Automatic Charging Control for Electric Vehicle to Grid Operations

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***Abstract*—Electric vehicles, whether fueled by chemical batteries or by liquid or fuel cells providing electricity onboard, provide benefits to grid operators as battery storages and power resources. In vehicle to grid operations, batteries provide ancillary services such as regulation up and down services to electric utilities. Balancing voltage frequency keeps power grids stable and sustainable. Vehicle to grid operations provide economic benefits to power grid operators, aggregators and to electric vehicle owners. An electric vehicle operator shares battery power with the power grid, an electric vehicle operator provides information about the coming journey, departure time and traveling distance as next trip requires. An automatic charging control can mitigate communication, and estimate the next trip with automatic charging control. Electric vehicle operators are not required to share information about planned travel as battery management charges batteries automatically. The proposed topic is interesting and worthy of investigation in order that the impact of vehicle to grid operations on battery durability plays a key role for the convenience of electric vehicle owners in supporting the electricity network with this kind of ancillary services. Main findings are lifetime reduction is decreased in vehicle to grid operations and a lifetime can be extended. For electric utilities, the increased battery storage provides benefits such as power system reliability and lower costs and facilitates the integration of intermittent renewable energy resources such as solar energy and wind power.**

***Index Terms*—automatic charging control, battery cycle aging, battery management, electric vehicle, frequency regulation, optimization**

I. Introduction

When introduced 120 years ago, Electric Vehicles (EV) looked very promising and were more popular than petrol-driven vehicles [1]. The lack of availability of domestic electricity for charging EV batteries, as well as the mass production and the invention of the starter motor for petrol vehicles meant EVs had limited commercialization [2]. The electric vehicle industry has renewed interest because of environmental issues. For example, the California State introduced its Low-Emission Vehicle (LEV1) program in 1990, which required automobile manufacturers to develop EVs [3] while the Tesla Roadster, developed in 2008 [4]. Most of the major automobile manufacturers have EV production using batteries recharged from the power grid [5]. However, this has put a load on the grid causing instability in both voltage and frequency.

Due to the load problems on the power grid, Vehicle to Grid (V2G) charging was devised to mitigate the problems by charging at times, where the grid load is minimal. However, as a consequence of the V2G, this has introduced the problem of decreasing battery life with electric cars. This is due to the fact that additional cycling, charging and discharge of the EV’s battery decreases its capacity and increases battery inner resistance, which in turn would make V2G uneconomical. However, the battery degradation can be mitigated by adopting intelligent charging control. Controlled charging improves battery life by choosing optimal State of Charge (SoC) level and charge rate. Driving pattern data was used to determine the charging rate of the battery. Cycle aging measurements and battery cycle aging model are needed for the development of automatic charging control.

An automatic generation control for V2G operations applies an optimization technique for power supply, which utilizes stochastic techniques to determine the control parameters for an electric power supply control [6, 7]. The automatic charging control for V2G operations and the system integration apply V2G operations and bi-directional charger. The charging control contributes to the actual realization of the V2G operations as an ancillary service to the power grid and the microgrid solution for the power and automotive industries [8]. The robust optimization and stochastic programming utilize power flow problem to integrate V2G operations into the distribution system [9]. Previous works, which have been done in the past to address the problem, has been development of automatic charging control [7, 8, 10-14] and driving patterns [15-18], cycle aging measurements [15, 17-38] and battery cycle aging model [16-27, 29-31, 33, 35-38] to provide automatic charging control. A battery model optimizes charging and discharging to increase battery life and are mostly related to our work. Development of automatic charging control research, which has been done earlier do not consider charge limits as a part of automatic charging control. In this paper, we use charge limits to disable or limit charging cycles to keep battery charge in the optimal area. Before the next trip, only the needed amount of electricity is charged to EV batteries.

