An intelligent control strategy for vehicle-to-grid and grid-to-vehicle energy transfer

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Abstract. In this work a Fuzzy logic based control strategy for Vehicle to Grid and Grid to Vehicle energy transfer with pricing strategy for EV (Electric vehicle) and PHEV (Plug-in Hybrid Electric Vehicles) is proposed. The method proposed allows the vehicles in the public charging station or in home to intelligently charge/discharge based on the preferences of owner also taking care of grid safe operational conditions. The system discussed in this work will charge or discharge the vehicles by assigning priorities among the vehicles at the public parking infrastructure based on information of initial State of Charge of vehicle, State of Charge to be achieved at the end of charging/discharging, duration for which vehicle stays in parking infrastructure, and also proposes pricing strategy based on prediction technique to maintain uniform energy consumption of EV or PHEV on day-to-day basis. By the proposed method these charging and discharging mechanics of EV or PHEV can be leveled, scheduled, and managed intelligently.

1. Introduction

1.1. Literature Survey

Electric vehicles and PHEVs are automotive technologies which are seeing increasing demand growth year by year and the way these technologies are perceived in the world automotive market is phenomenal. As the conventional IC engines have harmful effects on world climate the technologies of EVs and PHEVs can only see upward demand growth.

A process needs to be setup which can provide for coordination among different vehicles parked in public infrastructure which needs to be charged from the grid or discharged into the grid to avoid simultaneous charging or discharging. In upcoming years when there will be high number of electric vehicles on the road charging spots will be developed just like petrol bunks where owner can input his preferences for charging (G2V) or discharging (V2G) and get the required service from charging infrastructure without harming grid operational stability. This energy management system of V2G and G2V helps in maintaining balanced load demand by "valley filling and "peak shaving". There is also increasing trend of utilization of renewable energy sources in charging station which can be of advantage for both the vehicle owner as well as to the power distribution companies. As public charging spots will have large number of vehicles and renewable energy sources in the upcoming years, there is a very good opportunity to use these vehicles as Energy Storage Structures (ESS) for supporting the grid.

A fuzzy technique based control architecture for multi charging station is presented in[1],This work shows how a controlled charging and discharging of EVs can help both EV owner and power utility and also how charging infrastructure spots can serve as distributed energy source and provide assistance in maintaining smooth load profile. In second work[2] two controllers are modelled, First one is charging station controller and second one is V2G controller. Both of these controllers act together to control the right amount of energy flow between EV and grid. In this paper [3] solar
photovoltaic system used in residential is implemented using Artificial Neural Network (ANN) based controller for Maximum Power Point Tracking (MPPT) and inverter control for load voltage regulation. In this paper[4] Maximum Power Point Tracking (MPPT) controller for solar photovoltaic system has been developed by artificial neural network (ANN). In another work a method has been proposed for pricing of vehicles during V2G and G2V[5].In another work[6] priority based charging of EVs in charging station has been discussed and model of it has been developed. Electric vehicle load forecasting methods and their different merits and demerits is discussed in[7]. In this paper[8], work is done to attempt modelling the risk adjusted profit of microgrid central controller (MGCC) in a microgrid power market.

2. Methodology

2.1. Intelligent Charging Station

A working control setup is required for proper coordination among vehicles for charging or discharging in public charging infrastructure’s which takes into account battery SOC, customer’s desired SOC, duration for which vehicles stay in parking lot etc also a strategy is required to avoid random load fluctuations and maintain uniform electrical energy consumption pattern on day to day basis to avoid load peaking by Electric vehicles or PHEVs. If these high number of vehicles are managed and coordinated for charging/discharging then they can be beneficial for the vehicle owner and to the electricity distribution company in terms of power saving as well as cost saving.

This charging station will manage all the vehicles for either charging or discharging in and will provide a solution for scheduling the charging or discharging of EV’s or PHEVs such that entire system would operate within the installed capacity and also manage pricing strategy for charging vehicles based on prediction technique as a supplement measure to maintain grid stability.

Intelligent Charge Filling Station will prove to be advantageous for both vehicle owner and power utilities as it can accommodate both stakeholder’s preferences without violating the grid operational conditions. The figure 1 shows overall system of Intelligent Charging Station.

