Analysis of Distribution Substation Topologies for Energy Exchanging between EV and Utility Networks

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Abstract - This paper describes the integration of electric vehicle charging stations and energy storage systems with distribution substations for bidirectional energy exchange applications. Several challenges occur in connecting filling stations to power grid, which consist of several charging stations. Substation topology examples for energy exchanging between electric vehicles and utility networks are described and substation layout is presented.

I. INTRODUCTION

In recent years the race for manufacturing electric vehicles (EV) and charging methods for EVs has picked up considerably. The main reasons are firstly reducing the dependency of fossil fuels as oil has limited resources and oil prices are growing higher, secondly climate change issues with CO₂ reductions and greener thinking. Electric vehicles can improve air quality in cities, implement new and innovative technical solutions and technologies in the economy, increase public awareness of the importance and benefits of electric transportation and energy use. As car manufacturers are focusing on EV design and battery solutions, electric engineers are focusing on charging EVs with questions of connecting EVs to power grid and charging methods. In particular, EV and vehicle-to-grid (V2G) or vehicle-to-any load (V2X) concepts will have great impact to utility networks.

With new battery solutions (e.g. High-Density Lithium-Ion batteries) the cruising range of EVs has extended, making EVs more practical in everyday use, thus making EVs more competitive with fuel engines. The major problem with charging EV batteries is time. Charging procedure has to fulfil two main criteria regarding where it takes place: in public places the charging must be fast (people cannot wait for hours), in private homes and offices charging can be slower (fast charging equipment are also very expensive). Charging at homes will take the hole night and does not enable to travel several hundred kilometres with EV during day time. In the urban environment many citizens do not own personal garages nor there is not much space to develop single charging station areas for 8 hour charging periods. Charging can be done more efficiently at EV filling stations. In the near future new filling stations will all be built on a concept of fast charging. Preferably a discharged 16 kWh battery should be recharged to 80 % level in 30 minutes [1]. Private homes and offices will participate in the future in Smart Grid solutions, where EVs are connected to charging stations with bidirectional energy flow capability.

Several papers have looked into several topologies and control methods that can perform bidirectional power transfer using EVs as energy storing systems. However, there has not been much technical analysis about their applications in substations. Substation topologies should support Smart Grid principles with energy storage systems for V2G connections according to IEC 15118-1. In this paper charging principles and IEC 61851 charging modes are described. Later, an example bidirectional converter is analysed and its connection to the power grid is examined through substation topology.

II. ELECTRIC VEHICLE CHARGING PRINCIPLES

A plug-in electric vehicle (PEV) is any motor vehicle that can be recharged from any external source of electricity, such as wall sockets, and the electricity stored in the rechargeable battery packs drives or contributes to drive the wheels [2]. Battery electric vehicle (BEV) is one of PEV subcategories (other categories include hybrid technologies) and is defined as an electric vehicle (EV) that uses electric motors instead of an internal combustion engine (ICE) to propel a vehicle. The electric power is derived from a battery of one of several chemistries including lead acid, nickel metal hydride (NiMH) and lithium-ion (Li-ion).

Inevitably, batteries do discharge and need to be recharged with battery chargers. A battery charger is a device, where ac electric energy is converted into dc with an appropriate voltage level for charging the battery. Battery chargers control the charging process and therefore have a great impact to the condition and health of the battery.

Battery charging systems can be integrated either into the vehicle (on-board charger) or specially constructed charging station (off-board charger). On-board systems allow batteries to be recharged anywhere, where there is an electric outlet in present (e.g. home charging or charging at work with ground protection). The drawback with on-board charging systems is the limitation in their power output as their size and weight is restricted with vehicle design. Due to these restrictions it takes more time to recharge an EV battery compared to off-board systems. Off-board charging systems enable fast charging, where the vehicle is charged in less time. It is possible to charge a battery in 15-30 minutes with increasing battery's state of charge (SOC) from 20 % to 70-80 %. Off-board charging systems are limited in their power output only by the ability of batteries to accept higher charging currents.
The drawback with off-board systems is the restriction with flexibility to charge at different locations. As off-board charging systems are big in size, they are quite costly solutions as investments have to be made into property.

Additional charging options include contactless inductive charging or battery replacement services.

