MEETING THE RENEWABLE ENERGY TARGET BY THE INTEGRATION OF SOLAR PV AND PLUG-IN ELECTRIC VEHICLE STORAGE IN DISTRIBUTION NETWORK

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ABSTRACT

Growing penetration of photovoltaic (PV) in low-voltage (LV) distribution networks can cause significant reverse power flow in the system during noon time causing voltage-rise problem. This paper proposes to alleviate this problem by using the Plug-in Electric Vehicles (PEVs) storage in an LV distribution network when reverse power flow occurs. Such storage can also help to mitigate the problems with the intermittency of solar PV output and support the distribution network in the form of a vehicle-to-grid (V2G) system. An effective control strategy is proposed for the dynamic management in PEV charging and discharging operations. The effectiveness of the proposed strategy is tested by simulating an Australian 14-bus distribution system in MATLAB, taking into account the PV generation, load demand and PEV profile. Results of the simulation show that the proposed strategy helps in mitigating voltage rise and the potentially destabilizing effects of intermittent solar PVs and also provides support to the grid during the evening peak.

INTRODUCTION

Growing interest for clean energy has resulted in increasing interests for integrating renewable energy based distributed generation resources with distribution networks. Most countries in the world (including 27 EU countries) have introduced renewable energy targets to provide some proportions of the total electricity sales from renewable energy sources. In Australia, the current renewable energy target is 20% by 2020 to ensure that 20% of Australia's electricity will come from renewable resources in 2020. Solar photovoltaic (PV) power generation systems are predominant among other renewable resources in the low voltage (LV) distribution networks in Australia. However, distribution networks are traditionally designed to distribute electrical power to the loads installed at customer premises from substations acting as source, and not to generate power within the networks. Penetration of distributed generation resources, can therefore affect the normal network behaviour in several ways. For example, when PV generation exceeds the customer load level, a reverse power flow and voltage-rise may be created in the feeder [1]. To avoid such situations, one option could be to limit the penetration level of solar PV resources in the network. This option, however, could be difficult to implement if a certain level of renewable energy penetration is needed be achieved. A solution to mitigate the adverse impacts of solar PV penetration is, therefore, essential so that the penetration level can be increased while not affecting the network operation significantly.

This paper proposes the use of the storage in Plug-in Electric Vehicles (PEV) for mitigating PV impacts that can cause difficulty in meeting the renewable energy target. The storage in PEVs can absorb the excess solar energy to minimize the reverse power flow. In turn, the PEV batteries can be charged by using PV power instead of grid power, thus relieving the severe burdens on the distribution network and also reducing the charging cost [2]. An integrated PV-PEV system is proposed at residential houses to mitigate PV impacts, such as voltage rise issues and the intermittent PV power output due to cloud passing. Further, grid support can be provided from PEV during the evening peak. The PEV storage can be charged and discharged rapidly to compensate for the power fluctuations of solar PV and load [3]. An efficient and effective control strategy for adjusting charging and discharging rate of PEVs is proposed. MATLAB simulations, based on the direct approach load flow algorithm, are performed using an Australian 14-bus distribution system. The effectiveness of the proposed methodology is demonstrated by the simulation results.

METHODOLOGY

Load Flow Analysis

Some changes in the load flow calculation are required when PVs and PEVs are included in the distribution network analysis. In this paper, the direct approach for distribution load flow solution that is proposed in [4] is extended to distribution systems that have PVs and PEVs. The method uses the BIBC matrix representing the relationship between bus injections and branch currents; and the BCBV matrix which relates branch currents to bus voltages [4]. In a m-branch and n-node distribution system, BIBC will be a $m\times(n-1)$ upper triangular matrix with values of +1 and 0 only while BCBV is a $(n-1)\times m$

lower triangular one with values of line impedances [4]. The equivalent current injection of bus i at the k-th iteration of load flow solution I_i^K is calculated from (1).

$$I_i^{(k)} = \left(\frac{S_i}{V_i^k}\right)^* = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \tag{1}$$

where, $i = 1,2,...,n$ and P_i and Q_i are active and reactive powers of the bus i, respectively. Similarly the equivalent current injections for power injection by PVs and PEVs can be calculated using (1).