Manuscript received September 14, 2019; revised May 8, 2020.

doi: 10.18178/joace.8.1.1-8

Purpose of the study is to find a way to enhance the lifetime of the batteries. Optimal charging discharge cycles were based on cycle life battery measurements and a cycle life model. When daily driven patterns and V2G operations were connected to that model, we built a charging strategy for home, work, highway, and shopping center. We obtained charge limits to keep charging in optimal charging window. Annual driven distance, number of V2G cycles and battery package cost increase annual V2G cost. The contribution of this study is the development of automatic charging control and this research connects driving patterns, charge limits, cycle aging measurements, and battery cycle aging model to provide automatic charging control. The model optimizes charging and discharging to increase battery life. The novelty of this study in relation to similar study is the usage of different charge limits according to driving distance.

The structure of the remaining article consists of methodology, results, discussion, and conclusion. The methodology is provided in section II. Section III discusses the configuration of the auto charge controller, its flexibility, and the possible extension of its application area. Section IV discusses driving behavior based on EV trial and travel survey. Driving patterns are discovered for development of charging control. In section V, the measurements are connected to cycle aging model; the main outcome is presented and discussed. The development of automatic charging control and connections to driving patterns, charge limits, cycle aging measurements, and battery cycle aging model are described in section VI. The results of the application of the automatic charging control are presented. Finally, the discussion and conclusion summarize the main results and conclusions.

II. Methodology

Accelerated battery cell aging data were collected from battery measurements [19] and were constructed to support charge limits. Sanyo's cells tests were carried out with several measurements: 35 ℃, 1It current and six different SoC levels [19]. The battery charge was kept at an average SoC of 50%. The aging level was recorded several times during measurements.

Real driving data were collected from EV trial and travel survey. Demand for equivalent full cycles was recorded. V2G cycles drew 5% of battery energy in time based on the smallest charge limit. Aging data showed a number of cycles during the lifetime. These lifetime cycles were transformed to charge limits to optimize charging. Auto charge controller provided a platform for bi-directional charging. As a result, the automatic charging control was developed for V2G operation.

III. Auto Charge Controller

The EV owner would require disabling or limit the discharging level of the EV batteries. The simplest way to limit discharging would be installing a toggle switch to able or disable battery discharging. The auto charge controller limits the discharge level and recharges batteries before the next trip. The illustrative auto charge control panel (Fig. 1) intends to mitigate EV operator concern by introducing control switches that accommodate driver operational requirements. Within these discharge constraints for battery management laid down by the EV driver, the EV driver allows the electric utility to charge and discharge EV batteries whenever electric utility wants.

The EV driver informs to battery management the next trip departure time and estimated driving kilometers. Fig. 1 illustrates the control panel of automatic charging where the EV operator enters the coming traveling distance and the departure time for the journey [39].

In Fig. 1, an EV driver decides the minimum traveling distance maintained at EV battery, in this case, an EV driver selected 140 km. An EV driver specifies the required departure time and the estimated distance from the 'next trip' box. In Fig. 1, an EV driver specifies that the next planned trip is 25 km leaving at 7:15 the next morning. The cost since last reset meter (Fig. 1) indicates that an EV has gained $20.75 credit. An EV driver adjusts 'range buffer' to maintain range after all daily travel was completed. The right side control box, 'next trip', determines distance and departure time for driving needs. This interface illustrates that an EV driver gives permission that electric utility is allowed to manage V2G operations depending on the distribution network operational situation. Most of demand response schemes involve the active participation of electric utilities and V2G operations technology [40]. An automatic charge control extends the idea of the auto charge controller by reducing driver concern to control charging.