III. IEC 61851 CHARGING MODES AND APPLICATIONS

Standards for EV charging is a widely discussed topic nowadays. There are existing different types of charging modes, different types of connectors and protocols. Japan, e.g. has the CHAdeMO standard for ultrafast dc charging, while in Europe, IEC 61851-x standard is still under discussion for EV charging as well as the IEC 62196-x standard for the charging connectors.

According to the IEC 61851-1 standard there are 4 types of charging modes:

- **Mode 1 - slow charging from a household-type socket-outlet:**
  - For Mode 1 the electric outlet is non-dedicated, conventional household plug can be used. Earthing is essential for safety and a residual current device is mandatory. The charging mostly takes place with Single-Phase 230 V ac voltage, with maximum current of 16 A per phase, where the charging power is in the range of 3-11 kW.
  - This type of normal ac charging has a long charging time (approximately 8 hrs.) and is usually done overnight. This is mainly due to a fact that domestic household plugs are usually designed up to 16 A (moreover the maximum continuous current is also limited up to 10-13 A). The basic converter is located inside car. This type of charging is relatively simple and cheap.

- **Mode 2 - slow charging from a household-type socket-outlet with an in-cable protection device:**
  - Mode 2 is suitable for office workplaces (e.g. in/outdoor office garages or car parking places), commercial complex parking garages etc.

  For Mode 2 the electric outlet is non-dedicated. An additional inline control box is required, which must be located near the plug or in the plug. The supply network side of the cable does not require a control pin (it is required only on the side of the EV) and the control function is governed by the control box in the cable. Cable contains an intermediate electronic device for Control Pilot and residual current device. These provisions allow charging stations to be with low complexity, while extending the permissible range of charging currents compared to Mode 1 charging. The charging mostly takes place with 3-phase 400 V ac voltage, with maximum current of 32 A per phase, where the charging power is in the range of 7.4-22 kW. Mode 2 is suitable for semi-public charging, where EV charging takes place at office workplaces (e.g. in/outdoor office garages or car parking places), commercial complex parking garages etc.

- **Mode 3 - slow or fast charging using a specific EV socket-outlet with control and protection function installed:**
  - For Mode 3 the electric outlet is dedicated, socket outlet specific for EV must be used (5 or 7 pins for EV connection). The mode is commonly known as ac fast charging. Mode 3 connectors according to IEC 61851-x standard require a range of control and signal pins for both sides of the cable. EV power demand is regulated through the control pilot line modulating a pulse width modulation signal. Protection is realised with control pilot function. The charging station socket is dead, if no vehicle is present - the pilot pin in the plug on the charger side controls the circuit breaker. The charging mostly takes place with 3-phase 400 V ac voltage, with maximum current of 63 A per phase, where the charging power is in the range of 14-44 kW. The communication wire between car electronics and charging station allows integration into Smart Grid scenarios. This type of ac fast charging (semi-fast with charging power 6-10 kW, fast over 22 kW) takes approximately 2 hrs. The drawback with such charging is the necessity of an advanced converter inside the car, which has a high weight. Mode 3 is also suitable for semi-public charging.

  For Mode 4 the supply network ac power is converted in the charging station to dc, thus the mode is commonly known as dc fast charging. The electric outlet is dedicated, socket outlet specific for EV must be used. The plug type ensures that only a matching electric vehicle can be connected to the off-board charging station. Control pilot function extends to equipment permanently connected to the supply. The charging mostly takes place with 500-600 V dc voltage, with maximum current of 400 A, where the charging power is in the range of 50-150 kW.

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  This type of dc fast charging is ideal for public charging for quick top-ups of battery power. Charging takes approximately 30 min (e.g. for 25 kW battery). Mode 4 (and also Mode 3) charges the battery only to a certain degree (typically to 80 %). Fast charging does not allow final charging. The advantages with this type of charging is that only a basic converter is required inside the car, which has low weight. High power converter is located outside the car. Charging powers can go up to much higher values compared to the on board charging. The drawbacks include expensive costs for high power charger and investments into infrastructure as higher powers are not available in domestic environment. Infrastructure consists of a filling station, specific charging hardware (charging station, plug, cable) and software (station's panel). Software must be able to identify the user, collect data from electricity meter, manage payment and billing, roaming, remote maintenance and load management.