By applying KCL, the branch currents can be obtained by:

$$[B] = [BIBC][I] \tag{2}$$

Thus, the bus voltage mismatches caused by current injections can be calculated by the line parameters and branch currents as shown in (3).

$$[\Delta V] = [BCBV][B] \; = [BCBV][BIBC][I] = [DLF][I] \tag{3}$$

where DLF is the matrix multiplication of BIBC and BCBV.

The distribution load flow iterative process is achieved by solving;

$$[\Delta V^{k+1}] = [DLF][I^k] \tag{4}$$

$$[V^{k+1}] = [V^0] + [\Delta V^{k+1}] \tag{5}$$

where V^0 represents the no-load bus voltages.

PVs and PEVs can be modelled as negative PQ buses. Modelling PVs and PEVs units as PV buses require additional process in the load flow algorithm. Initially the units are considered as PQ buses, however when the solution is obtained, the voltage of where the PVs and PEVs are connected is checked, whether they are within a certain specified tolerance to the specified voltage values. If they are not, the reactive powers of these buses are increased or reduced to ensure that the voltage values will go closer to the specified values. An efficient and effective method to achieve this has been proposed in [5] and is used in this paper for load flow calculations of distribution network with PVs and PEVs.

Charging and Discharging Management

It is important to keep the SoC within the acceptable range to extend the battery lifespan.

Under clear-sky conditions, PEVs can absorb the surplus PV power to charge their batteries. Usually, the PV output power will reach the peak level at midday, going up from zero at the sunrise and will go down to zero again at the sunset. Thus, a strategy based on trigonometric shapes is proposed as shown in Figure 1 by using the rectangle, triangle, trapezoid and Gaussian charging profile. The charging rate can therefore be varied to fit closer to the actual sun profile.

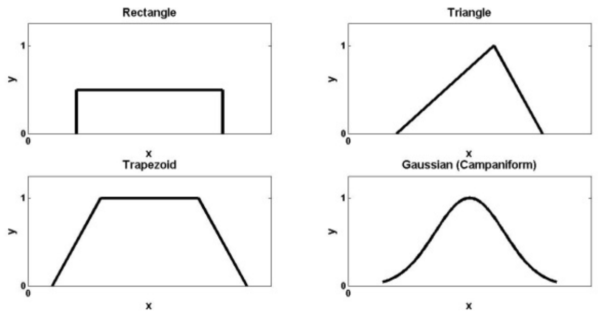


Figure 1: Possible charging and discharging profiles

For example, when using triangle or Gaussian charging profiles, from sunrise the charging rate should be increased to the peak value till midday and when the PV generation starts going down, PEVs ought to charge their batteries more slowly till sunset. At any given time, the charging current of a PEV battery can be controlled by [6]:

$$I_{char}(t) = \begin{cases} 0, \; if\ SoC(t-1) \geq SoC_{max} \\ I_{char}(t-1) + \mu\Delta t, \; if\ SoC(t-1) \leq SoC_1^{char} \\ I_{max}^{char}, \; if\ SoC_1^{char} < SoC(t-1) < SoC_2^{char} \\ I_{char}(t-1) - \mu\Delta t, \; if\ SoC(t-1) \geq SoC_2^{char} \end{cases} \tag{6}$$

where, I_{char} is the charging current at any given time; μ is the changing rate of charging current; Δt is the charging period; $SoC(t)$ is the state of charge of PEV battery at any given time; SoC_1^{char} and SoC_2^{char} are two SoC thresholds which determine the charging profile. In this way, the SoC level has to be kept at an acceptable value between SoC_1^{char} and SoC_2^{char}, with the purpose of preventing the battery from shortening its lifespan.

