotland and therefore small variations are possible. TABLE I presents the probability of the maximum values of production, consumption, and import and export depended on the wind speed. A production model for calculating the wind power production depended on the time is presented in [2].

2) Solar generation

The solar generation model was calculated based on data from Visby [11]. The model calculates the peak value under perfect weather conditions based on the height of the sun with respect to hour and month of the year.

IV. OBSERVATIONS FROM DATA

A. Weather Data

Observing the weather data during 2014, the temperature varied between: -20.9 and 28.2 °C at Visby Airport. This can be compared with the variation over a 40-year period from the same place as the temperature varied between -22.4 and 32.9 ° C. Noticing the wind speeds, the maximum measured was 18 m/s at Visby Airport and 20.7 m/s at Huborg during 2014 and the wind speed at its lowest on both locations were close to zero.

B. Electricity consumption, production, exports and imports

Electricity consumption varied between 13500 and 195900 kWh per hour for the entire island of Gotland, i.e. a maximum value of almost 15 times the minimum. Primarily, this difference is due to the variations in power consumption during summer and winter. The extreme values are because of the combination of other human activities such as industries, day or night power consumption variation, weekend or weekday variations and tourism.

Electricity production of wind turbines varies more. There were periods with no generation, and the maximum value of production over the year was 151500 kWh per hour. A general observation is that Gotland’s local electricity consumption is higher than its electricity generation. Since both electricity generation and consumption varies, there are both periods of net imports and net exports to/from Gotland via HVDC link to the mainland. During 2014, net imports i.e., Gotland's electricity consumption minus the electricity generation within one hour, had a maximum of 187100 kWh/h, and net exports peaked 68700 kWh/h.

C. Correlation in data

The correlation between the data used for the study is presented in TABLE II. The wind speed at both weather stations has a high correlation with electricity generated from wind. This high correlation suggests that analysis of the generation can be made based on the data available at Visby Airport.

Furthermore, the high correlation between temperature and power consumption is typical for Sweden and was shown in different studies [12]. There is a negative correlation because, the low temperature results in high energy consumption due to heating and the opposite may apply in hot countries where air conditioning accounts for a significant share of electricity consumption. No clear correlation between reliability and other inputs can be detected, but there is not enough evidence to draw conclusions.

Another relevant hypothesis is that, the correlation between electricity consumption and temperature is different for different hours of the day or days of the week. Household heating accounts for a higher proportion of electricity consumption, for example, during non-working hours.

TABLE II
CORRELATION BETWEEN UTILIZATION AND RELIABILITY DATA [2]

	Prod-uction	Consu-mption	Import/ export	Tempe-rature	Wind 1	Wind 2	Relia-bility1
Consum-ption	0,22						
Import/ export	-0,05	-0,71					
Tempe-rature	-0,05	-0,71	0,31				
Wind1*	0,78	0,15	-0,67	0,10			
Wind2*	0,84	0,22	-0,71	-0,04	0,81		
Relia-bility1**	0,01	0,03	0,01	0,05	0,05	0,05	
Relia-bility2**	0,01	-0,02	-0,02	0,01	0,03	0,03	0,68

*Wind1 is the measured wind at the Visby airport and Wind 2 refers to Huborg. In average is the wind in Huborg 22% stronger than Visby

**Reliability1 are the amount of registered disturbances in the power grid which cause at least one customer outage and Reliab2 is the amount shed customers in one hour

It may be noted that Gotland has a special consumer composition including a single company (Cement) accounting for about 30% of the total annual consumption [13]. Electricity consumption as a function of temperature was analysed for different time periods, day of week and hour of the day to observe variations in those periods.

TABLE III summarizes a survey that has been done on the impact of the week and times of day on power consumption. Electricity consumption changes for different hours during a week, but the correlation between temperature and power consumption differs insignificantly.

TABLE III
ILLUSTRATION OF HOW THE DAY TIME INFLUENCES POWER CONSUMPTION [2]

Categories	**Definition[1]**		**Average yearly deviation of electrical consumption[2]**		**Correlation with temp[3].**
	mon-fri	**sat-sun**	**max**	**min**	
Night	23-5	23-7	-4,7 %	-12,3 %	-0,83
Meantime	6-7, 19-22	8-22	10,7 %	-3,4 %	-0,81
Day	8-18	-	12,1 %	7,4 %	-0,84

[1] The times of the day where set based on significant changes in the electricity consumption

[2] Deviation from the average of the year; max/min represents the hour where the category has the highest/lowest average consumption

[3] Correlation between temperature and electricity consumption for the specific category.

V. REMARKS FROM ANALYSIS

The conducted study also included the development of a generic model to analyse power systems of any size, voltage level and composition and general observations regarding smart grid solutions can be drawn from this. More information can be found in [2].