  With public fast charging risks are considerably higher than with ac low voltage home charging. The two main risks are in personnel safety and higher short circuit levels. Also connectors used in charging must be able to handle higher power levels. Charging has to be comfortable, have an easy-to-use human-machine-interface for operation, client must be easily authenticated.

  Many car manufacturers develop their own electric vehicle models and charging methods. The variety in charging changes from (e.g. BMW, Mercedes, Mitsubishi [3]):

  - 1-phase 230 V ac, 13-32 A, charging power 3-7.4 kW for battery capacity 15.3-44 kWh;
3-phase 400 V ac, 16-36 A, charging power 11-25 kW for battery capacity 16.5-36 kWh; 330-345 V dc, 120 A, charging power 50 kW for battery capacity 16-24 kWh.

IV. CHAdeMO STANDARD

"CHAdeMO" is an abbreviation of "CHArge de MOve", equivalent to "charge for moving", and is a pun for "O cha demo ikaga desuka" in Japanese, meaning "Let's have a tea while charging" in English [4]. CHAdeMO is a charging protocol for rapid dc charging issued from TEPCO (Tokyo Electric Power Company). Common type of charging is with 50 kW dc voltage. Max figures include dc output 62.5 kW, dc voltage 500 V, dc current 125 A. CHAdeMO does not work for current battery chemistries to much over 90% SOC. Charging curves are typically 1.2 C - 4 C (up to 10 C).

High (ultra) voltage power grid can supply electricity to quick charger easily. If there are enough quick chargers in public areas, drivers will satisfy with small size on-board chargers.

EV computer decides optimal charging current based on its battery condition (BMS observation [5]). Charging current signal is sent to charger using CAN bus. Additional analogue communication allows fail safe design. Charger supplies dc current following order from EV computer.

CHAdeMO quick charger can change charging speed to meet each batteries characteristics and condition. When charging speed is well controlled there is no negative influence to the lifetime of battery (battery must support fast charging). The more higher current the battery can absorb the more higher power it can receive.

“Fig. 1" represents a basic off-board charger, which consists of: main supply income (power grid), ground fault interrupter (GFI) between grid and charger, ac input filter, input rectifier (e.g. diode bridge), dc link, full or half bridge inverter, isolation transformer, output rectifier, output LC filter, ground fault interrupter (GFI) between charger and EV [6].

Filter in ac part removes higher harmonics distortion to protect power grid. Power fraction corrector improves conversion efficiency and performance. Isolation transformer is necessary for separating battery circuit from grid for operator protection against electric shock. Output LC filter reduces ripple noise from output current to protect battery system. Ground Fault interrupters/earth leakage breakers (GFI/ELB) are for rapid response for earth leakage to protect operator from electric shock. One GFI/ELB is for monitoring charger's primary side of transformer and other for monitoring secondary side of transformer and vehicle.

Advanced off-board charger has in addition to basic configuration also bidirectional energy flow capability and additional energy storage device.

The charger's power cabinet can be separate from the charging station or integrated with the charging station. When separated, there is less visual impact for customers. With multi-output topology there can be one common input section for all the charging converters. Incoming power can be reduced, if a simultaneity index is considered. Should there be only one charging station the one cabinet solution is cheaper.

V. ANALYSIS OF POWER TRANSFER BETWEEN GRID AND CHARGER

For describing a charger working in 4 quadrants a simplified (ideal) model is represented. Positive current direction from the power grid to the inverter is firstly viewed. Schematic for the model is shown in “Fig. 2” [7]. The model parameters are given as follows:

\[ v_c(t) \] instantaneous charger voltage [V],
\[ v_s(t) \] instantaneous grid voltage [V],
\[ i_c(t) \] instantaneous charger current [A],
\[ L_c \] coupling inductor [H],
\[ d \] phase difference between \( v_c(t) \) and \( v_s(t) \),
\[ q \] phase difference between \( i_c(t) \) and \( v_s(t) \),
\[ f \] system frequency (50 Hz).

The grid voltage is assumed to be purely sinusoidal. For simplification, high frequency components of inverter output voltage, \( v_s(t) \), is neglected. Following equations can be derived:

\[ v_s(t) = \sqrt{2} V_s \sin(wt) \],
\[ v_c(t) = \sqrt{2} V_c \sin(wt - d) \],
\[ X_c = 2\pi f L_c \].