![Figure 1. Intelligent Charging Station.](image)

2.2. V2G and G2V Controller

V2G refers to supplying the electrical energy from vehicle to the grid and G2V refers to taking electrical energy from the grid into the vehicle. The controller discussed in this work takes the inputs of EV or PHEV owner such as charging price, discharging price and owner preferred SOC when owner wants to depart from charging station and compares with real time price table of power utility company. After making inference from inputs controller sends control signals to fuzzy logic controller so as to charge or discharge fleet of EVs. It is to be noted that at a time, either charging will happen or discharging not both. The detailed flow chart of the controller is as shown in the figure 2.
2.2.1. When grid voltage is greater than or equal to the standard voltage limits.
If this condition exits then it indicates that grid is having surplus power and EV could be charged from the grid. This algorithm compares user demanding charging price with utility offering charging price and after this comparison if consensus exists between two parties then algorithm will add vehicle to charging queue by sending control signals to fuzzy controller.

2.2.2. When grid voltage is less than the standard voltage limits.
This state indicates grid is in power deficient mode. The algorithm will then compare EV owner and power utility discharge price and if there is consensus between two parties that discharge price offered by utility company is greater than or equal to price demanded by user then algorithm will add EV into discharging queue.

2.3. Fuzzy controller
For each vehicle in the Charging Station there is fuzzy logic controller unit and they use Mamdani type FLC and triangular membership functions to drive FLCs. Three inputs are used for FLC i.e grid voltage, arrival and departure times of each vehicle in hours and SOC of each vehicle. The FLC will then decide amount of the current needed for each vehicle to charge or discharge. The figure 3 indicates three fundamental inputs to fuzzy system i.e three crisp inputs converted to fuzzy inputs indicating duration of vehicle in charging station, initial battery SOC of vehicle and grid voltage at the time of charging/discharging of vehicle.

SOC of each and every EV battery in charging station is fuzzified into three membership functions, namely low SOC (LS), medium SOC (MS) and high SOC (HS); For second input grid voltage crisp values are fuzzified into three membership functions, namely low voltage (LV), medium voltage (MV) and high voltage (HV); Duration of EV staying in charging station is initially crisp and is
fuzzified into three membership functions, namely low duration (LD), medium duration (MD) and high duration (HD). The output given by FLC will either do charging or discharging of EV based on its sign and it is fuzzified into six membership functions, namely positive high (PH), positive medium (PM), positive low (PL), negative low (NL), negative medium (NM) and negative high (NH). In this work, positive indicates the charging current and negative indicates the discharging current and figure 4 illustrates these membership functions.

The table 1 shows different combinations of membership functions of three inputs to the fuzzy system. There are 27 possible combinations and these are implemented in fuzzy system to charge/discharge vehicles in different proportions of current to adhere to customer and utility preferences.

![Membership Functions](image-url)

**Figure 4.** (a) Vehicle SOC; (b) Grid voltage; (c) Duration; (d) Charging Level.

| Table 1. Fuzzy rules. |
|------------------------|
| (Input 1) | (Inputs 2) | (Input 3) | (Output) |
| Grid Voltage | EV_SOC | Duration | Current level |
| LV | LS | LD | NH |
| LV | LS | MD | NM |
| LV | LS | HD | NL |
| LV | MS | LD | NH |
2.4. Forecaster

The FORECAST function is an inbuilt feature in Microsoft-Excel that is categorized as a statistical function. It can be used as a worksheet function in excel. As a worksheet function, the FORECAST function works on time oriented dataset in excel and generates forecast sheet which gives insight into future values of dataset and can be used to make real time decisions in business or any other commercial aspects. In this work dataset of initial SOC of car when it arrived at charging station and final SOC when it is leaving charging station of at least past 30 charging instances are taken to understand the charging pattern of car. Based on this dataset exponential smoothening forecast will be performed by making use of Excel 2016 inbuilt with forecast functionality. 95% confidence upper bound and 95% confidence lower bound are considered to adjust for the error in forecasting so that forecasted value lies within the range of values and matches with unexpected value of SOC requirement.