A. Model for dynamic load capacity

Dynamic load capacity or dynamic rating [14] means that the transmission capacity of components is affected by external parameters such as weather, usage, online component measurement, etc.. There are different 'levels' of the dynamic load capacity, ranging from standard levels to online measurement; different types of dynamic load capacity which takes into account different parameters, and so that it can be implemented with respect to various components of the power system.

The models studied within the project focuses on how wind and temperature variations can affect the cooling and thus the transmission capacity of overhead lines. The derivation and validation of the model presented in [15], which is based on the IEEE standard 738-2006 described in [16].

The study confirms that dynamic load capacity increases the possibility of using the grid more effectively by increasing the system's acceptable transmission limits. Low outdoor temperatures have cooling effect on electric components and thus in some cases potentially higher transmission capacity.

The study also shows that electricity consumption and also certain types of electricity generation have temperature dependence. Hence, future network models can have provisions that allow the grid to be loaded more when dynamic load capacity allows higher transmission.

Another weather parameter that can have a cooling and thus a capacity-increasing effect is the wind speed, but only on components such as overhead lines that are directly hit by the wind. This specifically directs to the potential to use wind cooling to be able to increase electricity transmitted from wind power turbines. An additional conclusion is that the benefits of dynamic load capacity for certain scenarios increase significantly, if such a risk is accepted. Dynamic load capability can also be used to increase the power line supply security under certain conditions, for both consumers and producers. One way to increase supply security is to introduce switching capabilities at fault locations so that a trench can feed more customers at fault compared to normal operation and thus reduce the impact during breaks. One challenge may be that overload is caused during periods of high electricity consumption. A solution can be dynamic load capacity where high transmission correlates with high electricity consumption. High transmission correlates also with high wind speed, which means that non-delivered energy from wind power with transmission constraints can be reduced or eliminated if the dynamic load capacity is introduced, especially if both temperature and wind speed allowance are utilized.

Dynamic loading capacity increases the possibility of using power systems more effectively. Consequently, costly investments can be avoided or postponed and the connection of more local generation such as wind turbines can be facilitated or favoured. In addition to financial savings, dynamic load capacity also provide environmental benefits such as more renewable electricity production and reduced need for manufacturing new or larger components.

A challenge with dynamic load capacity is that weather parameters may vary locally and can be different between the place of measurement and the component studied. Ground cables can be affected by outside temperature, but this relationship is more complex because it depends on soil characteristics and depth. However, submarine cables, such as the HVDC link to Gotland, are not affected by wind and the temperature dependence is less. Components not directly exposed by weather parameters can use other algorithms for dynamic loading capacity for example as a function of use and by online measurement. There is research and development of online measurements for temperature estimation in underground cables and transformer using dynamic load capacity [17].

B. *Energy Storage Model*

In accordance with the project's mission statement, the use of energy storage has been analysed from a technology-neutral approach. The project requirements are concerning: size, how quickly the storage must be able to deliver and absorb energy and what percentage should be filled in during normal operation. In order to cope with high electricity consumption, energy storage should be ready to deliver electrical energy and the opposite applies to handling high power generation. Equally sized energy storage can increase the installed peak power significantly more for solar power generation, compared with that for wind. This is because there may be high generation from wind power for a longer period, which makes the energy storage to consistently take care of surplus electricity without being able to 'recover' to the normal level. On the other hand, production of electricity from solar power only has maximum power for short periods. Electricity consumption has a similar result as wind power, but conversely, the energy storage needs to provide energy for a long period without being able to 'recover' to the normal level.

Size requirement for energy storage to manage excess electricity consumption and electricity generated from wind turbines is increasing rather exponential than linear as a function of how much overload that need to be handled. The conclusion is that if the energy store is used for any of these two categories, it should be able to deal with minor power peaks.

VI. Overview of Future Risks and Opportunities

The key observations relating the analysed data is already presented. In this section, the future risks and developments in smart grid operations in general are discussed. Knowledge of the correlations of various parameters observed within the smart grid Gotland project can be utilized while designing future smart grid networks.

No technical components or solutions are 100% reliable. It is particularly difficult to assess both risks and benefits of new technology and solutions with limited knowledge on the system impact. Even components whose task is to reduce the impact of disturbances in the grid, such as protective gear, can in it-self introduce their own errors and failure modes. Therefore, it is a trade-off between potential risk reduction of existing systems and new risks, along with the investment cost. Today, about 30% of all reported faults in electrical distribution networks are associated with secondary equipment, such as control and protection systems [18]. With the introduction of smart grid solutions, this proportion may vary as new risks are introduced while the total amount of error (measured in both the number and duration) will expectantly reduce [19]. It is important to develop combined approaches that manage the complexity of both primary grid components along with the information, control and protection systems understanding the dependencies between them.

VII. Closure

Because of the lack of experience regarding many new technologies and solutions of smart grid, demonstration plants such as Smart Grid Gotland are significant. Improved understanding of the correlations between reliability and utilization data was acquired and the potential of technologies such as dynamic load capacity and energy storage were investigated.

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