Fig. 1. Topologies of dc fast chargers according to CHAdeMO standard.
For describing power transferring from charger to grid in the model, two voltage sources should be viewed as decoupled in “Fig. 2” and coupling inductor is to be viewed as a source. From this model simplification line current can be written as:

\[ i_c(t) = \sqrt{2}I_c \sin(\omega t - q) . \]  \hspace{1cm} (4)

Since the default direction for active and reactive power transfer is from grid to charger, \( i_c(t) \) and \( v_c(t) \) are lagging the grid voltage:

\[ V_s = V_c + jX_c I_c . \]  \hspace{1cm} (5)

P-Q plane shown in “Fig. 3” indicates all the different operation modes in which the system can be working. Active power is provided by the grid as long as \( v_c(t) \) lags \( v_s(t) \), and it is sent to grid when \( v_s(t) \) lags \( v_c(t) \). Since \( v_c(t) \) and \( v_s(t) \) are sinusoidal, \( i_c(t) \) is also sinusoidal as shown before. Its phase angle, \( q \), determines the direction of the reactive power flow. If \( q \) is positive, reactive power is sent to the grid, and if \( q \) is negative, reactive power is provided by the grid to the charger.

VI. BIDIRECTIONAL CONVERTER TOPOLOGY

Bidirectional converters allow energy to flow in two directions (provide energy from the grid as a power source to charge the battery and to give power back to the ac power grid with discharging the battery). Several different power electronic circuit topologies for bidirectional converters are possible. The evaluation and development of the optimized converter is still a challenge. Optimized topology depends on the power rating. Single-phase Power Factor Corrector (PFC) mains interfaces can be used for low charging power levels (P < 7 kW).

For higher charging power levels 3-phase PFC interfaces have to applied. Voltage and current rating as well as the operating frequency are the main criteria for the selection of the power semiconductor devices. For dc fast charging the most suitable devices are IGBTs together with ultrafast switching diodes.

One optional EV charger topology is described in “Fig. 4” [8]. The charger is composed of ac-dc-dc isolated converter with bidirectional power flow capability. The analysed structure consists of a 3-phase current source converter and dc-dc isolated converter. In this dc-dc converter, the primary side of the high-frequency transformer is a current source converter and the secondary side is a voltage source converter. Current of the ac-side is controlled by the voltage of the inductor in the dc-side. Current and voltage in dc-side can be regulated in a wide range from zero to the rating value. Current and voltage in ac-side have low total harmonic distortion and power factor in a wide output power range.

3-phase current source converter consists of 6 fully controlled switches (S11-S16) and 6 diodes (D11-D16). Ac-dc converter is necessary to realise the line-side sinusoidal current curve with the pulse width modulation (PWM) control strategy.
Elements S17 and D17 provide a bypass to reduce the voltage spike of the switches, when they are turned on or off. The isolated dc-dc converter consists of high-frequency transformer with current source converter (S21-S24 and D21-D24) at its primary side and the voltage source converter (S31-S34) at its secondary side. Converter can change the direction of the current conveniently through the voltage polarity control of the CSC II in the dc-dc converter.

When charging the battery, input current phase is the same as the input voltage phase in the 3-phase ac grid system. Converter transfers power from ac-side to the dc-side. CSC I works as a rectifier.

When discharging the battery, the voltage phase is reversed to the current phase in a 3-phase ac grid system. The proposed converter transfers power from the dc-side to the ac-side. CSC I works as an inverter. The current direction is the same when charging or discharging the battery, but the voltage phase is reversed to the current phase at the ac-side.

For higher charging power levels, the necessary output current can be generated by connecting smaller modular chargers in parallel (“Fig. 5”). One charger will have to be the master and others slaves. Each individual modular charger has its own protection fuses, filters and IGBT bridges, which are controlled by using PWM-switching technology. Information from the main controller is sent to the IGBTs by means of an optical link. The maximum output current depends on the power ratings of individual chargers and also on how many modular chargers can one main controller handle. Depending on the topology of chargers, preloading circuit might be necessary to charge capacitors in the dc side to ensure a smooth start-up without excessive inrush currents.

