

Simple control strategy for a PV-battery system

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Abstract: Nowadays, energy storage systems, such as batteries, are spreading in many applications. Among the kinds of batteries, the lithium-ion technology is one of the most promising solutions. Considering the photovoltaic (PV) plants, it is very important to perform a correct sizing of the battery pack to both maximise the self-consumption and minimise the total costs. In general, PV plants need a dc–dc converter to maximise the electric power that can be extracted from PV panels and a dc–ac converter to connect them to the ac grid. The battery pack can be connected in three different ways: dc coupled and ac coupled using a dedicated converter or through a direct connection on the dc-link between the dc–dc and dc–ac converters. In the present study, the last solution, without any dedicated converters, is used and a simple control strategy to both maximise the power extracted from the PV panel and regulate the charging/discharging of the battery is proposed.

1 Introduction

Nowadays, energy storage systems, such as batteries, are spreading in many applications. From stationary applications, such as renewable energy source integration, to mobile applications such as electric vehicles. Amongst the batteries, the lithium-ion technology is one of the most promising alternative due to its high-energy density compared to other batteries, as lead-acid one. Considering the renewable energy sources, and in particular the photovoltaic (PV) systems, it is very important to perform a correct sizing of the battery pack for the integration in PV plants to both maximise the self-consumption and minimise the total costs. In [1], the authors

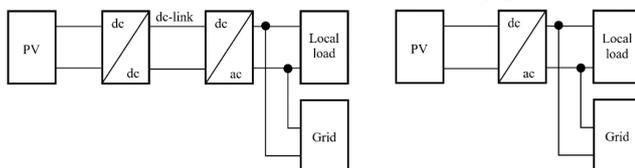


Fig. 1 General structure of a PV plant

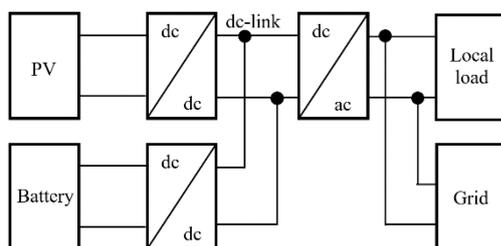


Fig. 2 DC coupled battery

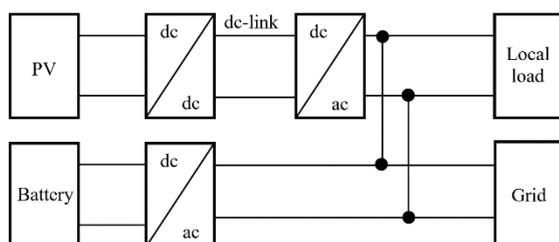


Fig. 3 AC coupled battery

proposed a procedure to optimise the mass of the batteries for a domestic PV plant in islanding mode, minimising the total costs during a period of twenty years. Afterwards, the same authors in [2] extended the previous proposed procedure also in the case in which the electric grid is present. In any case, both the control strategy and the topology used to connect the battery pack to the PV plant are not considered. In the literature, it is possible to find some works about these aspects.

In general, a PV plant needs a dc–dc converter to maximise the electric power that can be extracted from PV panels using one of the well-known maximum power point tracking algorithms, and a dc–ac converter to connect them to the ac grid. In Fig. 1, a general structure of a PV plant is depicted. Considering the possible kinds of connections of the battery pack to the PV plant, we can divide the possible interconnections in three different structures: dc coupled, ac coupled and direct connection.

In the first case, the battery pack is connected to the dc link through another dedicated dc–dc converter (Fig. 2).

In the second case, the battery pack is connected to the ac grid using a proper dc–ac converter (Fig. 3).

Finally, in the last case, the battery pack is directly connected to the dc link without any other additional converters (Fig. 4).

The latter solution seems not to be of common usage. Indeed, most of the research works in the literature analyse the other two solutions, as reported in [3–7]. Instead, in [8], the authors use the last solution where the charge and discharge of the battery is demanded to the dc–ac converter. According to the power flow conditions, due to the solar power and the power requested by the load, the operation of the proposed system is divided into four operation modes. They use a selector that based on these conditions switches to the opportune control strategy.