| Input 1 | Input 2 | Input 3 | Output |
|---------|---------|---------|--------|
| Grid_Voltage | EV_SOC  | Duration | Current level |
| LV      | MS      | MD      | NM     |
| LV      | MS      | HD      | NL     |
| LV      | HS      | LD      | NH     |
| LV      | HS      | MD      | NM     |
| LV      | HS      | HD      | NL     |
| MV      | LS      | LD      | PL     |
| MV      | LS      | MD      | PL     |
| MV      | LS      | HD      | PL     |
| MV      | MS      | LD      | NH     |
| MV      | MS      | MD      | NM     |
| MV      | MS      | HD      | NL     |
| MV      | HS      | LD      | NH     |
| MV      | HS      | MD      | NM     |
| MV      | HS      | HD      | NL     |
| HV      | LS      | LD      | PH     |
| HV      | LS      | MD      | PM     |
| HV      | LS      | HD      | PL     |
| HV      | MS      | LD      | PH     |
| HV      | MS      | MD      | PM     |
| HV      | MS      | HD      | PL     |
| HV      | HS      | LD      | PH     |
| HV      | HS      | MD      | PM     |
| HV      | HS      | HD      | PL     |

2.4.1. Pricing for Electric Vehicle Charging

Under the case of uniform SOC requirement of car in each charging instance the pricing of Electric vehicle charging is normal as compared to other vehicle charging and will be as per data provided to customer before charging. When SOC requirement of car fluctuates on every now and then vehicle will be penalized for its SOC requirement fluctuation and will be charged accordingly. Below is the algorithm implemented in charging station. For every 1 unit of SOC deviation 5 units of cost will be charged. Below algorithm illustrates the mechanism.

If (SOC requirement = Forecasted value)
Penalty of Electric Vehicle=0
Elseif (SOC requirement < lower confidence levels)
Penalty of Electric Vehicle= (lower confidence levels - SOC requirement) *5
Elseif (SOC requirement > upper confidence levels)
Penalty of Electric Vehicle= (SOC requirement - upper confidence levels) *5
Else
Penalty of Electric Vehicle=0
2.5. **User vehicle Buck-Boost Converter**

DC-DC Converter is an electrical converter which can provide both buck and boost operation. Through this converter bidirectional flow of electricity is obtained i.e from grid to EV and EV to grid. For positive reference current, the converter will act in buck mode. In this mode EV batteries are charged with current defined by FLC. For negative reference current, the converter will act in the boost mode. In boost mode EV batteries discharge at currents defined by the FLC. In this work a buck-boost converter which operates between the input voltage of 400V and battery nominal voltage of 366V and batteries of ratings 366V, 60Ah, 22kW corresponding to each EV in the charging station has been chosen. The figure 5 shows the implementation of Buck-Boost Converter.

![Figure 5. Buck-Boost Converter.](image)

2.6. **Battery Charge/Discharge Monitor System**

When EV/PHEV comes for charging or discharging at charging station and plugged for charge or discharge mode, Standard specifications of vehicle such as arrival and departure time, initial SOC and final SOC are submitted to the utility operator. Meeting standard specifications is very important for grid stability and to maintain charging queue of vehicles. This will not be achievable if car loads other than battery are in on state when ignition is in off state. There will be increase in charging/discharging time and car may not be able to reach desired SOC within time limits of arrival and departure time. This makes vehicle to stay longer time in charge/discharge mode interrupting other vehicles from charging or discharging.

So in order to optimise utility stability and enhance user profitability and also to reduce heating of battery “Battery Charge/Discharge Monitor” functionality is included in charge station controller. This system monitors charge/discharge process and shed the loads based on priority whenever ignition is off and restart the loads whenever car comes out of charging and discharging process. The inputs to this system are taken from sensors of car which monitor loads such as Air-Conditioner and infotainment systems. The signal Load_Shedding_Event is driven by different conditions and indicates whether load shedding will occur or not. The logical truth table shown in table 2 illustrates the system.
Table 2. Battery Charge/Discharge Monitor System.

