Potential Power Quality Benefits of Electric Vehicles

Milad Falahi, Member, IEEE, Hung-Ming Chou, Student Member, IEEE, Mehrdad Ehsani, Fellow, IEEE, Le Xie, Member, IEEE, and Karen L. Butler-Purry, Senior Member, IEEE

Abstract—Electric vehicles (EVs) are likely to have a continued presence in the light-vehicle market in the next few decades. As a result, EV charging will put an extra burden on the distribution grid and adjustments need to be made in some cases. On the other hand, EVs have the potential to support the grid as well. This paper presents a single-phase bidirectional charger topology which pairs a photovoltaic (PV) source with an EV charger resulting in production cost reduction. The presented topology is then used for vehicle-to-grid (V2G) services. The main focus of this paper is on power quality services which only slightly discharge the battery. Among these services, it studies the possibility of local reactive injection of EVs connected to the grid through a single-phase charger to compensate for voltage drops caused by motor startup or inductive loads. It also studies the possibility of active power injection of EVs for short time periods during PV transients in cloudy weather to keep the system stable. It also studies the potential of EVs to help during low voltage ride-through of the PV sources. The studies are performed using Simulink simulations and a real-time implementation in Real Time Digital Simulator (RTDS). The results demonstrate the effectiveness of power quality V2G services with small wear on the EV battery.

Index Terms—Electric vehicle (EV), plug-in hybrid vehicle, power quality, reactive power.

I. INTRODUCTION

According to the 2011 energy outlook, the transportation sector’s share in total oil consumption will rise from 40% in 2008 up to 54% by 2035 with the current trend [1], [2]. On the other hand, forecasts by the Energy Information Agency (EIA) anticipate rising oil prices over the next two decades can exceed $5.50 per gallon in a high price scenario. Therefore, technologies related to reducing the oil consumption of the transportation sector such as plug-in hybrid electric vehicles (PHEVs) or all-electric vehicles (EVs) are starting to take their share in the vehicle market and will potentially replace combustion engine vehicles in the future [3]. Some economic studies claim that depending on the future price of oil and the relative purchase price of internal combustion engine vehicles, EVs may take up to 86% of new light-vehicle sales by 2030 [4].

EVs have higher production cost compared to combustion engine vehicles, which makes them not the first choice for a large percentage of consumers at the moment. Further, with the relatively slow improvement of battery technology compared to other technologies, the total production cost of the electrical vehicles will not decrease substantially in the near future [5]. Some industrial reports claim that the total cost of ownership of Li–ion powered EVs, which includes initial price, fuel, maintenance, and other costs over the life of the car is less than the combustion engine vehicles over the vehicle’s lifetime [6]. However, the majority of consumers tend to focus more on initial cost and not total cost of ownership when they make vehicle purchasing decisions [3]. One method to make EVs marketable is to offer incentives or financing to consumers by the government or private companies.

In 2010, “Better Place” demonstrated the world’s first switchable batteries electric taxi transportation system for urban areas in collaboration with the Japanese government [7]. In a switchable batteries transportation system, network operators finance the cost of the battery by offering a pay-per-mile service contract to the EV drivers. These contracts include the price of charging infrastructure as well as the electricity price [4]. Financing the EV battery with a service contract has a number of advantages. First, a switchable battery eliminates the up-front cost of the battery for the customer. Second, it allows new battery technologies to be installed in older EVs. Third, it eliminates the risk of purchasing an EV with a shorter battery life than the life of the vehicle. Fourth, a switchable battery contract opens the door for vehicle-to-grid (V2G) services since it is easier to convince the customer to use their EV battery for V2G if the utility owns the battery.

Surveys show that most EVs are parked for an average of 95% of the time and remain connected to the grid in charging or idle mode [8]. During this time, their batteries and chargers could be used to let active and reactive power flow from the battery and internal capacitors back to the power lines and to the grid [9]. For this purpose, EV chargers should be designed to be able to send energy back to the grid. The possibility of V2G has been studied for more than a decade [10] and it is gaining more and more popularity as penetration percentage of battery-based PHEVs and EVs into the grid is constantly increasing [11].

