Coordination of Electric Vehicle Battery Charging with Photovoltaic Generation

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Abstract—**Increased penetration of residential photovoltaic (PV) systems over the past decade has led to an abundance of power being exported back to the grid during times of high irradiance. Electric vehicle (EV) ownership has also increased recently, with predictions of further rises in the short to medium term resulting in increased network loading. Both EVs and PVs present significant environmental and economic advantages however they also pose challenges for network operators. This paper describes the development of a tool for coordinating PV generation and EV battery charging such that each technology is exploited, while negative impacts are mitigated. The results obtained from testing the developed strategy reveal that under Tasmanian summer conditions an EV battery could gain significant increased charge through only charging during periods of the day where PV generation was greater than local loading. Winter conditions are also tested with positive, although less significant results achieved.**

I. Introduction

The number of EVs within the electricity grid has risen in recent years, with further increases expected in the near future [1], [2]. A report produced for the Australian Energy Market Commission (AEMC) predicts that sales of EVs in the eastern states of Australia will rise, potentially reaching 20% of total new vehicle sales by 2020 [3]. The increased loading EV battery charging places on the electricity grid, including increases in peak loading and associated degradation of distribution network elements have been the focus of past studies into the impacts associated with increased EV penetration [2], [4]. If EV charging is left unmanaged users are likely to charge their vehicles as they arrive home from work in the late afternoon [5]. This charge period coincides with current peak loading and thus has the potential to overload network components and cause a supply-demand deficit. Different charging strategies have been proposed to mitigate the effect EV loading has on the electricity grid, including time of day charge management [6], renewable energy generation coordination [7] and bidirectional energy flow between the grid and the battery [8].

Renewable energy sources (RES), such as solar and wind, also pose a major challenge to electricity network operators due to their inability to be dispatched as required [8], [9]. The intermittent nature of RES limits the efficiency of the total generation profile as large thermoelectric generating units operate below peak efficiency during times of high RES generation [5].

High generation from PV cells during the middle of the day, coinciding with a decrease in loading on the grid at this time, makes the coordination of PV generation and EV charging a novel method for reducing the impact of both technologies on the grid. During a daily load profile there may be portion of the day in which PV generation exceeds local loading thus resulting in a supply demand imbalance [10].

The objective of this study was to produce a switching method for charging EV batteries during the period of the day where PV generation exceeds load. The costly nature of both EV charging and PV curtailment mean that this method could produce benefits for grid operators, PV and EV owners. This approach differs from past studies which have generally focused on time of day charging and current peak loading strategies.

The tool has been tested according to a number of different case studies, to assess its usefulness in different conditions. As this method relies on the generation from PV causing a supply demand imbalance, conditions influencing this scenario such as weather have been considered.

Section II of the paper will describe the method utilized in the study, including outlining the PV, EV and load modelling considerations. Results under summer and winter case studies are presented in Section III. Section IV discusses the key findings and conclusions are presented in Section V.

II. Method

MATLAB/Simulink was used to develop and test the EV charge strategy, Figure 1 shows the basic logic followed. The proposed strategy aims to control the charging of an EV battery according to the generation of a PV array. The strategy

implemented is based on charging the battery only during periods of the day where PV generation exceeds local loading. While assuming that EVs are available for charge during the middle of the day may appear to exclude working commuters from the beneficiaries of this charge strategy, with the expansion of PV systems it may be the case that EV owners will be able to charge their vehicles during the working hours if PV generating systems expand to workplaces or carparks [11].

The "Detailed Model of a 100-kW Grid-Connected PV Array" [12] test example available in the MATLAB/Simulink library was extended for modelling PV and EV interaction in this study.

