Electrical Power and Energy Systems 64 (2015) 300–310

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Bi-directional electric vehicle fast charging station with novel reactive power compensation for voltage regulation

Jia Ying Yong [a,*], Vigna K. Ramachandaramurthy [a], Kang Miao Tan [a], N. Mithulananthan [b]

[a] Power Quality Research Group, Department of Electrical Power Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia
[b] School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, Qld 4072, Australia

ARTICLE INFO

Article history:
Received 26 September 2013
Received in revised form 10 June 2014
Accepted 6 July 2014

Keywords:
Electric vehicle
Reactive power compensation
Voltage regulation
Bi-directional
Fast charging

ABSTRACT

Excessive carbon emissions from the current transportation sector has encouraged the growth of electric vehicles. Despite the environmental and economical benefits electric vehicles charging will introduce negative impacts on the existing network operation. This paper examines the voltage impact due to electric vehicle fast charging in low voltage distribution network during the peak load condition. Simulation results show that fast charging of only six electric vehicles have driven the network to go beyond the safe operational voltage level. Therefore, a bi-directional DC fast charging station with novel control topology is proposed to solve the voltage drop problem. The switching of power converter modules of DC fast charging station are controlled to fast charge the electric vehicles with new constant current/reduced constant current approach. The control topology maintains the DC-link voltage at 800 V and provides reactive power compensation to regulate the network bus voltage at the steady-state voltage or rated voltage (one per unit). The reactive power compensation is realized by simple direct-voltage control, which is capable of supplying sufficient reactive power to grid in situations where the electric vehicle is charging or electric vehicle is not receiving charges.

Introduction

Electric vehicle (EV) attracts global attention lately and is expected to receive greater adoption into transportation sector in most countries due to its major advantage of zero tailpipe emissions. EV was first introduced in the nineteenth century but soon replaced by internal combustion engine vehicles. The reasons were the invention of muffler and electric starter, which reduced the noise of internal combustion engine vehicles and removed the need of hand crank to start the internal combustion engine vehicles [1]. On the contrary, EVs could travel relatively for short distance and were much more expensive than internal combustion engine vehicles. However nowadays, excessive carbon emissions from internal combustion engine vehicles have triggered governments around the world to find a solution. The return of EVs is seen as a promising solution in the effort to reduce carbon emissions, as well as to prevent dependence on fossil fuel resource.

EVs generally can be classified into three types, which are hybrid electric vehicles, plug-in hybrid electric vehicles and battery electric vehicles. In order to study the impact of EVs interconnection to the power grid, only plug-in hybrid electric vehicles and battery electric vehicles are considered since these two EV types can receive charges from power grid. Therefore, from here onwards, the term EVs are meant to represent plug-in hybrid electric vehicles and battery electric vehicles rather than hybrid electric vehicles.

The randomness of EV connected to power network makes the network planning and operation become difficult. Different possible charging mechanisms worsen the situation as EV drivers can choose to use either slow charging or fast charging to charge the EVs. A few standards are established for EV charging levels, such as SAE J1772, CHAdeMO and IEC 61851 [2–4]. Slow charging is a common and inexpensive way to charge an EV without draining much power from the distribution network. However, slow charging requires long charge duration to fully charge the depleted batteries of standard EVs, approximately 6–8 h. On the other hand, fast charging will be more preferable as it only takes 30 min to charge up 80% of the battery capacity [5]. However, fast charging drains very high power from the power grid and can stress the local power grid.

The availability of EV charging network is one of the crucial factors to realize the roll out of EVs in one country. In terms of preference between slow charging network and fast charging network,

* Corresponding author. Tel.: +60 17 2597352; fax: +60 3 89212116.
E-mail addresses: yongjiaying89@gmail.com, vigna@uniten.edu.my (J.Y. Yong).

http://dx.doi.org/10.1016/j.ijepes.2014.07.025
0142-0615/

the importance of the latter one is more prominent. Recently, Netherlands planned to build one of the world's largest nationwide fast charging network, which consists of more than 200 DC fast charging stations [6]. People are more willingly to accept EVs if fast charging network is ready because the charging process will only take up 30 min, which possibly can be even reduced with the development of EV technology to make it comparable to refueling time.

In the viewpoint of power utility, the roll out of EVs is not favorable since EVs need to receive charges from power grid. Many studies had shown that the interconnection of high penetration level of EVs to power grid could affect the system operation. The impacts of EV charging on harmonics [7], power demand load profile [8–10], system losses [11,12], voltage profile [11–14] and transformer overloading [15,16] have been comprehensively investigated. The results showed that uncoordinated EV charging with plug-in simultaneously during the peak demand periods, could go beyond the safe operating limits of power grid even for modest level of EV interconnection.