This paper studies the possibility of V2G quality support of the grid when the vehicle is parked and connected to the grid with a single-phase charger. Specifically, the study focuses on the potential grid quality services such as power injection during ride-through of renewable sources, and regulation of reactive power [12]. These services only slightly discharge the EV battery but improve the grid power quality significantly. Therefore, power quality services do not degrade the EV’s battery life. However, the incentive given by the utility to the customer for
quality support of the grid can potentially offset the up-front cost of the EV.

The ability to use EVs and PHEVs as energy resource depends on the existence of required support infrastructure, bidirectional chargers, and customers who are willing to provide the service [13]. Several papers have discussed bidirectional charger topologies as well as various control methods to use EVs as a potential distributed energy resource [14]–[17]. This paper presents a single-phase ac/dc topology with a common dc-link as a bidirectional EV charger depicted in Fig. 1. The main advantage of this topology is that the wall mount ac/dc charger can connect any other dc device to the grid even when the EV is not connected to the charger. Each dc device has its own dc/dc converter which changes the voltage level to the dc capacitor voltage level and controls the current flow. The dc-link capacitor connected to the single-phase inverter can inject reactive power to the grid. In addition, the same inverter with the same dc-link can be used to connect the EV battery charger and other energy sources such as photovoltaic (PV) or wind source to the grid. Therefore, this scheme results in reduction of the total design cost of the system. The bidirectional dc/dc converters that connect to the sources and EVs are current-controlled in this scheme. The inverter controller includes a reactive power loop that operates independent from the active power loop. The reactive current reference can have an arbitrary wave-shape as long as it does not have a real power component. Reactive power can be injected to the system by having a current with a different frequency than the voltage [18]. The traditional reactive power flow can be created by having a current with the same frequency as the ac voltage with a 90° phase shift. Fig. 2 illustrates a single-phase inverter control with active and reactive control loops.

The rest of the paper is organized as follows. Section II discusses possible V2G power quality services. This section discusses the possibility of V2G for reactive regulation, LVRT, PV transients, and motor starting in detail. Section III presents simulation results of reactive power regulation and regulation of PV transients using EV. Finally, Section IV presents the concluding remarks.

II. VEHICLE-TO-GRID QUALITY SUPPORT

A. Voltage Regulation

The literature lacks a deep technical analysis of reactive power compensation using EVs. The topology of a bidirectional charger needs minimal changes to make it suitable for reactive support. In [18] and [19], some single-phase inverter topologies have been studied for reactive power injection into the grid. The voltage rating of the dc-link capacitor of an ac/dc charger should be increased by at least 3% to be able to effectively inject reactive power into the grid. The current ripple rating of the dc-link capacitor is more than enough for reactive
power operations. The total losses of an ac/dc charger increases slightly by adding reactive power support operations with its normal operation. The EV battery and the input inductor current are not affected by reactive operation at all [12].

Reactive power compensation studies showed that the dc-link capacitor is enough to supply reactive power to the grid even without engaging the EV battery. In this case, the controller draws a small amount of active power from the grid to keep the capacitor voltage stable and injects reactive power to the grid causing no degradation of EV’s battery life [20]. This feature makes the EV charger the perfect candidate for reactive regulation since the standalone charger is enough for reactive power injection to the grid even when the vehicle is not connected to the charger. The amount of reactive power that the charger can supply during charging mode is limited by the charger’s power limit and the amount of active power drawn from the grid. Therefore, until the charger fully charges the battery, the reactive power support capacity of the EV is as follows:

$$q(g) = \sqrt{S^2 - p(g)^2} - q_{\text{Max}}$$

(1)

where $q(g)$ is the reactive power injected to the grid, $p(g)$ is the active power drawn from the grid, and $q_{\text{Max}}$ is the maximum reactive power limit of the charger.

According to (1), if the EV battery is drawing maximum power from the charger, then the charger is not capable of producing reactive power. However, if the apparent power capability of a charger $S$ exceeds the instantaneous real power drawn from the grid $p(g)$ by the battery, the range of allowable reactive power generation is given by (1) [21]. Fig. 3 illustrates the reactive power generation limit of the inverter. As mentioned earlier, the battery is not drawing active power from the grid most of the time so the charger is in idle mode and capable of injecting maximum reactive power to the grid.

