Development of an Intelligent Controller for Vehicle to Grid (V2G) System


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Abstract: Electric Vehicle (EV) is gaining popularity due to growing concern on pollution. But a large number of EV can have an adverse effect on power system as it acts as a huge load on the grid. The solution lies in having a co-ordinate system of charging and discharging which can be effectively used to support grid. Here a controller has been proposed which analyzes current grid status, EV battery state of charge (SOC), electricity tariff offered by power utility company along with EV owner preference. An analysis illustrates how the V2G feasibility is determined by the charging station controller and then based on grid status and EV battery SOC, charging and discharging rate of current is predicted by V2G controller. The proposed control algorithm has been simulated using MATLAB SIMULINK.

Index Terms: Electric Vehicle, V2G, Fuzzy Logic Controller

I. INTRODUCTION

Global warming has attracted the attention of whole world due to its adverse impact on Earth’s climate. Temperature rise due to global warming can be attributed to burning of fossil fuel which produces carbon dioxide and other greenhouse gases. Growing concern on climate change has led to very stringent emission norms across automotive industries. Hence at present emphasis is on the need to have a clean source of energy with minimum pollution. It has contributed to increase in popularity of Electric Vehicle (EV). EV uses rechargeable battery, electric motor and controller for propulsion system. EV battery can be charged or discharged using off-board or on-board charger. There are different types of batteries used in the EV, but Lithium ion batteries are preferred over other batteries due to high efficiency, greater energy, better cycle life, higher cell voltage. Higher cell voltage of Lithium ion batteries reduces the number of cells, which in turn reduces the size of battery. Due to rapid advancement in battery technology now it is being manufactured typically in the range of 15 to 85 kWh. When EV is connected to grid it acts as a huge load on grid. But on the other side EV battery due to its large energy storage capacity can also act as an alternative source of energy which can be used during peak demand to support grid. Thus there is a need to develop an intelligent controller for vehicle to Grid (V2G) system which takes care of current status of EV and grid. In this paper Section-II describes V2G system, Section-III provides the detail explanation of proposed controller, followed by Simulation Result & Performance Analysis in Section –IV and Conclusion and Future Scope in section-V.

II. VEHICLE TO GRID SYSTEM

Interconnection of EV and grid is called as V2G system. It supports bi-directional power transfer i.e. from vehicle-to-grid and grid-to-vehicle [1]. Fig.1 shows the typical diagram of V2G system which has been explained by W. Kempton and J. Tomic [2].

Fig.1. Vehicle to Grid System (V2G)
In consists of grid having renewable (thermal power) and non-renewable (wind power) sources of energy. EV when connected to the grid acts as a huge load to the grid which can have an adverse impact on the power quality. Government of India has announced to increase the share of renewable energy sources by increasing the currently installed capacity of Solar and Wind energy. But it will also cause uncertainties due to intermittency in the generation of the renewable energy. With increase in EV penetration in India V2G can act as a support to grid for mitigation the power quality issues [3]. It can be done by using co-ordinate charging methodology. In this methodology charging and discharging rate of current varies based on the current status of EV battery and grid. For example, electric vehicle Nissan Leaf has capacity of 30 kWh which is negligible when compared to grid fluctuation (in MW) [14]. But fleet of EV can be used to regulate the grid both during peak hour and off hour. During peak hour when demand is more and generation is less, it can act as an alternative source of energy to meet the demand by discharging the stored energy in EV battery to grid. Similarly during off hour when generation is more and load is less on grid EV can act as load by charging the battery by taking energy from grid [4]-[9].

As per SAE J1772 standard EV charger has been classified into three categories, Level 1, Level 2, and Level 3 for both ac and dc supply[10], [11], [13]. Summary of different power level are given in Table I.