A. EV Modelling

The Lithium-Ion battery model from MATLAB/Simulink was used to simulate the charging of a 16kW EV battery. The battery model and corresponding equations are shown in Figure 2 and (1) and (2) [13]. This battery type was selected due to its popularity among current EV manufacturers attributed to its favorable terminal voltage, power, size and energy density characteristics [14], [15].
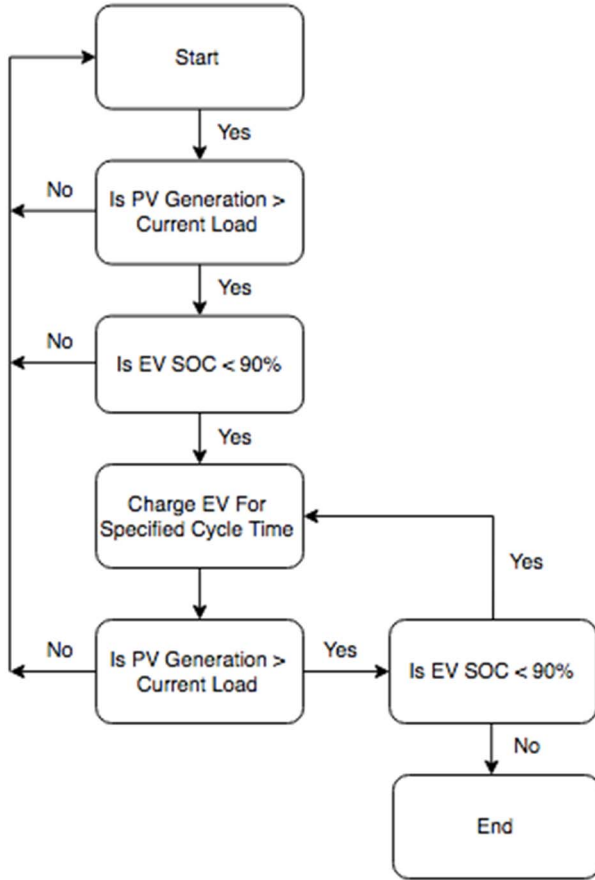

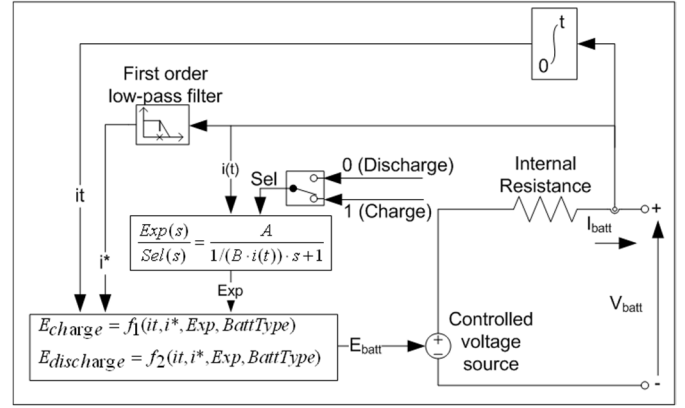Figure 1. Flowchart logic for charging strategy implementation.

Figure 2: Equivalent circuit for generic battery model implemented in MATLAB/ Simulink [13].

Discharge Model (i^*>0) for a Lithium-Ion Battery

$$f_1(it, i*, i) = E_0 - K \cdot \frac{Q}{Q-it} \cdot i - K \cdot \frac{Q}{Q-it} \cdot it + Ae^{-B \cdot it} \quad (1)$$

Charge Model (i^*<0) for a Lithium-Ion Battery

$$f_2(it, i*, i) = E_0 - K \cdot \frac{Q}{it+0.1 \cdot Q} \cdot i - K \cdot \frac{Q}{Q-it} \cdot it + Ae^{-B \cdot it} \quad (2)$$

Where:

$i*$ = Low frequency current dynamics (A)

E_0 = Constant Voltage (V)

K = Polarization constant (Ah^{-1})

Q = Maximum battery capacity (Ah)

it = Extracted capacity (Ah)

A = Exponential voltage (V)

B = Exponential capacity (Ah^{-1})

E_{Batt} = Nonlinear voltage (V)

$Exp(s)$ = Exponential zone dynamics (V)

$Sel(s)$ = Battery mode, 0=discharge, 1=charge

i = Battery current (A)

During periods where PV generation does not exceed local loading the EV battery is disconnected from the system in order to prevent it from discharging and supplying electricity to the load. A number of studies have highlighted the potential negative impact partially charging a battery can have on its long term performance [16], [17]. Lithium-Ion batteries are known however not to experience a 'memory affect' and as such the charging strategy proposed should not decrease the long term performance of this type of EV battery [13], [15].

