Intelligent Electric Car Charging System

INCA Report

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SYMBOLS

AC	Alternative Current
DC	Direct Current
LOM	Loss Of Main
LVDC	Low Voltage Direct Current
SOC	State Of Charge
V	Voltage
W	Watt
Wh	Watt hour
I/O	Input/Output

1. INTRODUCTION

This paper introduces the main concept of battery charging and discharging of an electric car with an intelligent charging system. The research includes also the possible usage of the DC distribution system, and therefore it is also acknowledged as one option for connecting the electric car to the grid. The main issue in this paper is to introduce the reader to the concept of using electric cars as small-scale generator units and to the intelligent charging of electric cars. Also the laboratory pilot of intelligent charging will be reviewed.

2. INTELLIGENT ELECTRIC CAR CHARGING SYSTEM

The next generation of cars may all be powered by electricity. Electric cars are more energy efficient, and the electricity needed for these cars can be produced from renewable energy resources [16, 17]. The electric cars have some drawbacks such as the long charging time and short range of operation. Yet, the battery technology has taken huge leaps in energy density, charging time and lifetime [2, 3, 15].

2.1. Electric car

The impact of electric cars on power supply systems can be huge. Massive numbers of electric cars can have a devastating effect on the power grid when plugged in almost simultaneously. Nevertheless, the large numbers of electric cars have their benefits. Until now, the power supply systems have not had electricity storage. Because of the batteries of electric cars, the power supply system now has a potential backup power supply, the size of which depends on the number of electric cars. The potential of electric cars as a part of the power grid have been subject in many studies [4, 18, 20].

2.1.1. Electric car properties

There are several different types of electric cars in the market. These electric cars have mostly different kind of battery also. However most of them are lithium-ion batteries. Even though the electric cars have battery charger implemented on them, most of the electric cars does not have any kind of discharge ability. The charger system needs to work with any kind of electric car. The most important issues is the voltage level differences of batteries between different electric car models. The battery voltage can vary from 60 V to 400 V. Five car types and their battery types and properties are presented in table 1.

Car type	Year	Battery type	Battery	Voltage	Electric motor power	Charge Time	Charge Power
General Motors EV1	1999	NiMH	26,4 kWh	312 V	116,4 kW (peak)	7 h	3,77 kW
REVAi	2001	lead-acid	9,6 kWh	48 V	13 kW (peak)	8 h	1,20 kW
i MIEV	2005	Li-ion	16 kWh	330 V	47 kW (peak)	7 h	2,29 kW
Tesla Roadster	2008	Li-ion	53 kWh	375 V	185 kW (peak)	3,5 h	15,14 kW
Chevrolet Volt	2010	Li-ion	16 kWh	330 V	111 kW (120 kW)	7 h	2,29 kW

Table 1. Car types and their properties

2.1.2. Battery technology

Lately, battery technology has advanced considerably. With improved energy density and faster charging times, the batteries can really start to compete with petrol [5, 6, 7]. The main problems with electric cars are the small travel area and slow battery charging. However, as the battery technology advances, these problems are alleviated. Several studies have achieved 10 times larger energy densities compared to batteries in the market at the moment. The higher energy density has been improved with different types of battery materials, and the charging and discharging rates have also improved. Nowadays the goal is to achieve charging and discharging rates over 10C. The C is used for batteries to describe the possible current amount what the batteries can withstand while charging and discharging. The C is possible current compared to nominal capacity (50 Ah battery with 50 A charge or discharge is 1 C). There are already batteries with rates of 6C [7]. With a 10-minute charging time, the difference between fueling a petrol car and charging an electric car becomes irrelevant. The only problem is to supply the electric car with enough power to actually charge the batteries within 10 minutes. With a 30 kWh battery pack, charging in 10 minutes will require 180 kW. However, large charging powers reduce batteries life time and the batteries needs to be proper types to even be able to charge them with high power. Even though the charged energy is small, the temporary charging power peak can have massive effects on distribution networks specially when charging several electric cars at the same time.

Advancement in battery technology also provides opportunities to use batteries effectively as backup power. With more than 10000 life cycles, the batteries can be charged and discharged several times a day, and they can still be operational over 10 years [7, 8].

