INTEGRATION, ANALYSIS AND OPTIMIZATION OF COMPONENTS IN SECONDARY SUBSTATIONS FOR E-MOBILITY

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ABSTRACT

Despite the significant advances in the battery electric vehicles, there are still some restrictions that have to be addressed by electrical energy stakeholders. These are mainly long charging times, lack of high-power charging infrastructure and power grid requiring additional energy resources to cope with the power peaks.

This paper provides an overview of different power electronics converters for e-mobility as well as power architectures for integration of high-power chargers within a secondary substation with battery energy storage and renewable generation. A cloud-based energy management system is also presented.

INTRODUCTION

In the today's booming segment of e-mobility due to ambitious targets to limit the CO_2 emissions, governments, car manufacturers, and charging infrastructure providers have entered into many agreements to create and develop charging networks.

In the actual electric energy systems, the generation is practically following the electrical demand. At the same time, the fluctuating renewable generation is increasing with the aim of achieving zero carbon emissions. This leads to a power generation not depending on the demand. Considering the above scenario of ambitious targets on electrical mobility and the already increasing electric vehicles (eV), the challenges for the energy systems are based on adaptation of the current generation with a flexible demand. The future increased demand of charging point along the distribution network leads to carefully review the grid infrastructure, which in some of the cases will not be worth economically to re-structure. In this aspect is where electrical energy storage within the distribution substations comes into the picture for balancing generation and demand in the point of connection.

The actual trend is leading to fast charge electrical vehicles in public places such as malls, supermarkets, parking places and on the highways. Long trips between cities and regions need a charging network connected to the medium-voltage (MV) in order to extend the use of eV to cover long distances. This is leading to new challenges for the distributor system operator (DSO) due to high demands in power with non-traditional load profiles as the charging starts when the car is plugged-in [1], [2], [3]. High power charging, in the range of hundreds of kilowatts, requires a medium-voltage network connection for the substation. Other options for low-power charging can be achieved via connection on the low-voltage grid.

In order to cope with the challenges and to be competitive in this segment, standard products with reduced on-site works are needed always having in mind safety for public as factor of paramount importance. At this point is where one complete package fully assembled and factory tested before delivery to customer comes into the picture as a secondary substation integrating all the needed equipment from grid connection to eV chargers having also the possibility to integrate energy storage as well as distributed generation such as solar and wind (see Fig 1).

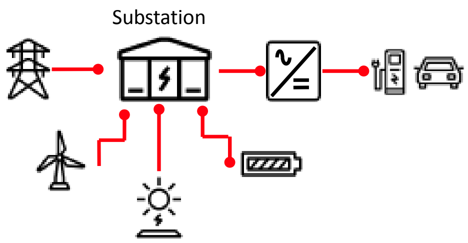

Fig. 1: Integration of equipment within a secondary substation for e-mobility.

In the competitive environment of the e-mobility, stakeholders are forced to rethink their equipment investment and maintenance strategies. Economic perspective points out the need for extended lifetime and reduced maintenance costs for substations and the equipment enclosed within them to reduce lifecycle costs. From the point of view of reliability, substations that offer benefits in terms of service conditions with extended lifetime are required.

The lifetime of secondary substations is mainly dependent on the lifetime of the equipment installed within them. However, the enclosure housing this equipment also plays an important role as it is the key element in providing protection to the equipment. Based on [4], due to the competitive advantage which glass-fiber-reinforced polyester (GRP) presents over steel or concrete as material for the housing, GRP is the material considered as the most convenient for the substation enclosure to comprise all the equipment needed for integrated e-mobility substation.

The charging of the eV is a key matter considering the two triggers of being convenient and economically feasible. Efficient solutions are needed in the distribution network to integrate the charging points into the overall electrical system. Taking into consideration the interfaces between the energy utilities, the charging substations and charging points as well as the eV, there is a need to have the right information on time and for that communication technologies have to be in place. At the same time the equipment mix within the substation leads to a need of having an energy management system (EMS) in order to be able to monitor and control the energy flow within different assets and at the same time serve as asset management (see Fig. 2).