| Variables                      | Condition 1 | Condition 2 | Condition 3 | Condition 4 |
|--------------------------------|-------------|-------------|-------------|-------------|
| Loadshed_Enable                | TRUE        | TRUE        | TRUE        | TRUE        |
| Ignition_Status                | TRUE        | TRUE        | TRUE        | TRUE        |
| B1_SOC_Acc                     | TRUE        | TRUE        | TRUE        | TRUE        |
| CarMode                        | TRUE        | TRUE        | TRUE        | TRUE        |
| BattChargedischarge            | TRUE        | FALSE       | TRUE        | FALSE       |
| Airconditioner_ON             | FALSE       | FALSE       | TRUE        | TRUE        |
| Infotainment_ON                | Action:     | Action:     | Action:     | Action:     |
|                               | Load_Shedding_Event =ON | Load_Shedding_Event =ON | Load_Shedding_Event =ON | Load_Shedding_Event =OFF |

3. Results and Discussion

The Simulation of Intelligent Controller is carried out with softwares MATLAB and Microsoft Excel. The simulation exhibits the concept of intelligent controller working and explores how fuzzy logic helps in achieving desired controlled operation of V2G and G2V in charging station to accommodate both stakeholders interests i.e vehicle owner preferences for charging/discharging as well as power utility preferences.

3.1. When all vehicles have same arrival and departure time

Table 3. User specifications.

| Parameters                   | EV1 | EV2 | EV3 | EV4 |
|------------------------------|-----|-----|-----|-----|
| Initial SOC (%)              | 70  | 40  | 50  | 85  |
| User SOC (%)                 | 25  | 45  | 60  | 50  |
| User Arrival Time (hours)    | 8   | 8   | 8   | 8   |
| User Departure Time (hours)  | 16  | 16  | 16  | 16  |
| User Charging Price/unit     | 5   | 4   | 5   | 5   |
| User Discharging Price/unit  | 6   | 6   | 6   | 6   |

3.1.1. Grid voltage=0.9 p.u

Grid voltage of less than 1 p.u. gives information that grid is in power deficient mode or overloaded. Under this situation vehicles can only be discharged into the grid and cannot charge from grid. 1 p.u is considered as nominal voltage, utility tariff as 4.5 per unit charging and 7 per unit discharging. The discharging price is higher than charging price because discharging activity is not as common as charging activity and grid accepts electrical energy only when there is steep decline in grid voltage which is rare. So grid is ready to offer high price due to heavy load in that situation. So for a given grid voltage of 0.9 p.u, vehicles EV1 and EV4 fall under discharging queue and start discharging till the SOC specified by user. The discharging current for EV1 is estimated to be -8.78A by FLC and it is -6.915A for EV4 as shown in figure 6 and figure 7 respectively. EV2 and EV3 do not meet owner/user criteria so they remain idle. Here SOC refers to vehicle battery SOC, current refers to current with which vehicle battery is charging/discharging, voltage refers to input voltage to buck-boost converter and this voltage appears across EV1 and EV4 batteries when vehicles are discharging so this voltage is justified to be EV1 and EV4 voltage.
Here EV batteries are discharging so it is needed to shed the loads if they are ON. This is performed by the controller in charging station. The status of loads such as Air-conditioner and Infotainment are initially obtained through sensors attached to them. If any one of them is ON during car charging/discharging then they will be shed on priority basis so that charging/discharging process continues to be completed within time limits set by the customer. Figure 8 indicates how loads are turned on and off depending upon whether load shedding event is happening or not. In the plot it can be seen that Air-conditioner is always OFF state as it was not turned ON during discharging process. It is to be noted that load shed function will work only when ignition is in OFF state. This case Air-conditioner will always be OFF. Infotainment feature was initially ON but after load shed event is activated it is turned OFF and when ignition is turned ON or load shed event becomes deactivated it is automatically turned ON and remains in this state until conditions for load shedding become true. The figure 8 shows status of loads and it apply for both EV1 and EV4.
3.1.2. Grid voltage = 1.05 p.u
Grid voltage greater than 1 p.u. conveys information that grid is in power surplus mode. Under this situation EVs will be charged in the charging station. Vehicle EV3 satisfies both stakeholders' conditions i.e user as well as power utility company and hence starts charging with a charging current of 2.19A as shown in figure 9 below. Remaining EVs stay idle.