2.2. System concept

The impact of increasing number of electric cars can be remarkable to distribution network. With high penetration level of electric cars the load peaks can raise up to 1.5 times compared to peak powers without electric cars. With the intelligent charging system these peaks can be reduced and even further with full household load control.

2.2.1. Background

When the charging of the batteries is carried out intelligently, the peak power of the power supply system will not rise dramatically. Actually, the batteries can work as backup power supplies in peak situations, and by intelligence charging the batteries can even out power fluctuation. Fig. 1 shows the estimated power levels in one suburban area when charging of the electric cars are made according to the plug-in principle. Almost all customers on the feeder start charging their cars at the same time in the evening. With non-controlled charging, the power peaks in the suburban area may double. This means that new investments have to be made for the transformers and other components [4].

With intelligently controlled charging, the power peaks can be lowered significantly compared to non-controlled charging. The estimated effect of intelligent charging on the distribution system is presented in Fig. 2. Optimal situation would be when the cars are plugged in the distribution network always when not moving. This situation would allow intelligent charging to have maximum effect. The situation would in fact lower the present peaks in the distribution network if the electric cars would be all smart charging [4].

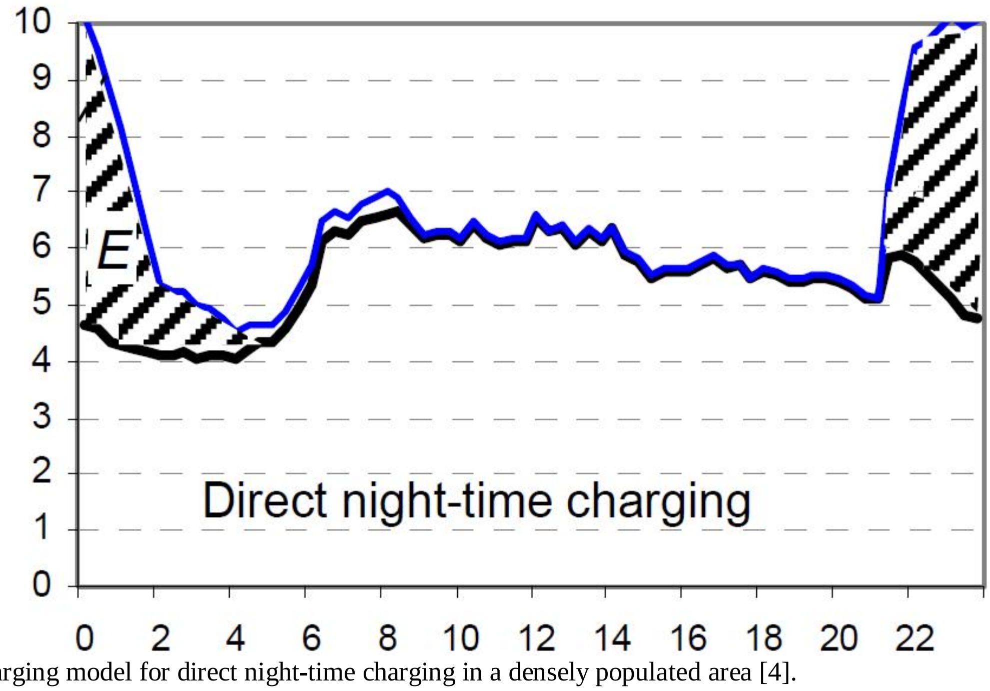

Fig. 1. Charging model for direct night-time charging in a densely populated area [4].