Table I EV Charger Classification

<table>
<thead>
<tr>
<th>Type</th>
<th>Voltage Level</th>
<th>Charger Location</th>
<th>Expected Power Level</th>
<th>Charging Time</th>
<th>Vehicle Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level-I</td>
<td>$V_{ac}(US)$ 120</td>
<td>On board 1-Phase</td>
<td>1.4 kW(12A)</td>
<td>4-11 hour</td>
<td>PHEV(5-15 kWh)</td>
</tr>
<tr>
<td></td>
<td>$V_{ac}(EU)$ 230</td>
<td></td>
<td></td>
<td></td>
<td>EV(16-50 kWh)</td>
</tr>
<tr>
<td>Level-II</td>
<td>$V_{ac}(US)$ 240</td>
<td>On board 1 or 3-Phase</td>
<td>4kW(17A)</td>
<td>1-4 hour</td>
<td>PHEV(5-15 kWh)</td>
</tr>
<tr>
<td></td>
<td>$V_{ac}(EU)$ 400</td>
<td></td>
<td>8kW(32A)</td>
<td>2-6 hour</td>
<td>EV(16-30 kWh)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19.2kW(80A)</td>
<td>2-3 hour</td>
<td>EV(3-50 kWh)</td>
</tr>
<tr>
<td>Level-III</td>
<td>$V_{ac}$ 208-600</td>
<td>Off board 3-Phase</td>
<td>50 kW</td>
<td>0.4-1 hour</td>
<td>EV(20-50 kWh)</td>
</tr>
<tr>
<td></td>
<td>$V_{dc}$ or $V_{ac}$</td>
<td></td>
<td>100 kW</td>
<td>0.2-0.5 hour</td>
<td></td>
</tr>
</tbody>
</table>

Based on the above research findings, it can be concluded that vehicle to grid charging and discharging & its impact on grid status have been studied. But there is need to do the feasibility analysis before connecting the EV to grid. Here an intelligent controller is presented which first analyzes the feasibility of EV connection to grid based on current grid status, EV battery SOC, current electricity tariff offered by power utility company and EV owner driving needs & preferred price for charging or discharging. If charging station controller output is feasible then only fuzzy based V2G controller predicts the optimized charging or discharging current rate based on current grid status and EV battery SOC.

III. CHARGING STATION AND V2G CONTROLLER

This section provides the working principle of the proposed controller and its simulation in MATLAB Simulink. It consists of a charging station controller and a fuzzy based V2G controller.

A. Charging Station Controller

Charging station controller is acting as an interface between EV owner, Aggregator and Power Utility Company as shown in Fig.2. Here Aggregator can be thought as a place which provides charging and discharging facility to many EV simultaneously. Power Utility Company facilitates the Aggregator present...
charging and discharging tariff as per the agreement signed among them. Charging and discharging price offered by Power Utility Company dynamically changes with grid status. For Indian scenario tariff with grid status has been researched by “BhanuBhusan” in the paper “ABC of ABT: A PRIMER ON AVAILABILITY TARIFF” in great detail [6]. Charging and discharging price per unit offered by Power utility company with changing grid status has been emulated in our project based on this paper.

When grid is in power surplus condition i.e. charging point voltage is equal to or more than 230 V and EV owner pricing criteria is matching with present charging price offered by Power Utility company then, power flow will be in G2V mode (grid to vehicle mode).

3) Discharging (V2G mode)

When grid is in power deficient condition i.e. charging point voltage is less than 230 V and EV owner pricing criteria is matching with present discharging price offered by Power Utility Company then, power flow will be in V2G mode (grid to vehicle mode). Here Vehicle will stop supplying power to Grid once it reaches SOC limit as preferred by the EV owner.

B. V2G Controller

V2G controller works on the principle of fuzzy logic which is used to calculate the optimized charging or discharging rate based on EV battery SOC and grid status as shown in Fig-2.

Output of charging station controller decides V2G or G2V support is feasible or not. If it is feasible then only fuzzy logic based V2G controller predicts the optimized charging or discharging rate of current based on grid status (charging point voltage) and current SOC of battery. Here positive sign of V2G controller output indicates discharging i.e. V2G mode & negative sign indicates charging i.e. G2V mode.

Actual power flow between vehicle and grid is decided by the magnitude of the output of fuzzy based V2G controller i.e. on the basis of optimized charging or discharging rate. So here charging/discharging rate of the battery will be dynamically changing based on battery SOC and grid status i.e. charging point voltage.
1) Introduction to fuzzy logic control
Concept of fuzzy logic was given by Lotfi A Zadeh in 1968. In binary logic we have two values i.e. either TRUE/FALSE or 0/1 but in fuzzy logic we have multi value. Fuzzy logic variables are expressed on the scale of 0 to 1 depending on the irtruthness. It works on the basis of simple IF-Then rule base and thus abolishing the need of complex mathematical modeling to implement the given system behavior. It is widely used for those systems whose mathematical model is very complicated and thus tough to implement. Mamdani type fuzzy logic controller has been designed in this paper. A typical architecture of fuzzy logic control system is shown in Fig.4.