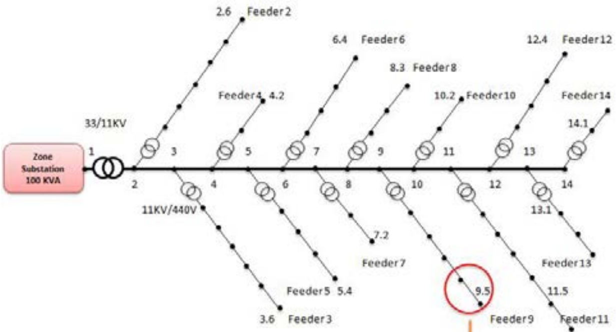
Discharging activities of the PEV battery is operated in peak load period in the evening when the PV generation does not exist. In this operation, the PEV discharging rate will be managed in a similar pattern with the charging mode and the discharging time can be determined when the load demand is higher than a threshold level. During the maximum peak load period the PEV battery ought to be discharged at a higher rate as compared to the rate before or after this period. In order to effectively utilize the battery capacity, the PEV discharging current at any given time can be managed by (7) [6].

$$I_{dsch}(t) = \begin{cases} 0, \; if\ SoC(t-1) \geq DoD \\ I_{dsch}(t-1) + \alpha\Delta t, \; if\ SoC(t-1) \geq SoC_1^{dsch} \\ I_{max}^{dsch}, \; if\ SoC_2^{dsch} < SoC(t-1) < SoC_1^{dsch} \\ I_{dsch}(t-1) - \alpha\Delta t, \; if\ SoC(t-1) \leq SoC_2^{dsch} \end{cases} \tag{7}$$

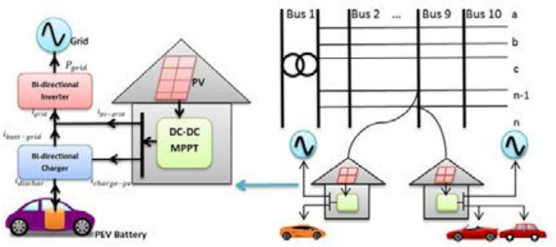
where, I_{dsch} is the discharging current at any given time; α is the changing rate of discharging current; Δt is the discharging period; DoD is the depth of discharge of PEV battery; SoC_1^{dsch} and SoC_2^{dsch} are two thresholds of SoC which determine the discharging profile. Also, the specified value of DoD for a PEV battery needs to depend on how much electricity should be retained for transportations before recharging modes.

SYSTEM STUDIED

Figure 2(a) presents PV-PEV cluster in a distribution system used for the simulation. In Figure 2(b), PV arrays are interfaced to the system DC bus by a boost DC-DC converter to realize maximum power point tracking (MPPT). A DC-AC inverter is connected with the bus to provide AC power. A bi-directional PEV charger is utilized in the system to link the PEVs with the Point of Common Coupling (PCC) and will also manage the charging and discharging rate of PEV batteries by monitoring the current. Under a clear-sky condition, PEVs will charge the batteries by absorbing the surplus PV power and conduct discharging operations for V2G purposes at night.



(a)



(b)

Figure 2: PV-PEV with Distribution System (a) PV-PEV cluster, (b) PV and PEV in the house

CASE STUDIES

All the simulations are carried out in MATLAB platform. A 14-bus distribution system containing transformers and feeders from an Australian distribution network, as shown in Fig. 2(a), is simulated to verify the applicability of proposed control strategy. The PV and PEV units are connected with every bus. The parameters of the system and the specifications of the PEV model are shown in Table 1. Moreover, the load demand profile including both active and reactive power is measured by every minute from a real Australian load demand curve. The daily PV output data is measured on 8th of Feb. 2011.

Case 1: Using low rectangular or constant charging and discharging strategy

In this scenario, the rectangular or constant charging and discharging strategy is used. The charging and discharging rate for the PEV storage is set at C/30. Figure 3 shows that with such low charging and discharging rate, there is only little voltage rise mitigation and voltage support. The SoC profile of PEV battery is shown in Figure 4, which shows how the battery energy accumulates. With a constant charging/discharging current, the value of SoC increases or decreases linearly but quite slowly because of low charging and discharging rate, reaching its maximum level at just over 70%.