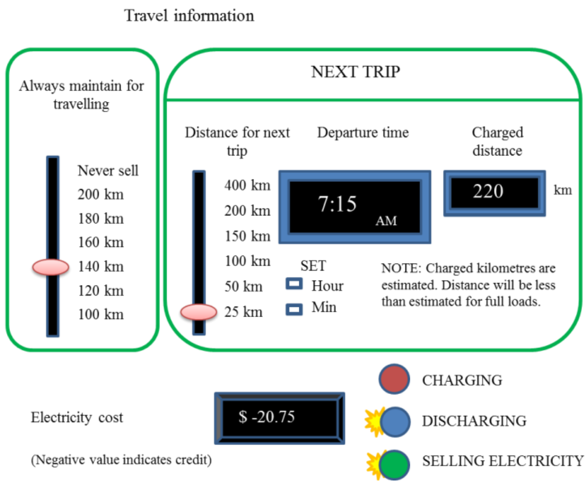

Figure 1. Auto charge controller for vehicle to grid operations, allowing the user to limit the discharge level of the batteries. In this case, the operator prefers to maintain 140 km for traveling and will travel 25 km at 7:15 in the next morning. The electricity cost reveals that the electric utility receives power from batteries and battery owner has earned $20.75 credit.

IV. Driving Patterns

The EV field trial indicates that the EV charging pattern follows the form of the electric power grid load demand pattern [41]. The peak time for charging occurs near a power grid peak demand time (Fig. 2). However, as most EV operators keep their EVs plugged in overnight, the charging control can shift the peak time for charging to low demand time.

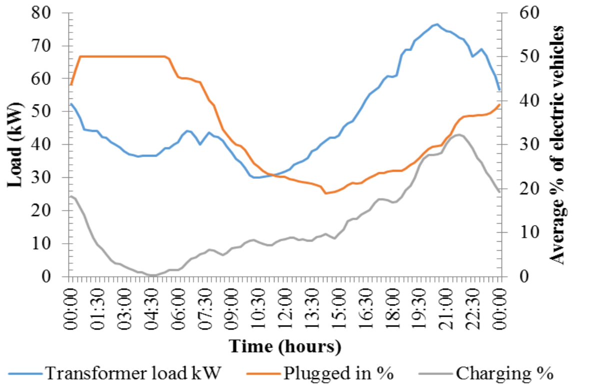

Figure 2. Outer suburb electric vehicles either charging or parking versus the pattern of electricity transformer load. The electric vehicle plugged in profile indicates the availability of the electric vehicles. Electric vehicle charging peak occurs about one hour after the transformer peak [41].

The power grid utilizes the chemical energy battery to stabilize power frequency fluctuations at the power grid [42]. Battery storages can shift the power demand (consumption peak) to the low power demand (valley hours). The EV battery operates as virtual battery storage for the power grid. The synergy benefits between the energy storage system and intermittent renewable energy reduce the operational cost of electric power systems [43]. However, V2G operations require EVs plugged in, that require standing in the parking place. In addition, the system need to provide guidance about available parking slots [44]. When EV operator drives with EV, batteries are not available for V2G operations. Most of the time EVs are located at the parking place (Fig. 3).

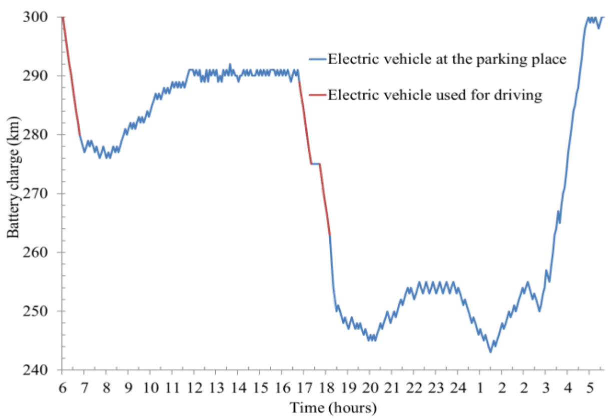

Figure 3. An electric vehicle battery charge one-day variation in vehicle to grid operations. Power grid operators carry out power frequency regulation during parking times. Battery management shifts peak demand to the hours between three and five.