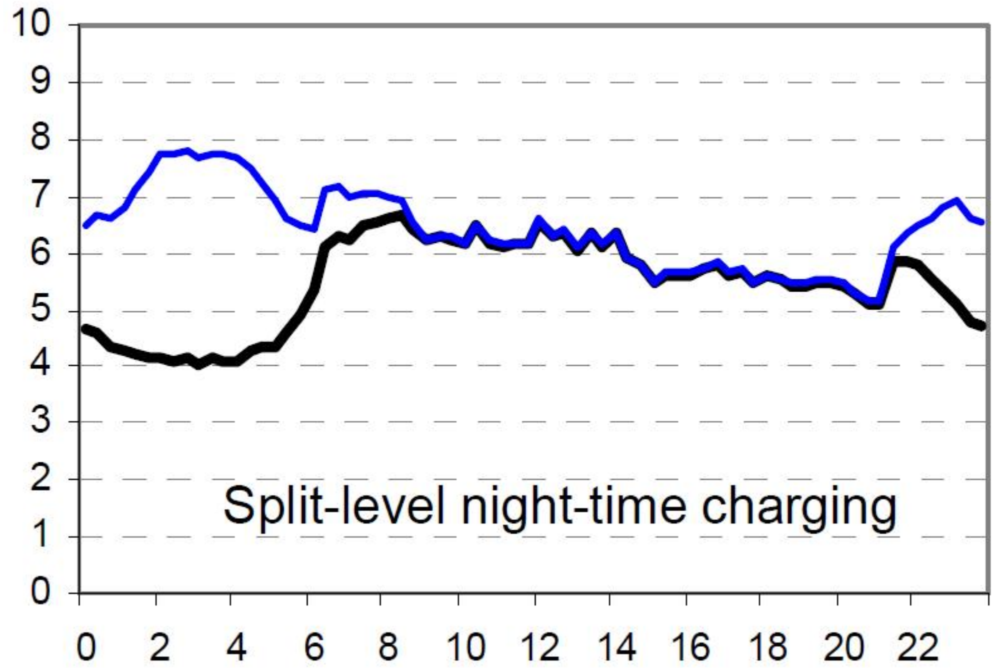

Fig. 2. Charging model for intelligent split-level night-time charging in a densely populated area [4].

Therefore, the growing numbers of electricity cars need an intelligent system that can control the cars within the power system. With controlled and energy-efficient batteries, the distribution system can be made more stable and energy efficient.

2.2.2. Requirements

Boundary requirements and definitions are needed for the intelligence charging system.

The system includes following properties:

- Charging and discharging
- Communication link with electric car
- Customer interface
- Capability to isolated operation
- Load control
- Monitoring the price of the electricity
- Remote communication
- Energy efficient DC/DC or DC/AC inverter for discharging
- Cost-efficient batteries

2.2.3. Concept description

The charging system has two different integration alternatives. The system can be integrated into an electric car or a property. However, today the charger devices in most of the electric cars are only capable of charging the batteries. Hence, some modifications have to be done to the electric car even when the charger system is integrated into the property to enable battery discharging.

The charging system affects several different parties. These are customer, electricity retail and distribution grid owner. These parties have different advantages and disadvantages from different situations. Least advantages has customer which doesn’t have any direct benefit from having intelligence charging system beside the capability sustain isolated operation.

Advantages and disadvantages of intelligent charging

- Capability to reduce bottlenecks
- Reduce investments to distribution networks
- Increased accuracy in energy consumption for market solutions
- Multiple electric cars enables fast and high backup power system
- Discharging is expensive for the customer because of the high price of the batteries

2.2.3.1. Electric car

One of the main problems when connecting electric car batteries to a distribution network is the variety of voltage levels. The variety of voltage levels affects the efficiency of the inverter. The Finnish low voltage distribution network can be one- or three-phase 230 VAC, 750 VDC or 1500 VDC in the future. On the other hand, the voltage in the batteries varies from 48 VDC to over 400 VDC. However, in most of the batteries in electric cars, the voltage level is close to 400 VDC. The voltage variety makes it difficult to form an energy efficient connection between an electric car and the distribution network. One solution could be to make several versions of the inverter for different voltage levels.

Even though the charging system maintains its basic system demands regardless of the placement of the system, the integration in a car poses more challenges to the communication and electronics because of mobility of the car. However, integrating the charging system into a car enables integration of the battery charger and can lead to a more energy efficient solution.

2.2.3.2. Inverters

Charging and discharging the battery unit can be carried out with one-phase or three-phase 230 VAC. There are also plans in Finland to replace some of the normal 400 VAC low voltage distribution lines with DC links. DC voltage allows a larger distribution distance per inverter. This means that the charging can also be done with 750 or 1500 DC. Hence, the charging unit must contain multiple inverters or an inverter unit, which can be changed.

Because the type of the inverter depends on the type of the distribution network, the energy efficiency of the inverter also varies depending on the inverter type. The conversion efficiency is important because of the possible discharging. With a high AC/DC, battery and DC/AC efficiency, the discharging becomes a viable option as a part of the intelligent charging of the electric cars.