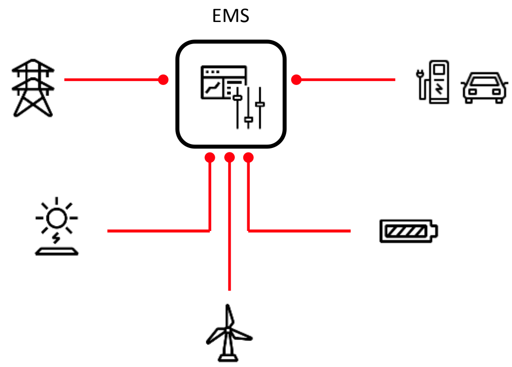

Fig. 2: Energy management system simplified scheme.

The present work is divided into the following sections: the first section presents the analysis of network components at secondary substation level available in the state-of-the-art for power architectures; the next section presents an overview of applications achievable with an integrated substation and deals as well with the monitoring and control needed to optimize the energy flow, followed by conclusions.

INTEGRATED SUBSTATION FOR E-MOBILITY

This section aims to analyse the power electronics converters for power charging and the architectures for the fast power charging based on these as well as the integration of renewable resources and battery energy storage within the secondary substation.

Power electronics converters for eV charging

AC/DC input stage

AC/DC topologies comprise from AC/DC passive rectifier to active rectifiers as input stage. Passive solutions for high-power charging will normally require a 12-pulse system fed from a MV/LV transformer with double secondary winding Δ and Y to reduce the harmonic content and fulfil the requirements of grid standards. However, 12-pulse solutions can be also used when considering active front end. The main advantage of passive solutions is the no need for digital control of the input stage, having as a downside the need of more complicated filters and the need of output diode before the charging post.

Active rectifiers, by means of the digital switching of IGBT or most recent MOSFET SiC together with passive filters present the following advantages compared to the passive solutions:

- Linear load seen from the grid with low harmonic content demanding a sinusoidal current from the grid.
- Possibility to control active and reactive power flow with the possibility to operate with a unit power factor.
- Bidirectional energy flow between AC and DC buses to allow return of energy to the grid from the eV to achieve vehicle to grid (V2G) functionality.

DC/DC output stage

In terms of the output stage, a DC/DC conversion is needed in both isolated and non-isolated topologies depending on where the needed galvanic isolation is provided between charging posts for multi-charging solutions.

Typical topologies such as Buck, Buck-Boost or ZETA for bidirectional energy flow can be used for the case of non-isolated solutions. For the case of high-frequency isolated converters, dual active bridge topologies are used in order to provide bi-directional energy flow. The main advantage of isolated solutions is the reduction of weight and overall dimensions due to the magnetics reduction based on high-frequency.

For high-power charging, in order to increase efficiency, having a modular converter comprised by *n* identical modules allows to utilize multi-pulse techniques with voltage shifting achieving thus a reduced current pulsation. At the same time, having a modular design lead to an easy optimization of parameters, dimensions and cost due to economy of scale.

Power architectures for fast charging with MV connection

In fast and ultrafast charging systems, the substation for e-mobility is normally connected to the MV distribution network by means of a MV switchgear which provides control, protection and isolation of the electrical system and a MV/LV transformer to accommodate the voltage levels. It has to be mentioned the possibility of having a multi-winding MV/LV transformer to provide the galvanic isolation between charging points in the case of multi-charging substations. This will lead to a simplified output stage of the DC/DC converter which feeds the eV. However, the design of the transformer becomes complicated and costly for more than three secondary outputs due to the unbalance of the impedances between outputs based on the unusual construction of the transformer with the primary winding close to the core and the secondaries placed around the primary. Due to these drawbacks, the present work considers a standard MV/LV transformer in both 6 or 12-pulse solutions.

