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A new perspective in grid connection of electric vehicles: Different operating modes for elimination of energy quality problems

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HIGHLIGHTS

- Smart grid compatible EV grid connection.
- Mitigation of power quality issues (harmonics, reactive power, etc.).
- Comparison of different EV charging strategies.
- Experimental analysis of the proposed structure.

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ABSTRACT

Lately, the depletion as well as negative environmental impacts of fossil fuels have directed the vehicle technology towards new alternative systems. Accordingly, the studies on electric vehicles (EVs) utilizing electric motor (EM) instead of conventional vehicles using fossil fuel consumer internal combustion engines (ICEs) have gained increasing importance. The EV technology firstly developed with the hybrid vehicles using both ICE and EM. Today, plug-in hybrid vehicles that can be charged via the grid have a leading position. Studies realized in many countries all over the world manifest the result of future widespread EV utilization. However, the power management and grid connection of EVs still comprise many unsolved problems. In this study, a power management is realized in order to reduce the battery stress of EVs and to solve the possible problems that can be faced while providing grid connection. In order to realize power management in charging process, smart grid is strongly necessary. For this reason, smart grid compatible relevant power converters are employed. A power conditioning unit is designed for the grid connection of EV enabling a controlled charge of the EV. With the utilization of the proposed power conditioning unit within the EV, the possibilities of solving the energy quality problems at the charging point, increasing the voltage quality, decreasing total harmonic distortion (THD) and even providing reactive power compensation by EV are obtained. The relevant results are discussed within simulation studies followed by a pre-evaluation of the proposed method with experimental real-time test bench based applications.

1. Introduction

The worldwide growing attention to the negative effects of fossil fuel utilization as well as the threats of the depleting reserves of conventional sources promote increasing number of research activities realized on alternative options for vehicular systems as a major fossil consumer. The main focus within the studies realized for reducing the vehicle emissions is recently on electric vehicles (EVs). Among the EV technologies, "plug in hybrid" vehicles come into prominience today [1,2]. These vehicles store the electric energy with charging or during braking and the stored energy is utilized via an electric motor during cruising. It is clear at this point that the vehicles meet their necessary energy demand directly from the grid or from an alternative energy source. The most common condition is the supply of EV energy demand directly from grid [3,4]. Regarding to this issue, a concern of possibility of obtaining a totally environmental friendly system with EV technology may arise as the most of the energy production for electric grid is based on utilizing fossil fuels. However, the studies realized on this issue shows that supplying the demand of vehicles from electric grid instead of utilizing fossil fuel based conventional

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technologies reduces emissions [5–8]. Besides, increment in the penetration of alternative and renewable energy systems can further provide decrease in emissions.

One of the main issues in the grid connection of EVs is the evaluation of grid capability of supplying the charging power of EVs. For this issue, it is necessary to forecast and analyze the charging requirements of a specific region for each hour of the day. Besides, it is also important to determine the power plants supplying the energy demand of the considered region and forecast the power production capacities of these plants. This issue is analyzed in detail for different regions within the concept of different research projects. Different related projects are also supported in Europe and the relevant results are recently presented in the literature [4–7]. Besides, many studies realized with the support of American Department of Energy continue in national laboratories (Oak Ridge National Laboratory, National Renewable Energy Laboratory, Pacific Northwest National Laboratory) [9–12].

The EV charging power requirement changes due to the fact that whether EV is hybrid or full electric. Besides, it is announced in realized research studies that the charging power that will be demanded from the grid may reach to high levels due to the forecasted widespread utilization of EVs [9,12]. This issue provides the requisite of applying an energy management algorithm for the supply of the mentioned energy demand from grid. Otherwise, significantly high levels of investment will be necessary for supplying this energy demand. The supply of the required energy demand at night times when the energy demand is comparatively lower instead of peak hours when energy demand is higher will be more economic [5–13]. Hence, it is significantly important to determine the maximum allowable power value to be drawn from the local charging points.