The reactive power injection can be controlled by two methods.

1) Reactive injection to the system can be controlled locally by injecting reactive power relative to the voltage drop at the connection point of the EV. This method is easy to implement and does not require communication infrastructure. In addition, it is not necessary for the utility to know the exact location of EVs to be able to use them for reactive power support.

2) The reactive regulation problem can also be formulated as a global optimization problem. This method requires power flow information of the system and communication infrastructure to send local measurements to the power management unit. The power management unit should also know the exact location of the connection of EVs to the grid. Therefore, this method is suitable for PV and EV pairs at fixed locations. The aggregate active power at node $j$ of the system shown in Fig. 4 is as follows.

$$p_j = p_{\text{DG}j} + p_{\text{EV}j} - P_{Lj}$$

(2)

where $P_{Lj}$ is the total load at node $j$, $p_{\text{EV}j}$ is the active power injection or withdrawal of the EV connected to node $j$, and $p_{\text{DG}j}$ is the active power generated by the distributed generator (DG) connected to node $j$.

$$q_j = q_{\text{EV}j} - Q_{Lj}$$

(3)

where $Q_{Lj}$ is the total load at node $j$, and $q_{\text{EV}j}$ is the reactive injection of the EV connected to node $j$. The power flow of the radial ac distribution system can be solved using DistFlow ac power flow [22].

$$\forall j = 1, \ldots, n$$

(4)

$$P_{j+1} = P_j - r_j \frac{P_j^2 + Q_j^2}{V_j^2} - p_{j+1}$$

(5)

$$Q_{j+1} = Q_j - x_j \frac{P_j^2 + Q_j^2}{V_j^2} - q_{j+1}$$

(6)

$$V_{j+1}^2 = V_j^2 - 2(r_j P_j + x_j Q_j) + \left(r_j^2 + x_j^2\right) \frac{P_j^2 + Q_j^2}{V_j^2}$$

(7)

where $P_j$ and $Q_j$ are the active and reactive power flowing away from node $j$ toward node $j + 1$, $V_j$ is the voltage at node $j$, $r_j + i x_j$ is the impedance of the line between node $j$ and $j + 1$, and $p_j$ and $q_j$ are the active and reactive power drawn from node $j$. It should be noted that both $p_j$ and $q_j$ are aggregate directing to the power leaving the node. The quadratic terms in (4)–(7) are relatively small in the local distribution systems studied in this paper. Mathematical manipulation using the approximation $V^2_k \approx V_k^2 + 2V_k(V_k - V_c)$, leads to following power flow equations:

$$\forall j = 1, \ldots, n$$

(8)

$$P_{j+1} = P_j - p_{j+1}$$

(9)

$$Q_{j+1} = Q_j - q_{j+1}$$

(10)

$$V_{j+1} = V_j - \frac{r_j P_j + x_j Q_j}{V_j}$$

(11)
The vehicle $j$ has the following reactive production limit at any given time:

$$\forall j = 1, \ldots, n : q_j \leq \sqrt{S_{j}^2 - p_j^2} = q_{j}^{\text{Max}}. \quad (12)$$

The cost function penalizes deviation of the measured bus voltages from the nominal bus voltages as follows:

$$\min_{q_j} \sum_{j=1}^{n} \left| V_j - V_0 \right|_2^2 \quad (13)$$

where $V_0$ is the nominal voltage of the buses in the system.

The advantage of the optimization method over the local control method is that EV charging can be stopped when voltage support is needed in the system making the charger capable of injecting maximum reactive power to the grid.

Reactive power support is usually needed in high loading hours of distribution systems. In addition, some loads such as induction motors need reactive power support for a short period of time during their startup. Large induction motors or combinations of medium size motors starting at the same time require a large amount of instantaneous reactive power for a short period of time during their acceleration period causing reactive power depletion in the system. This reactive power depletion can cause significant disturbances especially in weak distribution systems [23]. Local reactive power injection from EVs can help keep the voltage stable during motor startup.