An average traveled distance is 46 km [45]. Fig. 4 shows that 19%, 21% and 16% of the drivers who participated in the national survey would travel 8 km, 24 km and 40 km respectively on a daily basis, wherein total, 85% would travel up to 105 km. A number of vehicles were 179,484. Using this data, the battery charging was divided into four different charge limits according to the traveling distances: 25, 50, 75, and 100 km. Battery lifetime is optimized by choosing the optimal charge limit. Data values for Fig. 4 are 19.42; 21.23; 16.30; 11.30; 8.18; 5.78; 4.22; 2.79; 2.14; 1.62; 1.30; 0.81; 0.78; 0.58; 0.45; 0.39; 0.29; 0.26; 0.13; 0.13; 0.16. Traveling distances (Fig. 4) show, 21% would travel 24 km on a daily basis and longer distances gradually have less participation.

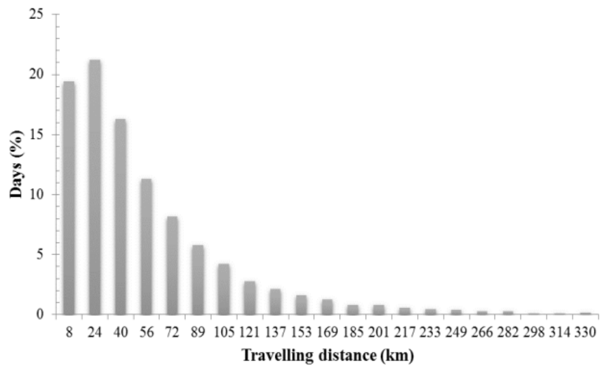

Figure 4. Traveling distance per vehicle during a one-year period according to a national survey.

V. Accelerated Aging Tests for Cycle Life Estimation

Battery cycle aging measurements show the capacity fade function of equivalent full cycles. When battery cells are fully charged and then fully discharged, a battery has made one full cycle or one complete cycle. When a battery is partly charged and discharged, for example, charged up to 75% of maximum capacity and then discharged to 25% of maximum capacity, only 50% of the complete charge is used. In addition, driving distance is then half that of the complete charge driving distance. When another similar half charge is made, up to 75%, and then discharged to 25%, we have two half charges, which is equal to one equivalent full cycle. When we use shorter fractions of cycles, we increase battery life and can drive longer distances with that battery package.

Fig. 5 shows the battery cell cycle aging tests for 25-75% and 40-60% SoC. In 40-60% SoC, the testing procedure charged cells up to 60% SoC and then discharged cells to 40% SoC. The SoC percentage means the percentage of maximum battery capacity. When we charge up to 60% of maximum capacity and then discharge to 40% of maximum capacity, only 20% of complete charge is used. We can do this 20% cycle five times and we have one equivalent full cycle.

Battery aging tests showed that the longest battery lifetime was achieved when the battery charge was around 50% [19]. Accelerated aging tests for cycle life estimation [46] were concluded at 35 ℃ and at current rate 1It with multiple SoC ranges. The current rate of 1It for 2.05 Ah cells is 2.05 A. Battery cells obtained the shortest lifetime when the test procedure carried out with full cycles. Tested cells reached a maximum of 440 cycles before the battery cells degraded down to 80% of the initial battery cell capacity. The test procedure carried out between 47.5 and 52.5% SoC reached the longest life of 8,500 equivalent full cycles. Fig. 5 compares the test procedure carried out between 25 and 75% SoC and between 40 and 60% SoC. The test procedure carried out between 25 and 75% SoC experienced sudden deaths for single cells; while cells cycled between 40 and 60%, SoC did not experience a similar phenomenon. Cycled cells die suddenly causing a spread and a challenge to predict cycle aging. Unexpectedly, sudden deaths for single cells happened when inner resistance reached 150% of their initial inner resistance and cells had capacities of about 80% of their initial capacity.

Accelerated aging tests for cycle life estimation indicated enhanced lifetime when the battery charge remains close to 50% SoC. There is a clear difference in a lifetime when cycled between 25 and 75% SoC and between 40 and 60% SoC (Fig. 5). When battery capacity decreased to 80% level, cycle pattern between 25 and 75% SoC reached 1,180 equivalent full cycles and cycle pattern between 40 and 60% SoC reached about 4,000 equivalent full cycles. Cells cycled between 40 and 60% SoC provides more than three times equivalent full cycles than cells cycled between 25 and 75% SoC. In the 550 km range EV, cycle pattern between 40 and 60% SoC has 110 km driving range and 440 km reserve driving range.