In this work, let us start from the optimal sizing procedure of the battery pack, based on the proposed procedure in [2]. Using the direct connection of the battery pack to the dc link, a simple control strategy of the converters to both optimise the power extracted by the PV panels and at the same time regulate the charging/discharging of the battery is proposed. Usually, to inject the maximum power extracted from the PV panels to the ac side, the control strategy of the dc–ac converter controls its output current keeping the voltage of the dc link constant. In such a way, the power generated by the PV panels is always equal to the sum of the power absorbed by the local load, the power exchanged with the battery and the power injected to the grid. This is possible in the

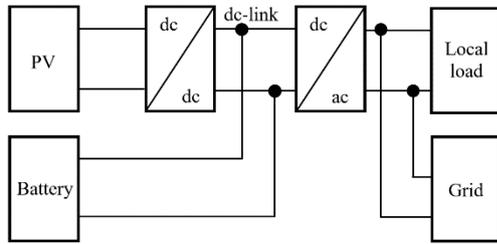


Fig. 4 Direct connection of the battery

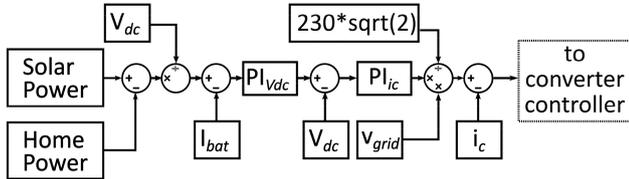


Fig. 5 Control scheme

first two cases in which a capacitor, whose voltage is controlled, is connected across the dc link, and the power flowing into the battery is controlled separately using the dedicated converter. In the case analysed in this paper, the voltage of the dc link cannot be kept constant because it is related to the state of charge (SoC) of the battery. Therefore, the output current of the dc–dc converter will be controlled to maximise the power extracted from the PV system and, at the same time, it will have to charge/discharge the battery according to a given criteria.

The criteria used in this paper are the one proposed in [2]: if the power generated by the PV system is greater than the power absorbed by the local load, the power difference is used to charge the battery until it is fully charged. If the battery is fully charged, the power difference is injected into the grid. Conversely, if the power generated by the PV system is lower than the power absorbed by the local load, the power difference is drawn from the battery until it is fully discharged. If the battery is fully discharged, the power difference is drawn from the grid. The selected grid for this study is a single-phase system whose nominal voltage is 230 V.

In Section 2, the proposed control strategy is explained; in Section 3, some simulation results of the proposed strategy are reported. Finally, Section 4 shows the conclusion.

2 Proposed control scheme

The proposed control strategy is based on the measurement of two powers: the first one is the electric power injected into the dc link by the PV system, the second one is the electric power absorbed by home utilities. The difference of these two powers divided by the actual voltage of the dc link, V_{dc} , yields to the reference battery current. The control scheme is reported in Fig. 5. The obtained reference current is saturated to take into account the capabilities and the actual operating conditions of the battery (i.e. maximum allowable current, actual temperature, ageing and so on).

A closed loop chain controls the battery current by means of a proportional-integral (PI) controller whose output is the dc link voltage reference, V_{dc_ref} . The saturation limits of this regulator must be set accordingly to the maximum and minimum desired or achievable SoC.

The error between the actual and the reference dc link voltage, is sent to a second PI controller that generates the peak current reference to be sent to the ac side converter. The tuning of this controller must make the system robust with respect to the noises due to switching, dc link voltage ripples and 100 Hz power oscillation typical of single-phase systems.

Finally, the reference of the ac current is converted into an instantaneous value in phase with the grid voltage. This, in turn, is sent to a controller that outputs the signal gates for the dc–ac converter.