B. Low Voltage Ride-Through (LVRT) and PV Transients

With an annual growth rate of 25%–35%, PV sources are among the fastest growing energy sources over the past decade. Prior to 1999, the primary market for PV sources was in off-grid applications. However, over 80% of the recent PV source market is for grid-connected applications where the PV source is connected to a strong grid or an isolated grid as a distributed generator. As the number of grid connected PV sources increases, their dynamic behavior becomes more critical to the stability of the ac power system. Until recently, grid codes enforced disconnection of grid-connected PV sources during faults. However, new grid codes are starting to permit the PV units to remain connected to the grid and even actively support the grid during faults and transients [24], [25]. For example, due to the significant penetration of PV sources in the German power grid, the sufficiently developed German grid code has renewed requests for PV sources to remain connected to the grid. Other grid codes will follow the same renewals in the near future.

Grid-connected EVs can support the grid during PV transients and LVRT conditions. The EV charger can perform grid support by injection of active or reactive power during PV transients. If EV and PV have separate ac/dc interfaces to the grid, reactive injection can be performed by the EV charger and the PV source simultaneously. Further, if the same ac/dc interface is used for the PV and the EV charger, the single-phase ac/dc interface can perform the reactive support. In the latter scenario, since the single-phase ac/dc interface is rated higher than the individual interfaces, the distributed source has the same reactive capability as the former scenario. In either scenario, the dc-link capacitor is usually enough to inject reactive power to the grid without engaging the dc sources.

PV sources go through active power production transients during faults or in cloudy days resulting in periods of low active power production. If the low active power production period of the PV source coincides with peak load, the line current will increase over the rated current to provide enough active power to the loads. In this case, EVs can help reduce the temporary tension on the line and the distribution transformers by injecting active power to the system. The active power injection discharges the battery, therefore; it degrades battery life. However, since the duration of such transients is usually short, the degradation is not significant.

III. SIMULATION RESULTS

A single-phase four bus lateral which included two EVs and two PVs connected to buses 2 and 4 depicted in Fig. 5 was studied in this paper. The system was composed of a 50-kVA distribution transformer connected to the distribution grid. The line between bus 1 and bus 2 was a relatively long line with a line length of 2 miles and the other two lines were short lines with lengths of 0.2 miles. The PV sources were rated at 15 kVA and the inverter was rated at 20 kVA. The EV battery was rated at 100 V with a rated capacity of 50 Ah, connected to a dc/dc converter, which stepped up the voltage to 400 V of the dc link capacitor. The dc/dc converters and the inverters were designed to be able to operate bidirectional. The bidirectional inverter was rated at 20 kVA and both of the dc/dc converters that connect the EV and the PV to the dc/ac inverter were designed to be able to operate at full power of 20 kVA. Each of the PV sources was able to produce 15 kW of active power in their peak production.

A. Case-Study 1-Motor Startup

This case-study was performed to analyze the effect of reactive power compensation using ac/dc charger to reduce the bus voltage drop during motor startup. In this case-study, each of the PV sources was producing around 10 kW of active power and the EVs were connected to the grid and fully charged. Therefore, each inverter was injecting 10 kW of active power to the grid leaving each inverter capable of injecting around 17 kVar to the system. A relatively large single-phase induction motor connected to bus 2 started operating at $t = 1$ s and drew startup current from the grid. A local reactive injection method was
used to inject reactive power using the ac/dc charger to compensate for the voltage drop. Table I shows the load parameters of case-study 1.

As can be seen in Fig. 6, the instantaneous reactive power demand of the induction motor resulted in a voltage drop on bus 2 and adjacent buses in the system for a few seconds. This voltage drop can result in flickering lights and nuisance relay tripping in some cases. As can be seen in Fig. 7, the charger did not need to draw any charge from the battery for reactive power compensation. Fig. 8 shows that the dc link capacitor voltage ripple increased during reactive power compensation.