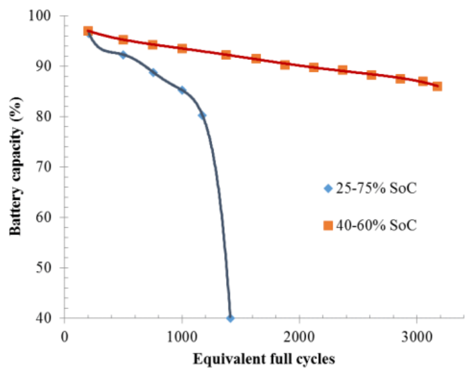

Figure 5. Equivalent full cycles when cycled between 25 and 75% SoC and between 40 and 60% SoC.

VI. AUTOMATIC CHARGING CONTROL

The automatic charging control intends to mitigate driver concern by introducing control systems that accommodate driver operational needs [47]. However, battery management requires optimum charging to enhance battery life. The initial expectation is that EV drivers do not drive at night; therefore, power grid operators use batteries for power frequency regulation in night hours. Further, power grid operators use batteries for power frequency regulation every time during parking, even during the charging time. For example, optimum charge for Li(NiMnCo)O_2-based cells is 50% SoC. While parking, the battery charge remains 50% SoC during power frequency up and down regulation. The EV battery achieves the longest life with 50% SoC charge. Automatic control charges batteries before morning, up to 60% SoC charge before the EV is used. During the daytime, charging control charges batteries according to the next trip. In addition, the charging control learns previous departure times and driving distances. Because of this learning feature, every driver has custom made, developing automatic charging control. When the EV is in parking spot during the daytime, the power grid operator uses batteries for power frequency regulation. When the EV driver returns home after the workday, battery management expects that power grid operator can utilize batteries during night hours. Battery management supply remaining excess battery charge back to the power grid as a peak demand power and during night hours charge level remains 50% SoC.

Charging can occur at the workplace charging point, at a shopping center parking place, along with the highway or another public or residential charging point. The location and charging time may reveal an EV driver's trip plan. For example, charging at a shopping center means that next trip is coming after an hour or two. Early hours charging along with the highway may indicate that EV driver plans to make a long trip; therefore charging control provides an extra amount of energy for a long trip driving. Charging control keeps the battery energy near 50% SoC to enhance battery life (Fig. 6). During parking, the charging control charges batteries before the departure. It is an EV driver's responsibility to follow the fuel gauge to ensure enough energy for the next trip.

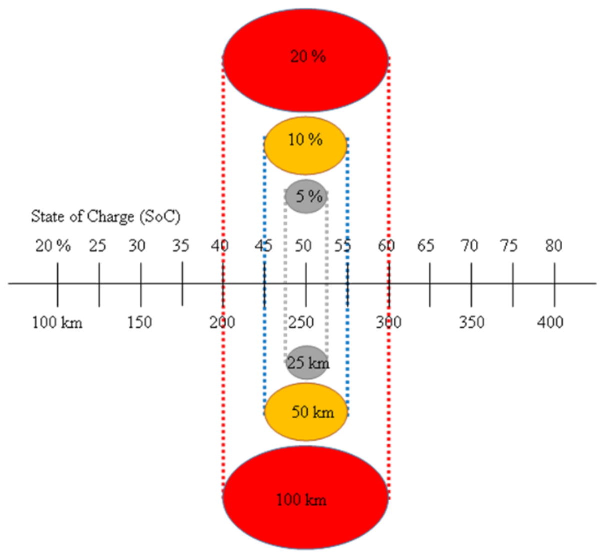

Figure 6. Electric vehicle battery charge limits around the optimum point of 50% SoC. The shortest distance charge limit provides 25 km range and uses 5% of the battery capacity.