A one-phase DC/AC inverter can have 90% efficiency, while a three-phase AC/DC buck boost PWM rectifier can reach the efficiency of 96% [12]. A back-to-back multilevel inverter (DC/AC) can have an efficiency of 98%. A single multilevel inverter can achieve as high as 99% efficiency [13]. However, the voltage levels and power levels in electric cars are so high that the inverter system needs multiple multilevel inverters.

Usually, the distribution networks are one or three-phase AC, but DC distribution system is also possible. The efficiency can be very high when charging from a DC distribution network (750 VDC charging a battery with nominal voltage of 400 VDC). However, discharging the battery's energy back to the distribution network can be less efficient. Nevertheless, a single buck-booster (DC/DC) inverter can have up to 98% efficiency [14]. However, placing the inverters in series will degrade the efficiency.

One of the system requirements is to be able to control the power flow. Nowadays, commercial inverter modules include several functions. The charging system does not need any kind of a special inverter unit, and it can be equipped with a commercial high-efficiency inverter unit. An opportunity to change the converter unit to correspond to the distribution voltage used is a great advantage for the system.

2.2.3.3. Core

The central unit processes data gathered from measuring devices and other units. The central unit needs measuring information from the kWh meter of the property and a control link to the possible inverter or to the separately installed load control unit. The central unit also needs a communication link to the car to be able to identify the battery back of the car.

A communication link with the kWh meter of the property can be very helpful in controlling the power-level of the inverter unit. It is not necessary, but it facilitates the operations of the charger system. In the case of a breakdown of the distribution system, the inverter unit can measure the voltage level of the grid in the property and maintain the balance. This, however, needs a switch that can disconnect the property grid from the distribution network. If the real estate grid is not disconnected from the faulted distribution network, the electric car feeds the failure with small power and can thus lead to breaking of distribution networks components. The communication link assists the inverter unit by providing information about the power consumption level. With this information, the charger system can disconnect unnecessary loads from the property grid if the power consumption level is too high for the batteries. However, if the public distribution system is in operation and there is no communication link, the charging system cannot know the power consumption in the property. Hence, the communication link between the charger system and the kWh meter of the property is needed – but only in those cases where the power consumption and the power production have to meet each other. This ability can be used by the administrator of the charger unit. In normal situations, the power production from batteries can be different from the power consumption, and a communication link is not necessary.

However, the balance of the property grid can be maintained with a frequency-controlled system in the case of distribution network failure. This as well needs a switch control to disconnect the property from the public grid but does not need power consumption information from the kWh meter.

The reconnection between public and property grid can be carried out by two different methods. The first method is to power down the battery pack and after a short time to connect the property back to the distribution network. This method does not require frequency adjusting from the backup power source. However, it causes a short power failure and most likely affects normal domestic electric devices. The second method is to adjust the frequency of the backup power to match the distribution network frequency. With a zero phase shift between the systems, the reconnection can be performed without any power failure. The frequency of the property grid can be adjusted to be a couple of digits lower or higher than the frequency of the distribution network to be able to achieve the same phase shift with the distribution network within 20 seconds. After the reconnection, the battery pack can be powered down slowly.

Nevertheless, the charger unit needs a communication link with the load control device. Even though the electric car can provide enough power for the real estate, the duration of the backup power is only about 3 hours with the full load (35 kWh battery pack and 11 kW maximum power for the real estate). Hence, the communication with the load control device is essential in order to provide backup power for a longer time. The charging system can disconnect the most unnecessary loads through a load control device and only allow the use of the most essential electric devices. This can greatly lower the power consumption in a property and lengthen the duration of the backup power to 24 hours or above.

An important issue about charging is also the maximum charging current that the batteries of the electric cars can uphold. Even though the electric car's battery charger controls the charging current, it is important for the charging system to know the SOC (State Of Charge) of the batteries. One reason is the ability to show the SOC for the customer without needing to enter the car to read the SOC. Knowing the battery's SOC makes it possible also to inform the customer about the duration of charging at the interface. However, this ability needs modifications or information gateway in the car's battery or information system. The modification means connecting the charging unit directly to the batteries. With this kind of a connection, the charging unit can discharge the batteries and measure the SOC. Nevertheless, measuring the SOC can be difficult as the battery packs voltage levels and properties differ greatly from each other. However, the charging is still done by the car's original battery charger. Information gateway would offer direct connection to the SOC and other cars information data. For example, the charger interface could show the estimated travel length with the current SOC based on the median stored in the information system of the car.