If the power generated by the PV system is greater than the power absorbed by the local load, the external PI controller changes the V_{dc} reference to charge the battery itself. The internal

Table 1 Lithium-ion cell characteristics

Item	Specifications
rated cell capacity	10 Ah
rated cell voltage	3.7 V
standard charge current	0.2 C
max charge current	1 C
charge cut-off voltage	4.2 V
discharge current	continuously: 10 C; max: 15 C
discharge cut-off voltage	2.75 V
impedance	≤12 mΩ

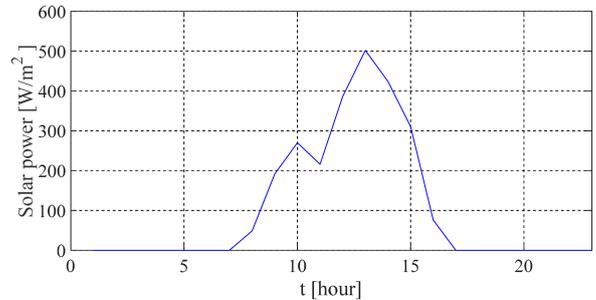


Fig. 6 Daily solar radiation profile Messina (Italy)

PI controller then regulates the current injected into the ac side. When the battery reaches its maximum voltage value, the saturation of the external PI controller fixes the voltage of the dc link to the maximum one. At this point, the battery current reference cannot be followed anymore, thus the power difference is injected into the grid. If the power generated by the PV system is less than the power absorbed by the local load, the external PI changes the V_{dc} reference to discharge the battery itself. Accordingly, the internal PI controller regulates the current injected into the ac side. When the battery reaches its minimum voltage value, the saturation of the external PI controller fixes the voltage of the dc link to the minimum one. The power difference is then drawn from the grid. In any case, the battery pack has to be dimensioned to ensure a minimum voltage level suitable to connect the dc/ac converter to the grid.

In order to improve the performances of the systems, a capacitor is added in parallel to the storage system. Since, its purpose is to limit the voltage ripples on the dc link, its value should be chosen accordingly to the internal resistance of the battery pack and on the dc–ac converter sizing power. In physical realisations, a compromise between the storage system size, capacitor size and measurement filtering has to be done.

3 Simulation results

The battery pack has been chosen according to the procedure reported in [2] and supposing a PV plant of 35 m² with an efficiency of 14%. Through that procedure, the lithium-ion battery pack is composed by 163 elemental cells whose characteristics are reported in Table 1. Therefore, the total energy of the battery pack is about 6 kWh. Since the selected grid voltage is 230 V (rms), to have a dc-link voltage that allows the dc–ac converter to work properly for any battery SoC, all the 163 cells are connected in series. In this way, the minimum and maximum voltage of the battery, i.e. of the dc link, are 449 and 684 V, respectively.

Fig. 6 shows the daily solar radiation profile of Messina (Italy) sampled each hour retrieved by [9] while Fig. 7 shows the daily domestic load power profile that has been generated using the tool reported in [10]. This profile is related to a mean Italian family composed by four people.

The model of the system (Fig. 4) and the proposed control strategy have been implemented in Matlab/Simulink. A simulation of 24 h was performed using the two aforementioned power profiles. To obtain a reasonable simulation time, the two converters have been modelled using controlled current sources. Indeed, in our case, what is of interest is the medium and long dynamic of the

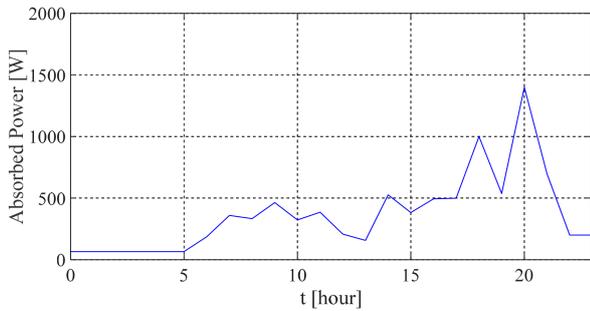


Fig. 7 Electrical power consumption related to a classic family composed of four people for each season, 3000 kWh/year