Automatic charging control mitigates communication between a power grid, EV battery management, and EV driver. Automatic charging control supports V2G operations. When the communication system fails, information for battery management is limited. In such a case, automatic charging control may secure continues operations by providing autonomous decisions based on estimations. According to manufacturers' recommendations, the EV battery charge should be within 20% and 80% SoC (Fig. 6). In the automatic charging control, the EV batteries achieve the longest lifetime by shifting battery charge towards 50% SoC in every situation. The longest lifetime window uses 5% (25 km) of battery charge, the next window 10% (50 km), and the largest window 20% (100 km) of battery charge. The rest of the battery charge is available for longer trips; however, in that window battery degradation is stronger than in the optimal window area [18]. The automatic charging control flow chart shows charging procedures in different locations (Fig. 7).

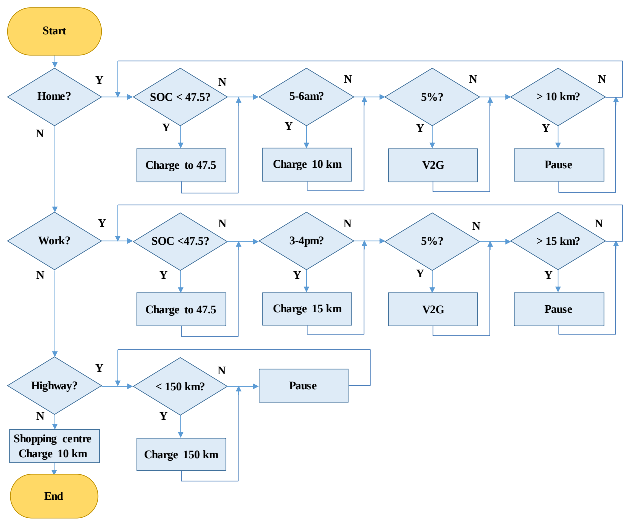

Figure 7. The automatic charging control charges electric vehicle batteries according to the next trip. In Vehicle to Grid (V2G) operations, the battery charge is between 47.5% and 52.2% State of Charge (SoC), covering 5% fraction to enhance battery life.

The first test in the flowchart is the location of a battery charging station. The first step charge EV batteries to V2G window, between 47.5 and 52.5% SoC. Estimated traveling distances are 20 km, 30 km, and 300 km. In order to keep the average charge near 50% SoC, the required charge is half of the next trip over the 50% SoC charge. Required distances to charge are 10 km for 20 km trip, 15 km for 30 km trip and 150 km for 300 km trip. When the EV battery charge is between 47.5 and 52.5% SoC, operating in the 5% window, V2G operations are available (Fig. 6). The battery management allows V2G operations only in the 5% window. When the battery charge is enough for the next trip, the charging procedure waits for the driver's response. While charging along the highway and at shopping center charging stations, charging control assumes that drivers park their EVs only for a short period. Therefore charging control charge batteries in the highway charging station to 150 km and a shopping center to 10 km immediately. The EV operator only plug-in the vehicle at a charging station and the automatic charging control charges EV batteries according to the situation.

VII. Interpretation and Discussion

One of the merits of this research is providing information for V2G battery selection. V2G reduces the lifetime of the batteries. Degradation was reduced by choosing an optimal charging window SoC. In Sanyo batteries, 47.5 to 52.5% SoC showed prolonged lifetime and is suitable for V2G operations.