The second issue is the control system of the charging systems. The control systems can remain in balance in the distribution network more easily when the system knows the demands and possible backup power provided by the batteries. With a database about the current SOC values of the batteries that are connected to the distribution network and the demand of the charging, the control system can decrease the amount of bottlenecks that a normal electric car charging could have. With an intelligent charging, the bottle necks can be reduced if the chargers are controlled locally. This issue becomes more important as new battery materials are invented. A new battery material can be charged more rapidly and contain more energy per kilogram. The possibility to charge a 100-kWh battery in 10 minutes can lead to severe problems in distribution networks if the future of the electric cars will not be acknowledged. Even though the fast charging is not possible in household properties, the number of electric cars to be charged simultaneously can be a problem. However, fast charging will most likely be carried out from the medium- or high-voltage network so the bottlenecks will not be problem. Nevertheless, the larger batteries mean larger backup power.

The charging system also needs to have communications links between load control, electric car and system controller. Also the communication link (interface) between the system and the user is needed. The system concept is showed in Fig. 3.

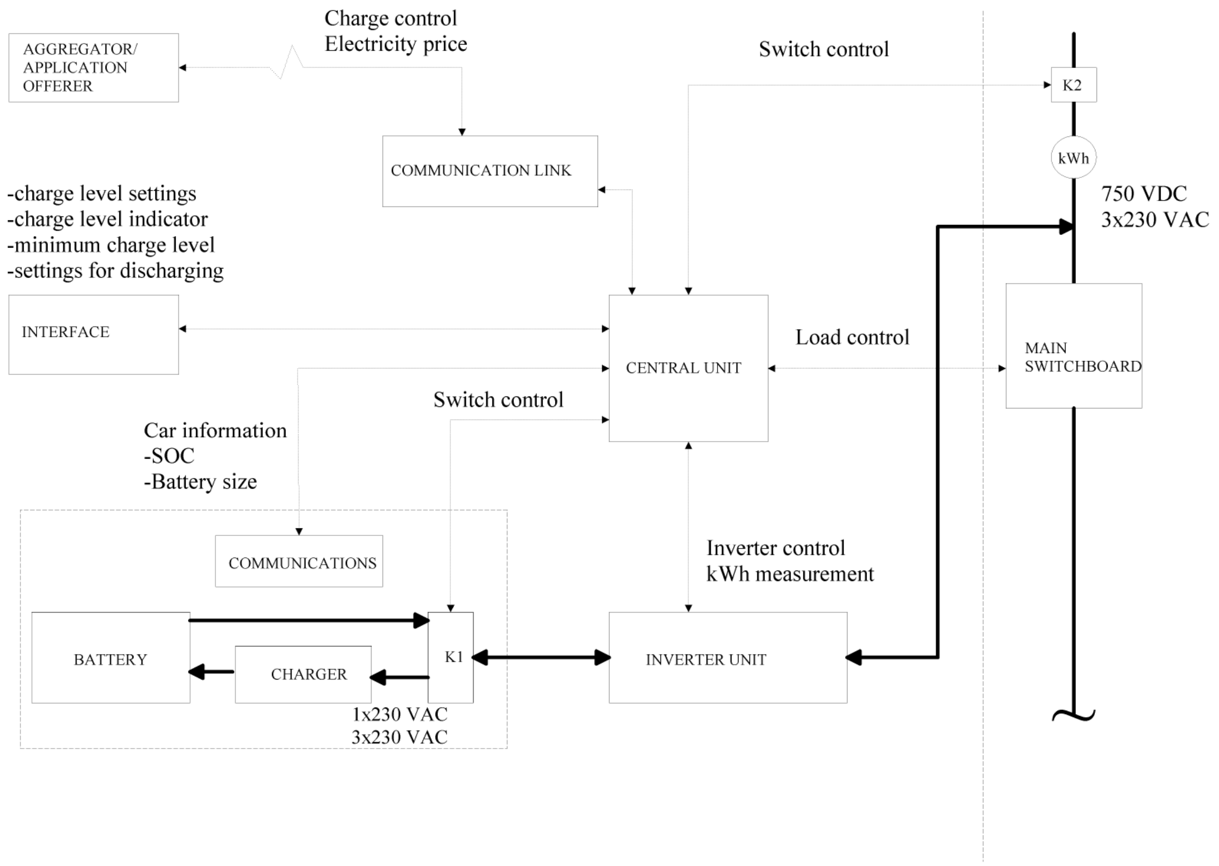

Fig. 3. System concept in general.