VII. SMART GRID

In the concept of Smart Grid, centralized power systems (top-down principle) [9] should change to distributed power systems in the future (“Fig. 6”). Smart Grid’s goal is to supply and consume energy in a reasonable way that sufficient energy can be available at all times and with high quality.

Smart Grid includes data communications Network, which is integrated with the power grid. Communication Network enables power grid operators to collect and analyse data about power generation, transmission, distribution, and consumption - all in near real time. Smart Grid technology predicts energy consumption and recommends to suppliers and consumers the best way to manage power.

Most of entities of Smart Grid become active. They are both users and producers of electric energy (e.g. smart buildings). Users of electric energy become prosumers. The EVs and charging stations can be a part of the interacting Smart Grid. EVs are mobile energy storing systems, which can participate in energy trading. Vehicle-to-grid (V2G) describes a system, in which EVs communicate with the power grid to sell demand response services by either delivering electricity into the grid or by throttling their charging rate. Energy storage systems enable storing energy and transferring energy back to grid, when necessary. Substation equipped with energy storing or V2G system enables peak load shaving and demand response, which will reduce/postpone the need to make new investments into building new power sources or power grids to meet peak demand. Energy storing systems enhance renewable energy resources efficiency, compensate reactive power peaks in the grid to reduce losses and enhance active power let through.

VIII. DESCRIPTION OF AN EXAMPLE SUBSTATION

Utility networks are typically designed for specific load carrying capability. When EVs are added to the utility network, load patterns will be changed drastically. This may lead to overloading of the utility in some periods of the day, making electric circuits and transformers vulnerable. Before integrating a filling station to an existing power grid, calculations have to be made to verify that the power grid can withstand filling station loads. In the concept of smart charging, EV charging is controlled with available sources in the power grid.

Calculations have to consider that dc fast charging should not take more than 30 minutes. If we look at an EV, which requires 15 kWh of electric energy to travel 100 km (rule of thumb in most cases), this will require minimum of 30 kW charging power (15 kWh divided by 0.5 hours). If we consider that recharging the battery should take as much time as refilling a petrol car, e.g. 5 minutes, this requires 180 kW charging power. For simplification, assume that a filling station consists of 10 charging stations (CS). If all 10 charging stations are occupied, the filling station requires minimum 300 kW charging power (30 minute charging time for 10 CS x 15 kWh) or maximum of 1800 kW charging power (5 minute charging time for 10 CS x 15 kWh). The difference between maximum and minimum is 6 times.
This difference is a challenge, when designing a new prosumer connection to the power grid, which includes a filling station. In 3 phase 400 V ac power grid, this will require minimum of 433 A transfer current and maximum of 2598 A transfer current. These figures indicate clearly that a dc fast filling station is a burden for the power grid and therefore cannot be designed to a low voltage grid (e.g. residential area), but should be designed into a medium voltage (MV) grid.

A substation for filling station should distribute and control electric energy flow from MV grid to charging stations, distribute energy to other ac consumers (e.g. nearby buildings), store electric energy and be a part of the power grid communication infrastructure for Smart Grid scenarios. Substation must enable for charging stations ac slow charging (1 phase charging power 3.7 kW, max. charging current 16 A, charging voltage 230 V ac), AC fast charging (3-phase charging power 22 kW, max. charging current 32 A, charging voltage 400 V ac) and dc fast charging (charging power 50 kW, max. charging current 125 A, charging voltage 50-600 V dc, power factor 0.97-0.99) [10]. Electric energy can be stored from nearby renewable resources, which can be taken into use e.g. in case of power grid supply interruption. As several converters are required in the filling station, filters have to be included in the substation to remove higher harmonics distortion to protect the power grid. Substations equipped with supervisory control and data acquisition (SCADA) remote terminal unit (RTU) systems cannot be scaled and should evolve to support next generation intelligence for Smart Grid scenarios. The medium voltage incoming cable from utility network is connected to the MV switchgear “MVSW” incoming cubicle “MVI”. The selection of type of switchgear depends on the medium voltage range. Commonly in Estonia 6-24 kV equipments are used.