The initial state of charge (SOC) of the EV battery was generated randomly to simulate the unpredictable nature of this variable. Battery SOC charge limitations were also implemented in the simulation to restrict the battery SOC to between 20% and 90% of full charge. This is in line with EV manufacturers specifications which limit discharge because as the EV approaches complete discharge it is unable provide sufficient charge to propel the vehicle [18]. Generally, the linear

section of the current-voltage curve also lies between these maxima and minima [17].

B. PV Modelling

The generic PV array available in the MATLAB/Simulink library utilizes the single diode model (SDM) equivalent circuit for a PV cell [19]. For the purpose of this research the accuracy provided by the SDM was sufficient to produce reliable results. The MATLAB/Simulink library contains a generic model PV array in which a number of different manufacturers and array specifications are available to choose from. For the purpose of this study SunPower manufactured panels were selected with 2 parallel connected strings with 6 series connected modules per string resulting in a 3.5 kW generating capacity. This generating capacity is consistent with residential PV systems in Australia [20].

To mitigate the extent to which non-uniform irradiance effects the power generated, maximum power point tracking (MPPT) techniques are implemented to differentiate between local and global maxima and 'search' for the true maximum point of the P-V curve [21]. The Incremental conductance method was used in this study; it is based on the derivative of the P-V curve equaling zero at the point of maximum power. This method also relies on the sign of the derivative in determining which side of the MPP the present array output lies [21], [22].

Temperature and irradiance of a PV array have the potential to significantly alter the output of the array [23]. Global solar irradiance data collected by the Australian Bureau of Meteorology (BOM) from Cape Grim in Tasmania's North West was used as an input to the PV array [24]. The irradiance data from the BOM accounts for large scale variability in irradiance incident on the earth's surface. However, smaller scale more localized shading caused by trees, dirt and debris were not taken into consideration.

The temperature input to the PV array was held constant at 25°C for the entirety of the simulations. While both irradiance and temperature have the potential to alter the output of the PV array, it was considered acceptable to hold the temperature constant as this variable does not affect the generation output severely [25].

C. Load Modelling

Constant resistive loads were periodically connected and disconnected throughout the simulation run time to mimic the changing daily load profile of a residential house. Two load scenarios were used to test the model with their values shown in **Error! Reference source not found.**I. The summer and winter load values shown were based on data obtained from [26]. The daily average electricity consumption for a four person household in Tasmania was used as a base rate for this data [27].

III. RESULTS

Two case studies are presented in this paper. These involve testing the model described above with two irradiance and load

scenarios, for summer and winter cases. The figures depicting the results of the summer and winter case studies show time measures in seconds, this was driven by the limitations presented in modelling the simulations over a 24 hour period and as such the 2.4 simulation run time represents the 24 hours in a day.

A. Summer Case

The results obtained from this case study used physical approximations for load and irradiance data for a Tasmanian summer, obtained from [24], [26]. Figure 3 depicts the increase SOC for the EV battery charged under the load and PV output power profiles shown in Figure 4. Stage II from Figure 4 represents the period of time the PV generation was greater than the load, and thus matches with the period of time the SOC of the EV battery is increased, shown in Figure 3. The simulation was run six times using differing initial SOC values, the results of these trials are shown in Table II.

B. Winter Case

The results obtained from this case study used physical approximations for load and irradiance data for a Tasmanian winter, obtained from [24], [26]. Figure 5 shows a SOC change for a winter irradiance and loading case, while Figure 6 depicts the load and PV generation profiles used as inputs. Again multiple trials were run using differing initial SOC values, shown in Table III. The results obtained from these simulations did not increase the battery SOC significantly. This was due to the limited amount of time PV generation exceeded the load. As the data used for irradiance and load were based on Tasmanian characteristics this result was expected. Tasmania's electricity load is winter peaking, which indicates an increased load, while irradiance is reduced during the winter due to less sunlight hours per day. The combination of these two factors has resulted in a significantly reduced portion of the day where PV generation exceeds the load.