There are four major modules in the fuzzy control system-fuzzification, inference logic, rule set and defuzzification module. Fuzzification and defuzzification modules are complimentary in nature. First one transforms the crisp value into fuzzy variables and second one transforms the fuzzy variables back to crisp values. It is obtained by means of a membership function. Rule is a set of IF-THEN statements which implements the control algorithm. The output from each rule in the rule base is deduced by the inference logic to arrive at a value for each output membership function. The centre of gravity (COG) method is used for defuzzification which gives a crisp output.

Fig.4. Fuzzy logic V2G control system

2) Fuzzy membership function
Defining the membership function is critical for fuzzification. Triangular membership function is mostly used due simplicity in calculation for academic purpose. In this paper membership function of battery SOC has been fuzzified into 5 stages namely Battery Very Low (BVL), Battery Low (BL), Battery Medium (BM), Battery High (BH) and Battery Very High (BVH). Fig-5 shows the membership function of SOC along with its five stages.

Fig.5. SOC membership function

Charging point voltage where EV is connected to the aggregator has been first converted into per unit system. Per unit system is defined as the ratio of actual value of any quantity divided by the base value of the measured quantity.

\[ Q_{pu} = \frac{Q}{Q_{base}} \]  

Where \( Q_{pu} \) is the per unit quantity (dimensionless)
\( Q \) is quantity in normal units
\( Q_{base} \) is the base value of the quantity in normal unit

In this paper 230 V has been taken as the base voltage and hence in per unit system it is represented as 1 pu. Similarly per unit value of 250 V is 1.086 pu. Here voltage range has been taken from 0.7 to 1.2 in per unit system. Membership function of charging point voltage which shows the grid condition has been fuzzified into 5 stages namely Grid Very Low (GVL), Grid Low (GL), Grid Medium (GM), Grid High (GH) and Grid Very High (GVH). Fig-6 shows the membership function of charging point voltage along with its five stages.

Fig.6. Charging point voltage membership function

Output membership function CRATE can have positive or negative value. Positive value means power flow is from Vehicle to Grid (V2G) i.e. battery is discharging. And negative value means EV battery is charging i.e. power flow is from Grid to Voltage (G2V). It has been fuzzified into 9 stages based on CRATE namely Negative High current (cNH), Negative Medium current (cNM), Negative Low...
current(cNL), Very Negative Low current (cVNL), Very Positive Low current (cVPL), Positive Low current (cPL), Positive Medium current (cPM), Positive High current (cPH) and Very Positive High current (cVPH). Fig. 7 shows the membership function of CRATE along with its nine stages.

Fig. 7. CRATE membership function

3) Fuzzy control rule set
A fuzzy control rule set is formed on the basis of human expertise in the actual application. It is a set of form of IF-THEN rules which determines the system output for a given set of input. Here rules can be expressed in linguistic way.

In this paper for our application rule is based on following inference:

Table II Rules of V2G controller

<table>
<thead>
<tr>
<th>SOC (→)</th>
<th>BVL</th>
<th>BL</th>
<th>BM</th>
<th>BH</th>
<th>BVH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage(↓)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GVL</td>
<td>cVPL</td>
<td>cPL</td>
<td>cPM</td>
<td>cPH</td>
<td>cVP</td>
</tr>
<tr>
<td>GL</td>
<td>cVPL</td>
<td>cPL</td>
<td>cPM</td>
<td>cPH</td>
<td>cPH</td>
</tr>
<tr>
<td>GM</td>
<td>cVN</td>
<td>cVP</td>
<td>cPL</td>
<td>cP</td>
<td>cPM</td>
</tr>
<tr>
<td>GH</td>
<td>cNH</td>
<td>cNH</td>
<td>cN</td>
<td>cNL</td>
<td>cVNL</td>
</tr>
<tr>
<td>GVH</td>
<td>cNH</td>
<td>cNH</td>
<td>cN</td>
<td>cNL</td>
<td>cVNL</td>
</tr>
</tbody>
</table>

a) If grid is in high need of power (GVL) and EV battery SOC is maximum (BVH) then, discharging rate (+ve) should be maximum (cVPH).
b) If grid is in high surplus power (GVH) and EV battery SOC is minimum (BVL) then, charging rate (-ve) should be maximum (cNH).