The “MVSW” switchgear consists of modular cubicles equipped with SF6 or vacuum air breaking technology. Circuit breaker feeders “MVF 1” to “MVF n” (“Fig. 7.”) are equipped with motor drives, opening/closing command coils and with earthing switches. Mechanical interlocks prevent operating earthing switches and breakers at the same time, guarantee earthing at working with cables. “MVF 1” to “MVF n” cubicles include multifunctional protection devices [11] with IEC 61850 communication protocol for protection, monitoring and controlling systems, metering and signalling, communication, auto diagnostics. Switchgear is provided with “MVT” cubicle, which includes MV surge arresters and voltage transformers for relay protection. Separate control switchboard “DCSW” is used for transferring supply voltages to different “MVSW” devices. “DCSW” includes ac-dc converter “ADC” and dc-dc converter “DDC”. “DCSW” switchboard supplies different relay and device circuits “DD1” and “DD2”. “DCSW” includes batteries “ESD” for uninterruptable power supply.

For remote control the MV side requires separate RTU (remote terminal unit) switchboard “RTU1” (“Fig. 7.”). Multifunctional protection devices are connected with fiberoptic cable to “RTU1” fiberoptic input terminal “FO”. Different relay signals “REL”, position and fault signals of devices “DIT”, different digital inputs “DI”, fiberoptic input terminal “FO” are connected to “RTU1” data concentrator and annunciator terminal “RTA”, which transfers and receives data from SCADA centres. “RTU1” is equipped with temperature sensor “TEMP”, which value is sent to SCADA system. “RTU1” transfers control signals (e.g. MV circuit breakers in or out), position signals (e.g. position of breakers and earthing switches, blown fuses or tripped breakers, battery faults in dc switchboard, security and fire alarms), measuring values (e.g. current, voltage, active and reactive power, short circuit fault location).

IX. SUBSTATION TOPOLOGIES

A. Medium voltage side and low voltage side in the substation

An example topology of medium voltage side of a substation for EV filling station is shown in “Fig. 7.”.

![Fig. 7. Topology of medium voltage side of the substation.](image)

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![Fig. 8. Topology of low voltage side of the substation.](image)
One of the “MVSW” outgoing cubicles (in this case “MVF 1”) is connected with the transformer (“TRANSFORMER” on “Fig. 7”). As an option MV metering panel “MVM” can be included before the transformer. Transformer converts MV voltage to low voltage (LV).

Low voltage side of the transformer (“Fig. 8”) consists firstly from devices for protection (ground fault interrupter “GFI”, surge arresters “SP”, undervoltage relay “VM”), main circuit breaker “LVCB”, devices for metering “LVM”, devices for self-consumption of substation “SCS” and “RTU2” for the low voltage. Substation’s self-consumption circuit consists of fused main switch “FSS” and several distribution circuit breakers and switches for controlling lighting and ventilation “LIG”, heating “HT” and socket connections “SOC” in the substation. Additional control circuits include relay circuits (“REL1”, “REL2”, “REL3”), emergency switch cut-off circuit (“EMG”), rectifiers to convert 230 V ac into 24 V dc (“ADC1”) and 12 V dc (“ADC2”). Main circuit breaker “LVCB” is equipped with motor drive for opening/closing the breaker automatically. The low voltage side in “Fig. 8” consists of a smart electric meter “LVM”, which is capable of transferring measurement value data with IEC 61850 protocol. Smart electric meter is particularly necessary to measure higher harmonics in the low voltage grid.

IEC 61850 communication links are collected to one main switch “SWITCH1” (“Fig. 8”), which supports IEC 61850 protocol. The switch transfers data to central controller “CONTROLLER1”. The controller is supplied through uninterruptable power supply “UPS1”. The central controller processes data gathered from measuring devices, bidirectional chargers and charging stations (presented later on “Fig. 9” and “Fig. 10”). The controller runs protective and controlling functions throughout several function stages: start-up stage, normal operation stage, emergency stage (e.g. supply interruption), restart stage (voltage returns). The central controller determines how many bidirectional converters have to be connected in parallel (to achieve the necessary output power to supply all the charging stations) based on the measuring information from the “LVM” meter and control links from the bidirectional chargers. The central controller also needs communication links to charging stations to be able to identify the battery back of the EV. Controller controls energy flow to the energy storing system and energy back from the storing system to the low-voltage grid.