This case study was implemented in RTDS using a step-time of 50 ms. The RTDS simulator had three general processing cards (GPCs) with IBM 750 GX RISC processors at a clock rate of 1 GHz. Fig. 9 shows the voltage of bus 4 when the motor started at $t = 0.6$ s. As can be seen in Fig. 9, the reactive injection through the dc/ac inverter was enough to recover bus 4 voltage back to the nominal value. Fig. 10 shows the same case study when the EV did not inject reactive power to the grid. As can be seen in Fig. 10, voltage of bus 4 dropped to 0.85 p.u. as a result of reactive depletion during motor starting.

The time is relative in RTDS simulations with a moving window of data going to the output. The waveforms at the

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<td>$P_1$</td>
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<td>$P_4$</td>
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Fig. 6. Bus voltages of buses 2 and 4 during motor startup.

Fig. 7. Battery current during reactive power compensation.

Fig. 8. DC link capacitor voltage during reactive power compensation.

Fig. 9. Bus 4 voltage (upper plot) and charger current (lower plot) at the beginning of motor starting period with reactive compensation.

Fig. 10. Bus 4 voltage (upper plot) and charger current (lower plot) at the beginning of motor starting period without reactive compensation.
end of the motor starting period are presented in Figs. 11 and 12. Fig. 11 shows the bus 4 voltage at the end of the starting period of the induction motor. The EV charger needed to adapt to the new reactive power need of the grid by decreasing the reactive power production. As can be seen in Fig. 11, the charger was able to adapt the new system need and kept the voltage at the nominal value and the inverter current settled to the predisturbance value after the system settled.

Fig. 12 shows the bus 4 voltage where the system did not have reactive compensation through the EV charger. In this case, the bus voltage gradually returned to the nominal value after the reactive power motor starting period was over.

**B. Case-Study 2-PV Transients**

This case-study was performed to study the possibility of using the EV’s battery to help the grid during active power ride-through of PV sources. Power production drop of the PV source typically occurs due to cloudy weather or a fault. It was assumed that the power production of one PV source reduced to 25% of its full capacity from $t = 1$ s to $t = 5$ s. In this case, the system was operating close to the rated power meaning that the outage in PV source resulted in an overload on the lines. The two EVs in the system took shares of the active power compensation to reduce the tension on the lines and the distribution transformer. Table II shows the load parameters of case-study 2.

As can be seen in Fig. 13, the active power compensation using EVs helped to prevent overcurrent of the lines and the distribution transformer during PV transient. Fig. 13 shows that the line current stayed within limit when EVs were used for active power injection during the PV transient. The line current decrease resulted in a decrease in distribution losses and a slight increase in switch conduction loss of the ac/dc power electronics interface. In addition, by avoiding the overcurrent, the transformer life was not reduced and protection relay tripping was avoided.

Fig. 14 shows the drop in the PV power production from $t = 1$ s to $t = 5$ s. Fig. 15 shows the active power drawn from the battery to compensate the transient active power drop of the PV source. Fig. 16 shows that the battery’s state of charge did not drop much since the period of active power injection was
short. Therefore, the battery life was not affected much by this compensation.

IV. CONCLUSION

This paper showed that EV can successfully pair up with other energy sources resulting in a total power electronics cost reduction. In addition, the possibility of supporting the grid using EVs was studied in this paper. The paper showed that reactive V2G services do not engage or only slightly discharge the EV battery. It also showed that EVs can support the grid during renewable ride-through and transients. Thus, the EV is perfectly suited for services such as reactive regulation or active power support during renewable ride-through conditions. Such services can reduce the total distribution line loss, avoid voltage drops, and relay tripping. The studies were performed using Simulink and RTDS simulations of a single-phase lateral in a distribution system.

REFERENCES


Milad Falahi (S’06–M’12) received the B.S. degree in electrical engineering from K. N. Toosi University, Tehran, Iran, in 2005, the M.S. degree in electrical engineering from University of Tehran, Iran, in 2007, and the Ph.D. degree in electrical engineering from Texas A&M University, College Station, TX, USA, in 2012.

He worked at ABB corporate research center at Raleigh, NC, USA, from 2009 to 2010. He is currently working at Itron Consulting and Analysis group as an Energy Consulting Engineer. His research interests include control and management of power systems, microgrids, grid integration of renewable energy sources, power electronics applications in power systems, smart-grids, and electric vehicles.