Different possibilities for power architectures in terms of smart AC or DC bus are possible when considering different topologies of AC/DC and DC/DC power electronic converters depicted above and multi-charging points.

Common AC bus (Fig. 3) is the preferred architecture for AC distribution networks to enable the energy management and flow between the charger systems, the renewable energy resources, the energy storage and the grid. In this case, the MV/LV transformer feeds a common AC bus where all the equipment is connected by means of a low-voltage switchgear to provide protection and control. In this solution, the electricity is distributed and controlled by the AC/DC active rectifiers present in the architecture available at the battery energy storage, solar converter and the eV chargers in the case of being bi-directional.

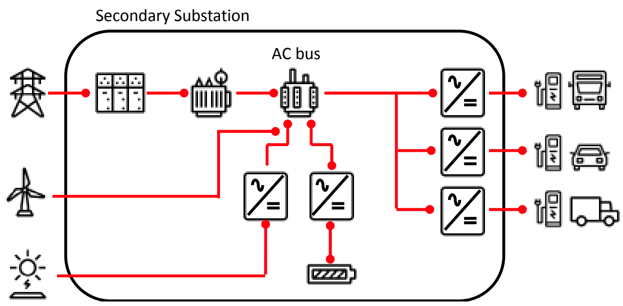

Fig. 3: Common AC bus power architecture.

New developments in distributed energy resources and renewable energy are leading to increased interest in DC energy distribution. Fig. 4 shows a DC common bus distribution system fed from a high efficiency AC/DC converter connected to the LV winding of the distribution MV/LV transformer. In this case, the eV chargers comprise only the output stage, having thus a reduction in complexity and costs. The efficiency is as well increased due to the less energy conversion stages.

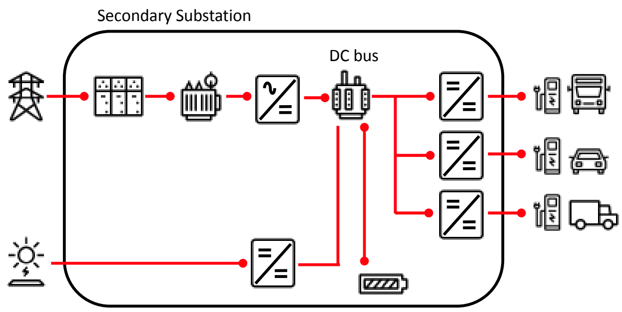

Fig. 4: Common DC bus power architecture.

Moving towards high-power for fast charging might cause issues on the network due to the amount of power which is required by the eV which has to be supplied from the grid via the secondary substation. These issues are mainly focused on voltage and frequency fluctuation due to demand and generation unbalance. A way of overcoming the possible issues is to provide the substation with a battery energy storage system (BESS). Fig. 3 considers an energy storage connected to the AC bus meanwhile Fig.4 considers this connected to the DC bus.

Renewable energy resources are possible to be integrated as well within the system by connecting the solar energy via a DC/AC converter in the architecture shown in Fig. 3 for common AC bus or via a DC/DC converter in Fig. 4 for a common DC bus architecture. Wind power generation is more feasible for the common AC bus architecture of Fig. 3 due to the on-the-shelf wind turbine solutions present on the market. In the next section, the advantages of the system considering renewable generation and energy storage are depicted.

New developments are moving towards connecting a cascaded high-frequency (HF) isolated AC/DC converter directly to the MV network. The IGBT technology nowadays reaches up to 6,5kV switches, therefore in order to be able to connect to typical MV networks of 10kV and 20kV, multilevel topologies are used. An example of a MV converter is shown in Fig. 5. In the case of multi-charging points needed as well as the integration of energy storage or solar energy, a multi-winding HF transformer can be used with cascaded AC/DC converters connected to the secondary windings.