Previous parts have described how electric energy is transferred in the substation from medium voltage grid to the low voltage grid. Following parts describe topologies how electric energy can be converted to dc voltage, for charging EVs, and stored, which enables Smart Grid scenarios.

**B. Common dc bus topology**

An example topology for supplying charging stations through substation is shown in “Fig. 9”. Bidirectional chargers “BC 1” to “BC n” convert mains ac voltage and current into dc voltage and current (“Fig. 9”). Chargers are protected with fuses “FABC 1” to “FABC n” and controlled through contactors “CBC 1” to “CBC n”. Charging stations “CS 1” to “CS n”, energy storage device “ESD” and renewable energy resources (“WIND POWER” and “SOLAR POWER”) are connected to the same dc main bus system (“common dc bus”).

![Fig. 9. Common dc bus topology.](image-url)
LCL filters “LCLF 1” to “LCLF n” must be used before chargers on ac side to reduce harmonic levels in the ac power grid. Common dc bus has a bus coupler “BCDC”, which allows energy to flow separately into the storing system “ESD” through bidirectional dc-dc converter “BCES” (e.g. battery pack has low capacity). Energy flow is controlled in the dc system through dc contactors (“CDCS 1” to “CDCS n”, “CES”, “CTW”, “CTS”), bidirectional dc-dc converters (“BCS 1” to “BCS n”) and protected with ultra-fast acting fuses (“FDBC 1” to “FDBC n”, “FDCS 1” to “FDCS n”, “FES”, “FDW”, “FDS”). “CONTROLLER2” controls “BCS 1” to “BCS n”, monitors common dc bus voltage and communicates with “SWITCH2”. Charging stations are separately monitored with ground-fault interrupters (“GFID 1” to “GFID n”, “GFIA 1 to “GFIA n”).

The 400 V ac main grid is used for transferring ac power to the charging stations for ac fast charging through circuit breakers “FACS 1” to “FACS n” and contactors “CACS 1” to “CACS n”). The ac main grid is also used to transfer energy to other ac consumers (“FEB”) connected with the substation (low voltage switchboards for buildings, residential areas, street lighting etc.).

The advantage with “common dc bus” topology is a fact that there is only one bidirectional charger in the ac power grid. The charger may consist of several smaller chargers in parallel (“BC 1” to “BC n”), but the controlling can be made through one common control link. In case the load of charging stations is low, some of the parallel chargers can be disconnected through contactors (“CBC 1” to “CBC n”).

The disadvantages with “common dc bus” topology are mainly related with charging of several EVs at the same time, which are connected to the charging stations at different times. Every EV requires different charging voltages for optimal charging and therefore bidirectional dc-dc converters (“BCS 1” to “BCS n”) are required in the system. Challenges are also with payment related issues as metering has to be done separately in the ac and dc side and inside the charging stations.

C. Individual charging topology

An example topology for supplying charging stations through substation is shown in “Fig. 10”. In “individual charging topology” every charging station (“CS 1” to “CS n”) has its own bidirectional charger (“BC1.1” to “BC n”). Chargers are protected with fuses “FABC 1.1” to “FABC n” and controlled through contactors “CBC 1.1” to “CBC n”. LCL filters “LCLF 1.1” to “LCLF n” must be used before chargers on ac side to reduce harmonic levels in the ac power grid. Dc energy flow is controlled through dc contactors (“CDCS 1” to “CDCS n”, “CES”, “CDES”, “CTW”, “CTS”) and protected with ultra-fast acting fuses (“FDBC 1.1” to “FDBC n”, “FDBE”, “FES”, “FDW”, “FDS”). Charging stations are separately monitored with ground-fault interrupters (“GFID 1” to “GFID n”, “GFIA 1 to “GFIA n”).

Fig. 10. Individual charging topology.
The 400 V ac main grid is used for transferring ac power to the charging stations for ac fast charging (through circuit breakers “FACS 1” to “FACS n” and contactors “CACS 1” to “CACS n”). The ac main grid is also used to transfer energy to other ac consumers (“FEB”) connected with the substation.