Table 1: Practical System and PEV Model Specifications

No. of Buses	14	PEV Battery Pack	Lithium-ion
Rated Power Base (kVA)	100	Rated Battery Capacity (Ah)	60
HV/LV Transformer (kV)	11/0.4	Charge Voltage (V)	230.94
PV Size (kW)	4	Charge Current (A)	Capacity/Hour
PV Penetration Level	2.20	Charger Efficiency	95%
Inverter	SMA Sunnyboy	SoC_{max}	95%
Load Multiplier	2.20	SoC_{min}	50%

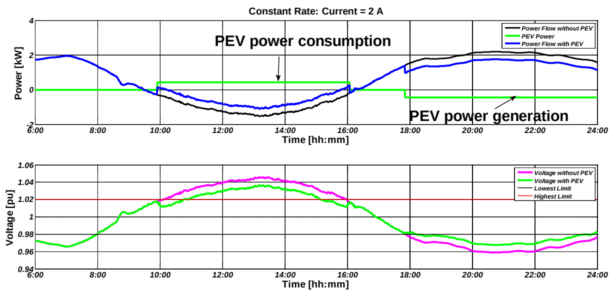


Figure 3: Power and Voltage Profile (I = 2A)

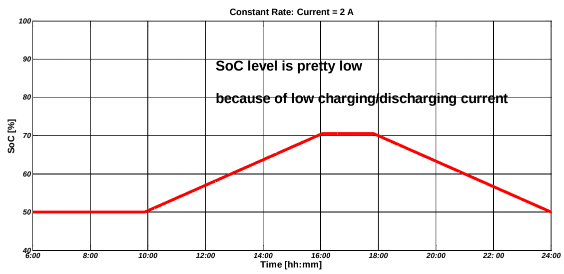


Figure 4: PEV SoC Profile (I = 2A)

Case 2: Using higher rectangular or constant charging and discharging strategy

In this scenario, the charging and discharging rate of the 60Ah battery storage is C/10. Figure 5 shows that the storage is fully charged too early causing the voltage to be higher again. Similar result is obtained with grid support in the evening. Figure 6 shows that the value of SoC rises linearly at a very high rate, reaching its maximum value very early (in scenario 1 the PEV battery stops charging at approximately 16:00). Similarly in the discharging operation, the SoC level also drops very fast and the battery pack is half discharged (because the other half of the energy is reserved for travelling) almost 2 hours earlier.

Case 3: Using more optimized rectangular or constant charging and discharging strategy

In this scenario, the charging and discharging rate is set at

C/15, or at a constant rate of 4 A. A better result is obtained as shown in Figure 7 such that the voltage rise impact caused by surplus PV power is mitigated to a very large extent. Also, the bus voltage is above the lowest limit during most time in peak load period. In the day time, however, the voltage is not smooth at all and still higher than 1.02pu when the PV generation is maximum. Figure 8 shows the SoC profile goes up from 50% to nearly 95%. Also in the evening, the PEV unit constantly supplies the power to the grid till 24:00 hour when the battery is almost discharged to half of its value (the remaining 50% is reserved for travelling).

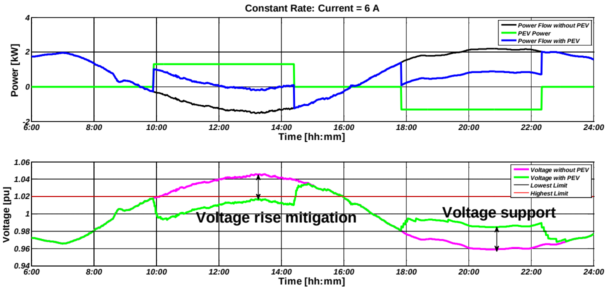


Figure 5: Power and Voltage Profile (I = 6A)

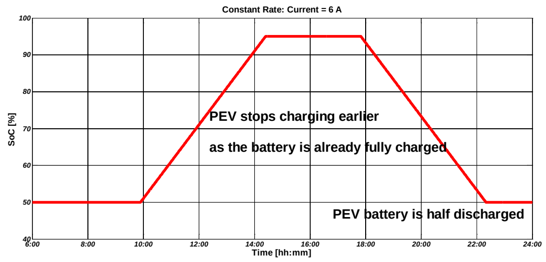


Figure 6: PEV SoC Profile (I = 6A)