The system concept shows general functions and data communications between the main parts of intelligence charging system. The parts of the intelligence charging system are central unit, interface, inverter unit and communication link. The charging system is controlled by aggregator or application offerer. Battery and charger box represents electric car with few added modifications (communications and K1 switch). The distribution grid and customer grid is on the right side of the picture.

2.2.3.4. Customer interface

An interface is needed to provide the customer with a connection to the charging system. Through the interface, the customer can set the charging time and the desired state of charge, the minimum state of charge when discharging and settings related to the price of electricity. From the interface, the customer can also see the car's state of charge and the electricity price. The charging system can also show the estimated time for the charging to be completed. This option is useful when determining the charging start time. However, if the customer wants the charging to start as soon as possible, the system can show the time when the charging is complete as well as the amount of kilometers that can be traveled with the current SOC. This option, however, can produce bottlenecks if carried out in a large scale since it is similar to non-controlled charging. Hence, the option to start charging the batteries as soon as possible needs some restricting functions or load controlling methods. If there were an extra payment determined by the market price of electricity for using the option to start charging immediately, the usage of the option could be reduced significantly, and the electricity provider could gain considerable advantage in the markets because of the capability to accurately predict the energy consumption. However, this could also be done differently; a customer could have some benefit such as lower price from the electricity charged in the electric car.

Communications allows the system to have an intelligent control of charging and discharging. A communications unit is needed as a link between the charging system and the control system. Through the communications unit, the control system can instruct charging and discharging of the electric cars in a certain area. A customer can give a single dead line for the charging to be completed, and the system should charge the batteries during this charging window. Without any control, the charging of the electric cars can have a fatal effect on the distribution network. With a large number of cars, the effect on the peak load would be substantial. With a decent control system, the peak load can be avoided by distributing the charging evenly over the grid. However, this can only be done in situations where the charging time is smaller than the charging window.

2.2.3.5. Public distribution network

The impact of increasing number of electric cars can be remarkable to distribution network. While the load peaks can be a problem for the distribution grids, the possibility to discharge can have significant advantages to distribution grid. However, discharging can affect the stability of the distribution system and therefore must be considered at large scale. The car battery has capability to provide all needed power to the household for a period of time. Therefore, large scale simultaneous power request from electric cars could affect the frequency of the distribution grid. Nevertheless, with proper control load controlling and discharging has great benefits for distribution companies while they can avoid bottleneck situations.

3. Laboratory pilot

The concept will be tested with a low-voltage DC system. The goal is to have a system that controls itself load and energy storage. System has also simulated wind power generator. System can also be accessed remotely for load controlling and market controlling and it can independently sustain itself in the case of network blackout.

3.1. Components

The proposed interactive customer gateway demo setup includes many different components:

- Control PC
- Central PC

- Controllable Power Source (CPS)
- Relay Control Circuit Board (RCCB)
- Hydro Boy SMA Inverter (SMA)
- DSPACE

Artila Matrix512 embedded PC works as a main unit/computer (Central PC) of the interactive customer gateway. It handles all monitoring and decision making and load controlling tasks. Those tasks are specified later in this document. The pilot environment build in LUT laboratory consists of rectifier, 198 meters of AXMK cable and inverter, which together form the LVDC distribution system. Behind the inverter in the customer's network there are Artila embedded computer (Central PC), personal computer (Control PC), different sized loads, relay box that controls the loads (RCCB), controlled power source (CPS) that acts as a wind turbine or other small scale production unit and demonstrates battery discharging, and SMA/Hydro Boy (SMA) that supplies the power from controllable power source to the customer power grid. One main component of the customer gateway is also DSpace which is used to control the customer inverter. It also measures rectifier and SMA power. System setup is presented in Fig. 4.