Power network reinforcement and components upgrade are simple ways to cater for negative impacts of EV charging. However, this solution requires high investment cost for implementation. The authors in [17] showed that investment cost can increase up to 15% of the existing network cost to provide sufficient power supply if high penetration level of EVs are included into the power grid. Hence, that is a need to find a more economic and efficient solution. EVs post challenges to the network operation, but at the same time, EVs are also potential energy sources. Instead of installing new components to solve the negative impacts of EV charging, EV itself has great potential to be used as a solution.

EVs have battery storage and charger to control the power flow. The EV charger can be designed to allow the active power to flow bi-directionally in between EV batteries and power network. This concept is called Vehicle-to-Grid (V2G) and has become a popular research topic recently. V2G helps to level the power demand load profile and reduce the system losses [18]. In addition, the charger can be designed with the capability to export reactive power into the power grid with the use of charger's DC-link capacitor and controlled switching. Reactive power compensation can provide voltage support, power factor correction and reduction in system loss [19]. Several papers have addressed the concept of bi-directional charger with different control strategies to solve EV charging problem [20–23].

This paper presents the design of a bi-directional EV charger with novel control topology. The switching of charger's power converter modules are controlled to fast charge the EV, as well as to provide reactive power compensation for voltage regulation and power factor correction. The bi-directional EV charger is capable of supplying sufficient reactive power to grid in all situations. The rest of the paper is arranged into sections. Section 'Principle of bi-directional power transfer' describes the principle of bi-directional power transfer. Section 'Control description and component modeling' explains the modeling and control of bi-directional EV charger as well as EV storage battery. Section 'System modeling' shows the system modeling of the test network. Section 'Results and discussion' presents the results and discussion of study cases with and without reactive power compensation control. Section 'Conclusion' concludes the paper.

Principle of bi-directional power transfer

Fig. 1 shows two buses, Bus 1 and Bus 2, connected by an impedance of $Z\angle\gamma = R + jX$. Each bus has an ideal voltage source, $V_1\angle\delta_1$ and $V_2\angle\delta_2$, respectively. Fig. 1 is used to describe the transfer of real power (P) and reactive power (Q) between this two buses. Both buses are assumed to have the ability to supply and absorb P and Q. With reference to the direction of current, I_{12}, the P flow and Q flow can be given by equations, as follows [24]:

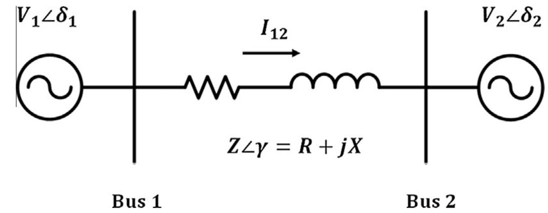

Fig. 1. Schematic diagram of two interconnected buses.

$$P_{12} = \frac{V_1^2}{Z}\cos\gamma - \frac{V_1V_2}{Z}\cos(\gamma + \delta_1 - \delta_2) \tag{1}$$

$$Q_{12} = \frac{V_1^2}{Z}\sin\gamma - \frac{V_1V_2}{Z}\sin(\gamma + \delta_1 - \delta_2) \tag{2}$$

By assuming $X \gg R$, Eqs. (1) and (2) can be simplified to Eqs. (3) and (4), as follows:

$$P_{12} = \frac{V_1V_2}{X}\sin(\delta_1 - \delta_2) \tag{3}$$

$$Q_{12} = \frac{V_1}{X}[V_1 - V_2\cos(\delta_1 - \delta_2)] \tag{4}$$

Both Eqs. (3) and (4) consist of voltage magnitudes (V_1 and V_2) and voltage angles (δ_1 and δ_2). However, change in voltage angles has more significant effect on real power flow while change in voltage magnitudes has more impact on reactive power flow [24]. Table 1 shows the conditions that allow power transfer between two buses happens.

Table 1
Conditions of power transfer.

Conditions	Power transfer
$\delta_1 > \delta_2$	Real power transfer from Bus 1 to Bus 2
$\delta_1 < \delta_2$	Real power transfer from Bus 2 to Bus 1
$V_1 > V_2$	Reactive power transfer from Bus 1 to Bus 2
$V_1 < V_2$	Reactive power transfer from Bus 2 to Bus 1

Control description and component modeling

Bi-directional DC fast charging station

EV chargers can be installed on-board and off-board of the vehicles. On-board chargers are usually small in size and have low power rating to be used for slow charging. Off-board EV chargers are built at dedicated locations to provide fast charge service. Fast charging network plays an important role to promote EVs as fast charging can minimize range anxiety among EV drivers. This paper considers a 50 kW off-board DC fast charging station, which has the voltage rating ranges from 50 to 600 V_{dc} and current rating up to 125 A_{dc} [4].

A common configuration of DC fast charging station consists of power converter modules or more specifically, an AC/DC converter and a DC/DC converter. One-directional DC fast charging station rectifies the three-phase AC input supply into DC output. DC/DC converter is then used to shift the DC output to an appropriate level, which is suitable to charge the EV battery. Meanwhile, bi-directional DC fast charging station has controllable power converter modules. The control topology is the key to control the power flows in both ways between DC fast charging station and power grid.