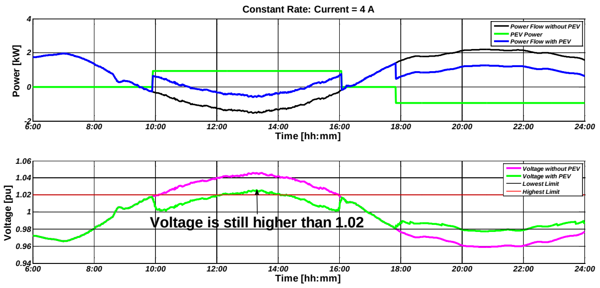


Figure 7: Power and Voltage Profile (I = 4A)

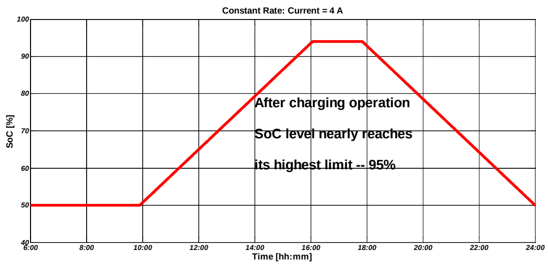


Figure 8: PEV SoC Profile (I = 4A)

Case 4: Using optimal and varying charging and discharging strategy

In this scenario, an optimal pattern is simulated such that the power absorbed by the PEV battery is set to equal to the value of reverse power flow. Figure 9 shows that during the reverse power flow period, all the excess power is charged to PEV and the peak load in the evening has been reduced to the specified limit. Figure 9 shows that the bus voltages are always within the limits during the charging and discharging period respectively. Figure 10 shows the SoC level changes no longer in a linear relationship with this dynamic strategy. As the PV data and load profile cannot be obtained ahead, this pattern will be hard to realize.

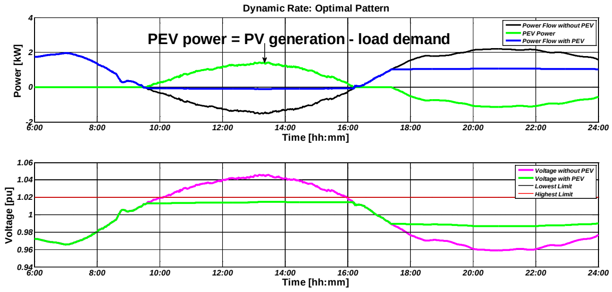


Figure 9: Power and Voltage Profile (Optimal)

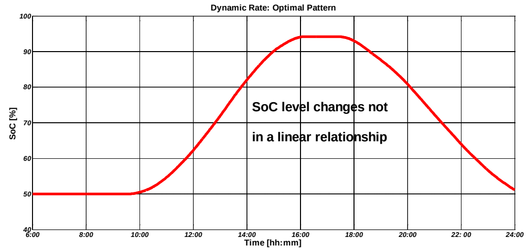


Figure 10: PEV SoC Profile (Optimal)

Case 5: Using triangular and varying charging and discharging strategy

In this scenario, the charging and discharging profile of the PEV battery are designed in a triangular pattern. Figure 11 shows the voltage profile in the morning and in the evening following the triangular pattern. Figure 11 shows that the voltages for all 24 hours are all within the reasonable range. However, as the charging rate is at the highest level during midday, the voltage at that time is relatively low compared to the other time in the charging operation period. Figure 12 shows the PEV SoC profile with triangular pattern where the highest change of charging and discharging rate can be seen at approximately 13:00 hour and 21:00 hour respectively.