Hung-Ming Chou (S’08) received the B.S. degree in electrical engineering, in 2004, from the National Chiao Tung University in Taiwan. He received the M.S. degree in electrical and computer engineering, in 2009, from Texas A&M University.

He joined the Ph.D. program in Power System Automation Laboratory in the same department in 2009. His research interests include power electronics, power system dynamics and control, renewable energy integration, and hardware-in-the-loop real-time simulation.

Mehrdad Ehsani (S’70–M’81–SM’83–F’96) has been at Texas A&M University, College Station, TX, USA, since 1981, where he is the Robert M. Kennedy Endowed Professor of electrical engineering and Director of Sustainable Energy and Vehicle Engineering Program and Power Electronics and Motor Drives Laboratory. His current research work is in sustainable energy, power electronics, motor drives, electric and hybrid electric vehicles and sustainable power systems.

Dr. Ehsani is the author of over 350 publications in sustainable energy, power systems, pulsed-power supplies, high-voltage engineering, power electronics and motor drives, automotive power and propulsion systems, and sustainable energy and transportation. He has been the recipient of the Prize Paper Awards in Static Power Converters and motor drives at the IEEE-Industry Applications Society 1985, 1987, and 1992 Annual Meetings. In 1992, he was named the Halliburton Professor in the College of Engineering at A&M. In 1994, he was also named the Dresser Industries Professor in the same college. In 2001, he was named the Dow Chemical Faculty Fellow of the College of Engineering at Texas A&M University. In 2001, he also received the James R. Evans Avant Garde Award from IEEE Vehicular Technology Society. He is the recipient of IEEE Field Award in Undergraduate Teaching in 2003. In 2004, he became the holder of Robert M. Kennedy Endowed Professorship of Electrical Engineering at Texas A&M University. He is the co-author of 16 books on power electronics, motor drives, vehicle power and propulsion systems, and a contributor to an IEEE Guide for Self-Commutated Converters and many monographs. He is the author of over 30 U.S. and EC patents and patent disclosures. He was a member of IEEE Power Electronics Society founding AdCom, past Chairman of PELS Educational Affairs Committee, past Chairman of IEEE-IAS Industrial Power Converter Committee, and founding chairman of the IEEE Myron Zucker Student-Faculty Grant program. He was the General Chair of IEEE Power Electronics Specialist Conference for 1990. He has been a Distinguished Speaker of IEEE Industrial Electronics Society, Vehicular Technology Society, Industry Applications Society, and Power and Energy Society. He has been the associate editor of IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY. He is the founder of IEEE Power and Propulsion Conference and the founding chairman of its Steering Committee. He was elected to the Board of Governors of IEEE-VTS in 2003. In 2005, he was elected Fellow of the Society of Automotive Engineers (SAE). He is also a registered professional engineer in the State of Texas.

Le Xie (S’05–M’10) received the B.E. degree in electrical engineering from Tsinghua University, Beijing, China, the M.Sc. degree in engineering sciences from Harvard University, Cambridge, MA, in 2005, and the Ph.D. degree in electrical and computer engineering from Carnegie Mellon University, Pittsburgh, PA, USA, in 2009.

He is currently an Assistant Professor with the Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX, USA. His industry experience includes an internship (June to August 2006) with ISO-New England and an internship with Edison Mission Energy Marketing and Trading (June to August 2007). His research interest includes modeling and control of large-scale complex systems, smart grid application with renewable energy resources, and electricity markets.

Karen L. Butler-Purry (SM’01) received the B.S. degree (summa cum laude) in electrical engineering, in 1985, from Southern University in Baton Rouge, LA, USA. She was awarded the M.S. degree in 1987 from the University of Texas at Austin and the Ph.D. degree in electrical engineering in 1994 from Howard University, Washington, DC, USA.

She is Associate Provost for Graduate Studies and Professor in the Department of Electrical and Computer Engineering at Texas A&M University where she has served on the faculty since 1994. Her research interests are in the areas of protection and control of distribution systems and isolated power systems such as all-electric power systems for ships, mobile grids, and microgrids, cybersecurity protection, and intelligent systems for equipment deterioration and fault diagnosis.