TABLE I. LOAD SWITCHING TIMES AND VALUESZ

Load Switching Times and Values						
Time Interval (h)	00:00-04:00	04:00-08:00	08:00-12:00	12:00-16:00	16:00-20:00	20:00-24:00
Summer Load (W)	417	434	650	523	674	571
Winter Load (W)	528	747	1251	878	1258	1225

TABLE II. REPEATED SIMULATION RESULTS FOR SUMMER IRRADIANCE AND LOAD CASE

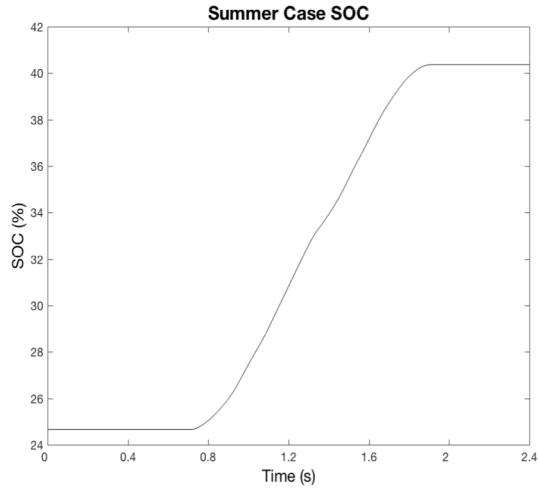| Load Switching Times and Values						
	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**
Initial SOC	24.6	41.2	64.9	67.0	28.8	45.3
Final SOC	40.4	56.8	80.6	82.6	44.3	61.2
% Increase	15.8	15.6	15.7	15.6	15.5	15.9

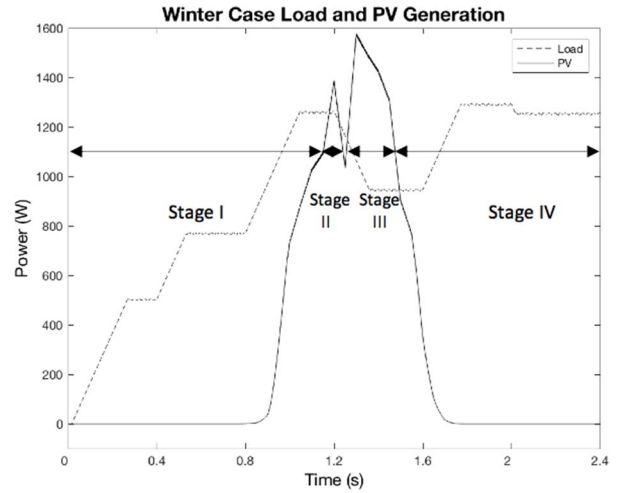Figure 3. SOC profile under summer irradiance and load data, 0.1 seconds represents 1 hour.
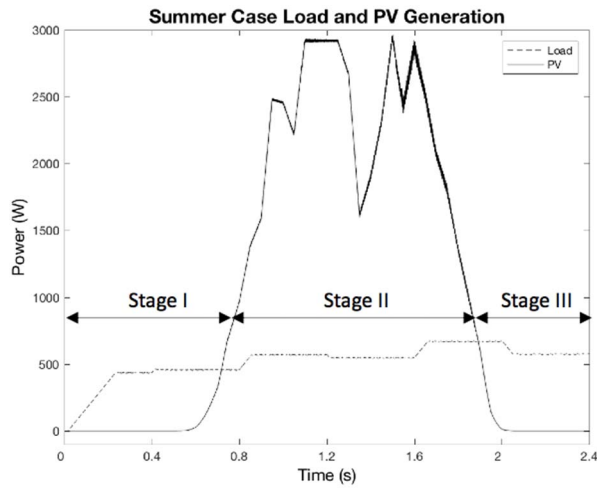

Figure 4. PV generation and load profiles for summer test case, 0.1 seconds represents 1 hour