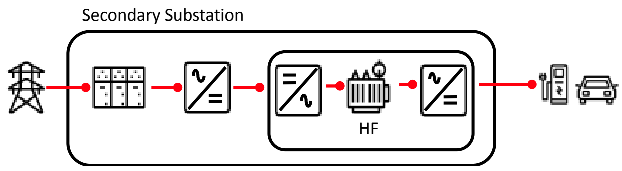

Fig. 5: Architecture with MV AC/DC converter.

The main advantages of using this technology and architecture are based on the reduction in weight and dimensions of the power transformer, as in this case, the galvanic isolation is achieved by a HF transformer within the DC/DC output stage. Other advantage is also achieved due to the modular design. The main drawback of this solution is the number of gate drivers needed to switch the IGBTs in the input AC/DC converter, making the solution hard to control where the reliability might be jeopardized based on the number of drivers and modules.

OPTIMIZATION OF A SECONDARY SUBSTATION FOR E-MOBILITY

Although common AC bus power architecture as the one depicted in Fig. 3 is not the most efficient in terms of power conversion stages, integrated substation manufacturers trend to modularize the products in a sense that the system can be easily upgraded. For example, a substation with common AC bus as the one depicted in Fig.

3 delivered and operating without BESS and PV can be upgraded by the connection to the AC bus of the pertinent converters and the upgrade of the control. Therefore, for the present work the integrated substation is considered as shown in Fig. 3 with common AC bus for a high-power charging substation connected to the MV grid integrating renewable local generation and BESS.

Integrated substation owned by DSOs or for behind-the-meter applications as the one under discussion in this section, where eV chargers are present as load together with local PV and wind generation and BESS as storage solution, provide numerous applications and advantages for different stakeholders.

Peak-shaving is the main goal of the BESS within the substation. This application is achieved by reducing the demand to a much smaller and constant power than the one required by the eV. This can have big economic impact on those countries where power fee is present, benefiting thus the main stakeholder of the substation. This also benefits and support the grid as there is no need to reinvest in power lines and main transformers on those locations where a bottle neck in the grid might appear.

The renewable integration is done with the BESS support. Fluctuating generation can be smoothened up via charge or discharge of the batteries. In a situation where eVs are not charging, the renewable energy is stored in the batteries in order to increase the state-of-charge (SoC) of the batteries for further dispatch to the eV. In the case the SoC is close to 100%, the renewable energy is injected in a smooth way into the grid or used to feed the auxiliary services of the eV charging substation.

Other applications, though not primary for this case, are achievable by having an integrated substation as the one in the present work. These applications besides others are harmonic mitigation, reactive power compensation, voltage and frequency support.

It has to be noted that the combination of applications can be an important key feature in a near future. However, control strategies for the system with a mix of applications may be challenging due to the involvement of different stakeholders. Future grid with high penetration of renewables, distributed energy storages and electrical mobility as main means of transportation, points out the need of pooling and coordinating multiple integrated substations as the one in the present work.

Different modelling tools are available in the market as the one depicted in [7]. However, different challenges such as revenue maximization, efficiency maximization or CO_2 impact minimization can only be achieved using specifically adapted optimization techniques. The benefit of an integrated substation for e-mobility comprising BESS and renewable generation is affected besides others by the following factors depending on the number of the charging points: dimensioning of the BESS and the renewable generation, optimal place in the grid infrastructure as well as the energy dispatch and control obeying the desired applications.

Monitoring and control

In the present area of the digitalization, the Internet of Things (IoT) is a reality which leads to an increasing number of decentralized systems with distributed control. At the same time, these distributed control systems can operate in a coordinated or non-coordinated way.

Due to the uncertainties involved in the control of an integrated charging substation (renewable generation, eV demand, grid status, etc.) the control system has to be able to adapt in real time.

The architecture of the control system presented in Fig. 6 is a cloud-based energy management system. As all the equipment is housed within the same enclosure, this control system includes all the interfacing between different power electronics converters, thermal management system, protection devices and environmental conditions.