4) Defuzzification
Most popular defuzzification technique used is centre of gravity (COG) type. By applying COG method we can converts fuzzy system output into crisp output i.e. defuzzified output. In this paper all membership function has triangular shape and now if triangle is partitioned into two parts by passing a straight line horizontally depending on membership value then base portion of triangle will have trapezoidal shape. Each rule follows the above process and corresponding to these trapezoids shapes are formed. Superimposing of all these trapezoids form a geometrical shapes whose centroid is calculated. Co-ordinate of the centroid is the defuzzified value. Below is the sample output for charging point voltage as 0.8 p.u. & SOC = 90. Fig. 8 shows the calculated value of CRATE in rule viewer interface of MatlabSimulink.

Fig. 8. CRATE output after defuzzification

IV. SIMULATION RESULT & PERFORMANCE ANALYSIS

Proposed Controller has been simulated in Matlab Simulink. Table III shows the various input and output parameters of charging station controller and fuzzy based V2G controller which emulate the real time grid scenario for peak hour, off hour and balanced condition.
Charging station controller output has two possibilities. It can be either feasible for which one value has been shown or not feasible for which zero value has been shown in Fig. 10. Based on charging station controller output V2G fuzzy based controller can have three different output values.

1) Zero
When Charging Station Controller output is not feasible i.e. zero then fuzzy based V2G controller output is also zero.

2) Positive numeric value
Positive numeric value of V2G controller output means EV is operating in V2G mode i.e. discharging mode.

3) Negative numeric value
Negative numeric value of V2G controller output means EV is operating in G2V mode i.e. charging mode. Considering all possible scenario of Charging station Controller and V2G controller, here four different cases have been simulated. Input and output parameters of charging station and V2G controller are shown in Fig.9 & Fig.10. Below is the summary of four different cases:

Case-I: When Charging point voltage is 235 V i.e. grid is in power surplus condition (G2V mode). In this scenario charging station controller output is feasible i.e. at t=0 to 0.2 second and optimized discharging current rate predicted by V2G controller is -50 amp.

Case-II: When Charging point voltage is 220 V i.e. grid is in power deficient condition (V2G mode). In this scenario charging station controller output is not feasible i.e. at t=0.1 to 0.2 second because here minimum discharging price set by EV owner is Rs 6 and current discharging price offered by power utility company is Rs 5 only which violates the predefined condition of charging station controller. Here V2G controller output will also be zero.

Case-III: When Charging point voltage is 180 V i.e. grid is in power deficient condition (V2G mode). In this scenario charging station controller output is feasible i.e. at t=0.2 to 0.3 second and optimized discharging current rate predicted by V2G controller is 70 amp.

Case-IV: When Charging point voltage is 200 V i.e. grid is in power deficient condition (V2G mode). In this scenario charging station controller output is not feasible i.e. at t=0.3 to 0.4 second because here minimum level of SOC of EV battery preferred by EV owner is 51 and current SOC of battery is 40 which violates the predefined condition of charging.
station controller. Here V2G controller output will also be zero.

V. CONCLUSION AND FUTURE WORK

Proposed controller was simulated using MATLAB Simulink under different condition. Charging station controller has been implemented to analyze the feasibility of V2G or G2V support for a given EV based on current grid condition. If feasible then only fuzzy based V2G controller is used to predict the optimized charging or discharging rate of current based on grid status and EV battery SOC. It is useful in balancing the uncertainties introduced by the intermittency of the renewable energy which in turns increases the reliability and stability of power system. It also gives an economic benefit to the EV owner as they can discharge the stored energy in EV battery back to grid (V2G) during peak demand as electricity tariff will be high & can charge the EV battery during off hour (G2V) when electricity tariff is low.

In future proposed controller in this paper can be integrated with a bidirectional EV charger to study the real time behavior of an individual EV and its interaction with grid to assess the impact on power system. Optimum charging/discharging current predicted by the controller can be taken as a reference to the EV charger in order to minimize the adverse impact on grid and thus improving the power quality.

REFERENCES