Another important point mentioned in the literature is the investigation of the supply of EV charge requirements in terms of energy quality. With the wider penetration of EVs within transportation sector, EVs may have possible impacts on grid such as phase imbalance, energy quality problems and overloading of transformers. The imbalance in phase currents may occur with the charging of different number of EVs from different single phase charging stations. Thus, unbalanced voltage drops and accordingly voltage imbalances may occur [14]. On the other hand, EVs require DC voltage as battery is utilized as energy storage system even AC voltage is employed for electricity transmission and distribution. Thus, the AC voltage should be converted to DC voltage by a power converter for charging of EVs. The mentioned DC voltage may be further utilized for EV battery charging via a DC/DC converter. There may be harmonic distortion caused by every step of this process [15]. The wider utilization of these charging equipments with a nonlinear structure may cause a significant increase in voltage and current harmonic distortions. These harmonics may lead to many problems in the power system operation such as over currents of neutral point and overheating of transformers. Moreover, due to the possible wider penetration of full EVs and PHEVs, it is foreseen that they will have negative impacts in transformer lifetime due to their energy demands from the grid. First of all, the loading and accordingly the heating of the transformers will increase due to the increase in charging demand. Different peak points may occur and stress may be seen for the capacities of distribution transformers due to different charging times when the market share of EVs reaches to a critical ratio. This extra overloading will further reduce the lifetime of the transformer [16].

With the foreseen increase in the market share of EVs, the possibility of facing the aforementioned problems is significantly high. Thus, research activities should be conducted to overcome such problems. The first method that can be considered to prevent these problems is to increase the capacities of all components related to the existing electric system. However, this issue both causes a significant investment cost and requires a significant manpower. Realizing these investments in a longer period is more logical. Because of these issues, the best method to prevent the problems mentioned above is to utilize the existing electric system in the most effective and efficient way. In order to utilize the electric system effectively, regulations and additions in both EV design and electric system infrastructure are required. In order to utilize the existing electric system more efficiently, it is more important to control the electric consumption demand. There are several operating conditions for the control of energy demand, such as Grid to Vehicle (G2V), Vehicle to Grid (V2G) and new generation smart charging-discharging operation methodologies. In order to operate the EV in these conditions, the proper design of the power electronic circuits of EVs is strongly required. Firstly, the design of the inverter unit in EVs should be realized properly in order to operate without providing harmonics and negatively effecting power factor. Even it should be aimed to provide solutions if the grid structure includes problems.

This study aims to provide a power conditioning unit that is capable of providing reactive power compensation and eliminating harmonic distortion of the connection bus caused by other loads at the same time, which is a novel structure (for the existing literature to the best knowledge of the authors) that enables more numbers of EVs to be charged from the same connection point. The proposed power conditioning unit with the relevant power management strategies employed for regulating the energy transfer between EV and grid in both directions is designed with the capability of providing solutions to power quality problems. First of all, the proposed structure can regulate the battery charging and discharging current in order to prevent undesired operating conditions that can give harm to electrochemical structure of the EV battery. Besides, the reactive power compensation in order to avoid the possibility of reduction in maximum number of EVs that can be simultaneously charged from a common point can be achieved with the developed methodology. Moreover, the proposed system can even act as an active filter that can eliminate the harmonic content of the other loads connected to the relevant bus of the grid. Thus, the most important power quality problems can be evaluated and overcome with the provided systematic design procedure. Besides, the proposed structure is suitable for future smart grid applications as charging active and reactive power values are determined by grid operator. The results are firstly derived in MATLAB/Simulink/SimPowerSystems simulation environment followed by an experimental pre-evaluation of the proposed structure.

This paper is organized as follows. Section 2 gives the fundamental methodology with relevant basic equations utilized in the paper. Section 3 presents the conducted simulation studies with proposed control methodologies while Section 4 gives the experimental results derived from the constructed test prototype. Finally, the overall study is discussed and conclusions are presented in Section 5.

2. Methodology

As the EVs penetrate in the vehicle market with an increasing ratio, it is possible for EVs to have some negative impacts in grid. AC voltage is utilized for electricity transmission and distribution. As battery units are employed for energy storage in EVs, they need DC voltage. Thus, for the charging process of EVs, the AC voltage should be converted to DC voltage with a power converter firstly. Then, the obtained DC voltage is used for the charging of vehicle batteries via a DC/DC converter. Harmonic components may be induced within all steps of this process [15]. Loads such as inverters and battery charging devices that include nonlinear elements