V2G operations interact with the electric system as storage and load. Electric industry electric system benefits are revenue, reliability, lower cost transmission, and distribution of electricity. A framework for distributed energy systems design and operation combines various distributed renewable energy sources, energy supply interactions between renewable energy sources, power grid constraints, and EV integration flexibility [48, 49]. Operational time for light vehicles is 1 hour per day, light vehicles idle 23 hours per day covering 96% of the time. Availability to V2G operations, we refer 5% charge window when EV is not on the road. Availability to the power grid depends on parking places having electrical connectors to V2G operations. The comparison to availability, the EVs are available for virtual battery storage and supply electricity about the same period as baseload power supply despite the EVs are unavailable when there are on operational use. When we compare EVs, as grid operators would think about its power supply facilities, EVs power and battery storage facilities are grossly under-utilized. When a substantial fraction of the EVs was in V2G operations, EVs would dwarf the power supply of the power grid, at an economic price, reasonable availability, and located near the electrical load. The value of electric battery storage to grid operators is that EVs allow charging utilizing surplus electricity, when power grid has low-cost supply, and EVs allow discharge during periods of peak demand time when electricity market price is high. The electric battery storage has additional benefits when the EV battery has a fast response and can be utilized as a distributed power supply. For instance, EV battery mitigates power station generation at the low efficient idling power and mitigates power stations idle in spinning reserve to mitigate power generation failures or unexpected electrical load fluctuations. EV owners presumably sell battery power during peak demand and power supply failure, when aggregator is able to sell electricity to the power grid at the low demand rates. Electric utilities would need to address technical solutions, tariff systems, and electrical safety requirements to allow for reverse power flow from the EV batteries to the power grid.

To the EV battery owner, providing electricity to the power grid for the grid operator's benefit, reduce battery life and is energy lost for EV batteries. The cost of V2G operations depends on a number of recharge cycles and frequency of recharge cycles and the state of charge and EV battery configurations. An electric utility is able to use charging and discharging cycles for battery storage. In this role, charging control charges a battery storage plant during low demand periods, and the discharge process dispatches stored battery energy back to the power grid during high demand periods.

A grid operator's avoided costs are incremental costs for generating electric energy. These costs include power capacity costs ($/kW) and electric energy costs ($/kWh).

An electric utility's avoided costs provide possibilities for co-operation with EV owner. An EV owner would be willing to sell V2G services to the electric utility if the price is higher than V2G costs for an EV owner. An economical staging plan model reduces the annual cost for V2G charging. The approach accommodates the electric distribution supply to accommodate EV penetration level predictions and secures investments [50].

A large EV fleet provides virtual battery storage for the power grid and enables increased penetration rates and demand for intermittent renewable energy generation such as solar energy and wind power. To engage EV batteries in V2G operations, battery lifetime challenges need to be addressed. Today's EV battery research should emphasize the durability of batteries, as cycle aging is the biggest cost factor in V2G operations.

VIII. CONCLUSION

Principal findings are lifetime reduction is decreased in vehicle to grid operations and a lifetime can be extended. Optimal window of a state of charge was used in vehicle to grid operations and selected state of charge windows are used in driving use. This study is important to the community and is worthy of note because it shows an extended lifetime with battery management instead of developing battery chemistry. Implications of the findings are the importance of battery management system in vehicle to grid operations and vehicle to grid operations will become more compelling technology. The research, as well as the findings, have addressed the defined objective by degreasing lifetime influence from vehicle to grid operations.

Presented automatic charging control charge and discharge electric vehicle batteries without electric vehicle drivers' control. An electric utility uses electric vehicle batteries as power regulation up and regulation down, mitigating peak demand and low demand, and as an electrical power source and load. The battery management keeps battery charge close to 50% state of charge and charges batteries according to coming traveling distance. The battery management optimizes battery usage to provide the longest lifetime. At a parking place, the automatic charging control provides electric vehicle charging automatically. The automatic charging control mitigates driver concern to control charging and discharging operations. After parking driver needs to plug the electric vehicle into electrical connections. The automatic charging control mitigates driver's need to communicate with charging control. The automatic charging control locates charging spot; adjust charging power level and charging time, and checks power grid and battery storage availability to the vehicle to grid operations before required charging decision.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

TAL and AZ conducted the research, analyzed the data, and wrote the manuscript. Both authors had approved the final version.

ACKNOWLEDGMENT

This work was in part supported by the College of Science and Engineering and the Graduate Research School, James Cook University, Australia.

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