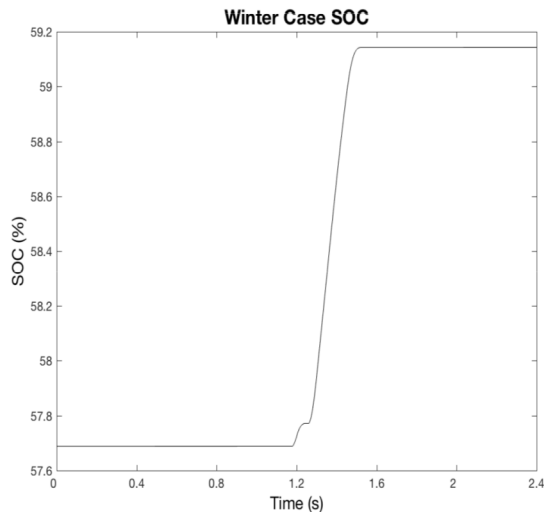Figure 5. SOC profile under winter irradiance and load conditions, 0.1 seconds represents 1 hour

Figure 6. PV generation and load profiles for winter test case, 0.1 seconds represents 1hour

TABLE III. REPEATED SIMULATION RESULTS FOR WINTER IRRADIANCE AND LOAD CASE

Load Switching Times and Values						
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Initial SOC	57.7	48.4	77.3	38.1	53.6	30.8
Final SOC	59.1	49.8	78.7	39.5	55.0	32.3
% Increase	1.4	1.4	1.4	1.4	1.4	1.5

IV. DISCUSSION

The limitations associated with intermittent RES are combatted with the implementation of this charging strategy, as the amount of PV generation exported back to the grid is reduced. Charging an EV battery according to the strategy developed results in less power generated by a PV array being exported back to the grid. This reduces the need for large generating units to be operated away from their point of maximum efficiency, which is currently the case during periods of low loading and high RES generation [5]. Other benefits of this strategy may also include a reduction in voltage and frequency deviations caused when large amounts of PV generated power is being fed onto the grid [28].

Results obtained from the summer loading and irradiance test case highlights the potential this strategy has using current EV and PV specifications. Figure 4 shows the significant portion of the day where the load is less than the PV generation, during summer conditions. Under current circumstances this additional power would be exported back to the grid, posing significant challenges for the electricity network operator. While the amount of excess power is not as great under winter test conditions in Tasmania, small advantages are still observed.

Significant economic advantages are also associated with this strategy, as feed in tariffs for PV generated power are

currently less than the consumption tariffs. The rate the Tasmanian electricity retailer purchases PV generated electricity from system owners is 6.67c/kWh, while standard electricity rates can reach up to 31c/kWh [29]. Thus using as much PV generated power as possible, and reducing the amount exported to the grid presents large economic benefits for PV system owners. With predicted increases in PV systems and EV ownership, the strategy presented in this research poses significant benefits to those who invest in both of these emerging technologies [3], [30].

As the load data simulated in this research influences heavily the success of the charging strategy analysed, it is important to note that the load data used was based on a four-person household. As such, a reduced number of people per house will increase the proportion of the day in which PV generation exceeds the load. Thus the results obtained would reflect a greater SOC increase for households with lower loads, either due to a reduction in people, or by making a concerted effort to reduce electricity consumption.

Other factors which may increase the advantages gained through implementation of this strategy include considering increases in irradiance as a result of differences between geographical locations. Tasmania's load is winter peaking which coincides with a reduction in solar irradiance and thus reduces the benefits gained through this strategy during winter months. In other parts of Australia loading and PV generation are summer peaking which would alter the results obtained, as increases in PV generation would coincide with increased loading. Ultimately for maximum advantage to be gained a location with periods of higher PV generation coinciding with lower loading would be optimal.

V. Conclusion

This study succeeded in developing a strategy to increase the economic and environmental advantages of PV and EV technologies, while limiting their current drawbacks. The strategy developed focused on charging an EV battery during periods of the day where PV generation exceeded local loading.

A MATLAB/Simulink model was constructed to test the effectiveness of the strategy proposed under two sets of load and irradiance conditions. The results presented indicate that the charging strategy developed provided greatest benefits in Tasmania during summer conditions, due to higher PV generation and lower loading. Simulations run using winter data still provided benefits however their relative scale was not as significant.

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