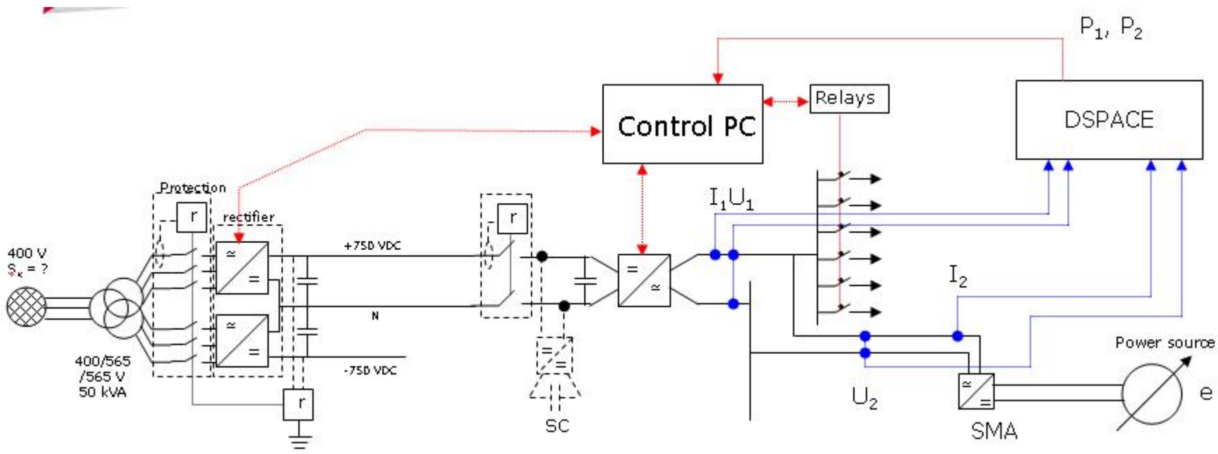

Fig. 4. Laboratory prototype system

3.2. Operation

Controllable power source is connected to the grid via SMA Hydro Boy. Controllable power source acts as a wind generator unit as well as simulates discharging battery. Battery charging will be simulated by setting up the load. With power measurements the consumption of the load (connected via relays) can be calculated. In case of overload the system will activate batteries as backup power or drop loads following priority list. For example the system can be instructed not to take more than 3 kW power from the DC grid. The system will drop the loads or discharge batteries depending on consumption and state of batteries and wind generation.

4. CONCLUSION

Growing numbers of electric cars will have effect on distribution networks in Finland. An intelligent charging system can be made for minimizing the effects. Electric cars can even be used as small scale backup power. However, for discharging applications the cycle life of the electric cars batteries must increase to become affordable. Also the efficiency of the charging and discharging cycle should be as high as possible for load controlling and electricity market applications to make them beneficial. The main advantages and disadvantages of intelligent charging are listed below.

- Capability to reduce bottlenecks
- Reduce investments to distribution networks
- Increased accuracy in energy consumption for market solutions
- Multiple electric cars enables fast and high backup power system
- Discharging is expensive for the customer because of the high price of the batteries

Even though the charged energy is small, the temporary charging power peak can have massive effects on distribution networks specially when charging several electric cars at the same time. Advancement in battery technology provides opportunities to use batteries effectively as backup power. With more than 10000 life cycles, the batteries can be charged and discharged several times a day, and they can still be operational over 10 years. The main issues about batteries are listed below.

- Most used batteries in electric cars are Lithium based
- Lithium-nanotitanate has at the moment highest cycle life (over 10000 cycles)
- Several studies have achieved 10 times larger energy densities with different types of battery materials
- Charging and discharging rates have improved

The control systems can remain in balance in the distribution network more easily when the system knows the demands and possible backup power provided by the batteries. With a database about the current SOC values of the batteries that are connected to the distribution network and the demand of the charging, the control system can decrease the amount of bottlenecks that a normal electric car charging could have. With an intelligent charging, the bottle necks can be reduced if the chargers are controlled locally.

The concept will be tested with a low-voltage DC system. The goal is to have a system that controls itself load and energy storage. System has also simulated wind power generator. System can also be accessed remotely for load controlling and market controlling and it can independently sustain itself in the case of network blackout.

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