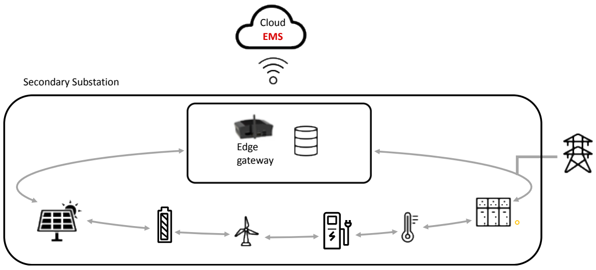

Fig. 6: Cloud-based energy management system for an integrated substation for e-mobility.

Due to the different sensors and devices present in the substation which generate thousands of data per second, an edge gateway is used in order to collect and pre-process the data locally before sending it to the cloud. This approach allows also the possibility to implement a basic local control in the case there is no requirement for cloud connectivity and complex control algorithms, making the solution modular.

An added value of this solution is the possibility to implement at the same time asset management and obtain in real time the health of all the interconnected equipment. This reduces the operational costs due to the approach of condition-based-maintenance driven by the technical condition of the equipment. Both EMS and asset management can be visualized and managed remotely.

CONCLUSIONS

In order to cope with the actual challenges of the integration of e-mobility in the power grid with an increased and punctual demand of energy, reinvestment in the network is not always an option. BESS has been identified as the most convenient way to balance demand and generation, which in some cases can be local by means of PV or wind.

In terms of a cost-effective solution, standard products with reduced on-site works are needed, as the integrated substation for electric mobility which has been presented. This comprises a different number of power electronics converters: eV charging converters, BESS converters and renewable generation converters.

An analysis of different power converters for eV has been presented as well as the possible different power architectures for an integrated substation considering common AC or DC bus. Due to simplicity, availability in the market, possible modularization and ease of upgrade, an integrated substation with common AC bus has been considered as the most feasible solution nowadays.

Different applications of the BESS within the substation have been briefly discussed pointing out the need of a real-time control of the system. For this purpose a cloud-based energy management system has been presented.

REFERENCES

[1] G, Mauri, D. Bertini, E. Fasciolo, S. Fratti, 2013, "The impact of ev's fast charging stations on the mv distribution grids of the Milan metropolitan area", *Proceedings 22nd International Conference on Electricity Distribution - CIRED conference*, no. 1266, 22-24.

[2] C. H. Dharmakeerthi, N. Mithulananthan, T. K. Saha, 2012 "Modeling and planning of EV fast charging station in power grid," Proceedings *IEEE Power Energy Soc. Gen. Meet*., pp. 1–8.

[3] G. Celli, S. Mocci, F. Pilo, G. G. Soma, E. Fasciolo, 2013, "Distribution Network Planning in Presence of Fast Charging Stations for Ev," *Proceedings 22nd International Conference on Electricity Distribution - CIRED conference*, no. 1500, pp. 1–4.

[4] C. M. Nieto, D. Türk, A. Palgi, 2017, "Comparative advantage of using GRP in compact substations" *Proceedings 24th International Conference on Electricity Distribution - CIRED conference*, no. 0091, pp. 62–64.

[5] F. Ciccarelli, A. DelPizzo, D. Iannuzzi, 2013, "An ultrafast charging architecture based on modular multilevel converters integrated with energy storage buffers". *Proceedings Eighth IEEE International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER)*, pp. 1–6.

[6] F. Mwasilu, J.J. Justo, E.K. Kim, T.D. Do, J.W. Jung 2014, "Electric vehicles and smartgrid interaction: A review on vehicle to grid and renewable energy sources integration". *Proceedings Renew. Sustain. Energy*, vol. *34* pp. 501–516.

[7] HOMER Energy LLC. "Hybrid Optimization of Multiple Energy Resources". *Available online: www.homerenergy.com* (accessed on 10th January, 2019).