When chargers are placed inside the substation the charging stations take less space and fewer investments have to be made into property. Charging stations consist of connectors for the EV, controller for the communication with EV, payment system and interface panel. Metering for payment can be made inside the substation in the ac side (“CSM 1” to “CSM n”). One metering system is suitable for both ac and dc charging. Metered values are sent via IEC 61850 communication link to servers and charging stations for payment and charging information. Chargers for charging stations may consist of one charger “BC n” or several smaller chargers in parallel “BC 1.1” to “BC 1.n”. The number of charging stations defines how many charging stations the central controller (in “Fig. 8”) has to control at the same time. The energy storage system “ESD” requires separate bidirectional converters “BCES1” and “BCES2”, filter “LCLE”, ac fuses “FABE” and ac contactor “CABE”.

The advantage with “individual charging topology” is the possibility to charge EVs in a short time and every charging station can determine the most optimum charging algorithm for its connected EV. This the most crucial criteria for filling stations in public areas.

The disadvantage with such topology is that it is costs more compared to “common dc bus topology” as more chargers and devices are required in the system.

**D. Topology with two incoming transformers**

For ensuring higher reliability, topology with two incoming transformers can be considered (“Fig. 11”). In normal operation, both transformers (“TR1” and “TR2”) distribute energy to charging stations and other ac consumers. Transformers are separated from each other through bus coupling switch “LVBC”. In case of supply interruption, bus coupling switch will connected all charging stations to one of the operating transformers and disconnects the interrupted circuit’s low voltage side main circuit breaker (“LVCB1” or “LVCB2”). The switching is controlled through automatic transfer switch system (“ATS”), which can operate independently from the central controller (in “Fig. 8”). The “ATS” system can be designed on relay connections or smaller logical controller. The “ATS” status signals are connected with central controller

**E. Proposed layout of the substation**

For illustration, an example 500 kVA substation layout with “individual charging topology” is represented on “Fig. 12” and “Fig. 13”. The substation supplies five 50 kVA charging stations and 250 kVA of other ac consumers. The substation can be constructed according to customer’s specifications. Substation’s enclosure should be made out of reinforced concrete to withstand the total weight of the equipments. Separate base module is necessary for cabling. In order to prevent environmental damage, an integrated oil collector has to be installed in the base.

Substation transforms 6…24 kV medium voltage to 400 V ac voltage. The appearance (exterior finishing) and overall dimensions of the substation can vary with different requirements presented by the customer. In general, the substation consists of a medium voltage switchgear, low voltage transformer, low voltage switchgear and electric energy storing system (e.g. battery pack). The length of the switchgear depends of how many outgoing feeders are required in the medium voltage side and in the low voltage side. The substation must have internal air ducts and ventilators to extract heating losses from bidirectional chargers and remove pressure gasses from medium voltage switchgear in case of a short-circuit.
X. FUTURE STUDIES

Tallinn University of Technology is constructing a sample microgrid, from where it is possible to study energy flow and communication movement during EV charging. Microgrid consists of amongst several devices from a charging station for EV charging and battery pack for storing electric energy. The basic functions and operation modes (including protection algorithms) such as energy transmission from power grid to energy storing system, EV battery charging, balancing power loads etc. have to be developed, tested and analysed. Management softwares have to be fine-tuned. During experimentations data and measurement values will be collected to server for further analysis. Primary goals in the construction of microgrid is to analyse energy flow quality and harmonic levels during EV charging through microgrid, electromagnetic compatibility related issues. The analysis will indicate where modifications have to be made in the microgrid structure for optimization and to improve overall efficiency and power factor levels in the system to ensure quality of electricity in accordance with International standards. The practical applications will show possible drawback areas in the communication between devices, which will then have to be solved with different control algorithms. Future studies will focus more on V2G and Smart Grid solutions. In V2G connections energy will be firstly saved from EV to energy storing system and used inside the microgrid. Further studies will look into possibilities to transfer energy to outside power grid with synchronization related issues.

XI. CONCLUSIONS

This work has given a brief overview of substation topologies. Before constructing a real life substation a smaller prototype has to be constructed. This is planned to be realized in constructing a microgrid in Tallinn University of Technology. Experiments with the microgrid will give vital data about charging algorithms and communication movement between devices. From these studies it will be possible in the future to construct a larger real life substation, which would be able to supply power to several charging stations and be part in Smart Grid solutions.

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