Case 6: Using trapezoidal and varying charging and discharging strategy

The last scenario investigated is where the PEV battery is charged and discharged in a trapezoid pattern. Figure 13 shows how the PEV is charged during the day. During the midday period the PEV battery will be charged at a higher rate as compared to the rate in the morning and afternoon. Different from the triangle pattern, the charging rate stays at the highest level for a period of about 2 hours in this scenario. The PEV power profile is shown in Figure 13, where the PEV consumption and PEV generation are in the shape of a trapezoid. With this control strategy the bus voltages will be maintained relatively stable in the range between 0.98 p.u. and 1.02 p.u. during the two operations, as shown in Figure 13. The SoC profile of the PEV battery is displayed in Figure 14. The SoC level at the end of the charging operation is higher than that of the triangle pattern, which means that the PEV battery can accumulate more energy with this pattern.

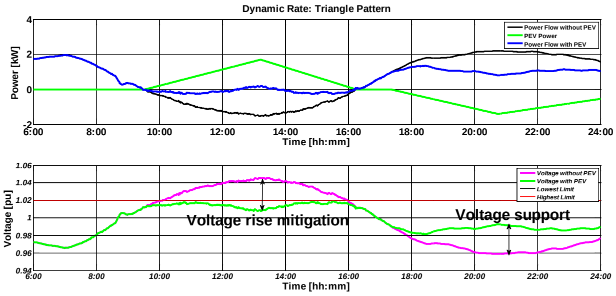


Figure 11: Power and Voltage Profile (Triangle)

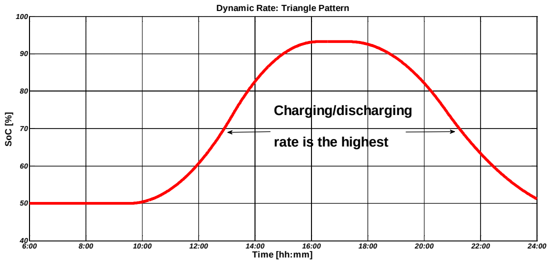


Figure 12: PEV SoC Profile (Triangle)

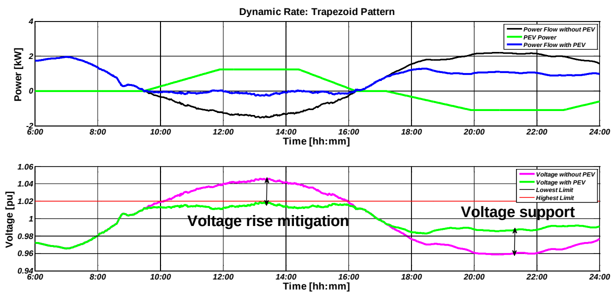


Figure 13: Power and Voltage Profile (Trapezoid)

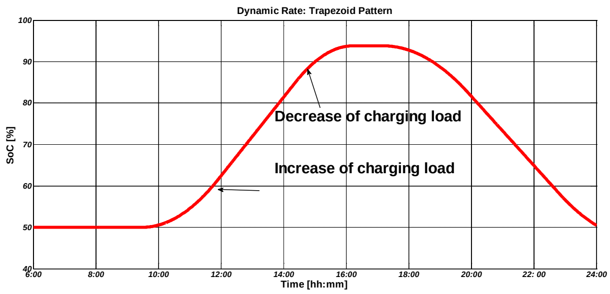


Figure 14: PEV SoC Profile (Trapezoid)

Conclusion

This paper has proposed a control strategy to effectively utilize the PEV storage capacity in an LV distribution system with high PV penetration, considering PV impact mitigation during the day and grid support in the evening. Several trigonometric shapes are used to control the PEV charging and discharging current, thus adjusting the shape of PEV consumption and generation to match the PV generation and peak load demand profile. In this way, during the day PEVs can charge their batteries at a higher rate when the reverse power flow is most significant compared to the morning or the afternoon. Similarly, the highest discharging rate should appear when the load demand is highest in the evening. A 14-bus distribution system is simulated in MATLAB to verify the effectiveness of the proposed methodology by using a direct approach as the load flow solutions and a wide range of case studies have been conducted. Results show that the trapezoid strategy is more likely to provide a better mitigation and voltage support performance compared with the triangle or constant strategy.

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