Here EV3 battery is charging so it is needed to shed the loads if they are ON, which is indicated by following figure and figure 10 apply for only EV3 vehicle as other vehicles neither charge nor discharge. Here load shedding is being done for Air-Conditioner and Infotainment systems which are in ON state.
Forecasting is carried out for EV3 as it is charging. Monthly charging patterns of EV3 are obtained in excel and forecasting is carried out with first 30 days of data to arrive at forecasted data on 31st day of every month. The 31st day gives real time SOC requirement. Based on forecasted value and it’s comparison with real time demand for SOC for vehicle charging a pricing strategy for EV/PHEV charging is devised. It is to be noted that considering upper confidence level and lower confidence level to adjust for error in forecasting is done and if real time demand goes outside of this interval of upper confidence level or lower confidence level then extra pricing will be levied upon electric vehicle otherwise not. Excel data table gives the trend of SOC consumption of every month and corresponding pricing for charging on 31st day of every month.95 percent upper and lower confidence intervals are used in forecasting. Upper confidence level of 95% conveys that 95% of future points greater than forecasted value are expected to fall within this radius from the result of FORECAST function. Lower confidence level of 95% conveys that 95% of future points less than forecasted value are expected to fall within this radius from the result of FORECAST function.

31st Day of First month
Real time SOC Difference between Initial SOC and Final SOC=30
Forecasted value SOC Difference between Initial SOC and Final SOC =30
Upper confidence level of forecasting=30
Lower confidence level of forecasting=30
Real time SOC Difference= Forecasted Value of SOC Difference
Penalty per unit of SOC deviation = 5 units
Penalty on Electric Vehicle=0 Rs

31st Day of Second month
Real time SOC Difference between Initial SOC and Final SOC =70
Forecasted value SOC Difference between Initial SOC and Final SOC =28.95
Upper confidence level of forecasting=48.19
Lower confidence level of forecasting=9.73
Real time SOC Difference > upper confidence level of forecasting
Penalty per unit of SOC deviation = 5 units
Penalty on Electric Vehicle= 109.05 units

31st Day of Third month
Real time SOC Difference between Initial SOC and Final SOC =35
Forecasted value SOC Difference between Initial SOC and Final SOC =49.57
Upper confidence level of forecasting=67.88
Lower confidence level of forecasting=31.27
Real time SOC Difference > lower confidence level of forecasting and
Real time SOC Difference < upper confidence level
Penalty per unit of SOC deviation = 5 units
Penalty on Electric Vehicle=0 used.

3.2. When all vehicles have different arrival and departure time

| Parameters               | EV1   | EV2   | EV3   | EV4   |
|-------------------------|-------|-------|-------|-------|
| Initial SOC (%)         | 70    | 40    | 50    | 85    |
| User SOC (%)            | 25    | 45    | 60    | 50    |
| User Arrival Time(hours) | 8     | 9     | 11    | 10    |
| User Departure Time(hours) | 16   | 15    | 15    | 15    |
| User Charging Price/unit | 5     | 4     | 5     | 5     |
| User Discharging Price/unit | 6     | 6     | 6     | 6     |

3.2.1. Grid voltage=0.9 p.u
The discharging current is estimated by FLC as -8.782 for EV1 and -12.01A for EV4 as shown in figure 11 and figure 12 respectively. EV2 and EV3 will not conform to user preferences so they will
stay idle.

![Figure 11. EV1 discharging](image1)

![Figure 12. EV4 discharging](image2)

Here EV batteries are discharging so it is needed to shed the loads if they are ON. This is performed by the controller in charging station. The status of loads such as air conditioner and infotainment are controlled by Charging station controller based on load shedding event in vehicle which is indicated by following figure 13 which apply for both EV1 and EV4.

![Figure 13. Load status for EV1 and EV4.](image3)

4. Conclusion
The work on controller is implemented in Simulink of MATLAB software for different scenarios of user and power utility preferences. The work designed and implemented Fuzzy controller, V2G and G2V controller and Buck-Boost Converter. V2G-G2V controller worked on classifying vehicles to be
added to either charging queue or discharging queue based on inputs such as initial SOC, expected SOC before departure, duration of vehicle stay, charging price and discharging price of customer and power utility. FLC calculated the charging/discharging currents for the vehicles present in the ICFS based on the user inputs and grid conditions. Buck-boost converter providing bidirectional electricity flow is between grid and EVs. Thus charging/discharging of EV and PHEV in ICFS (Intelligent Charge filling station) are controlled according to user preferences and power utility preferences avoiding simultaneous charging/discharging at charging station and hence providing economical benefit for both vehicle owner as well as power utility.

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