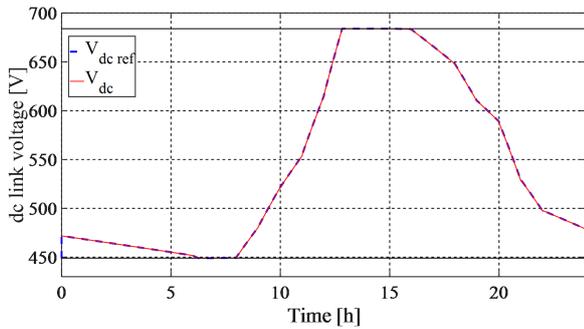


Fig. 8 DC link voltage

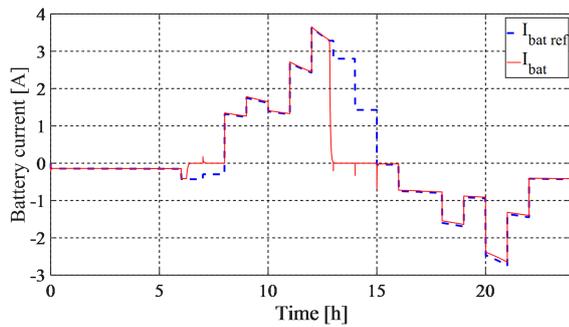


Fig. 9 Battery current

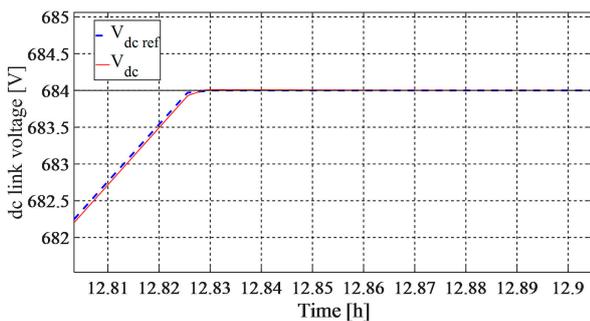


Fig. 10 Zoom of the dc link voltage in the upper limit

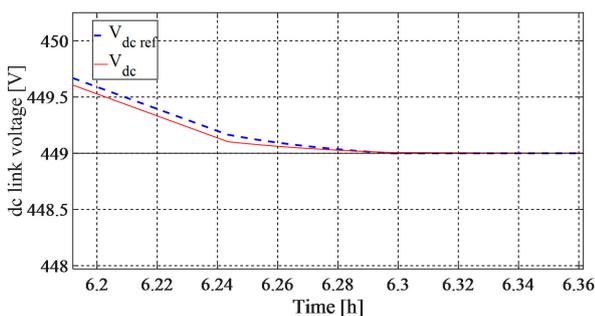


Fig. 11 Zoom of the dc link voltage in the lower limit

system and not the high switching frequency effects of the converters.

Fig. 8 shows the behaviour of the dc link voltage. From this figure, we can see that during the period 0:00–8:00, in which the power absorbed by the load is greater than the one generated by the PV system (night-time and sunrise), the battery, which starts with a SoC equal to 10%, is discharged until its minimum voltage is reached. After that event, the grid feeds the surplus power requested by the load. During the period 8:00–16:00, in which the power absorbed by the load is less than the one generated by the PV system, the latter is sufficient to feed both the load and to fully recharge the battery. In particular, from 13:00 to 17:00, the battery gets fully charged, and then, the power difference between the PV and the load is injected into the grid. During the period 17:00–24:00, the power generated by the PV system, decrease because of the sunset, thus the battery feeds the power of the load.

Fig. 9 shows the battery current together with its reference. From this figure, it is possible to note that, when the battery is fully discharged or fully charged, the battery current is not following its reference. This is because, in this case, the first PI regulator saturates in the upper/lower threshold, and then, the system starts to work as a normal back-to-back system in which the voltage of the dc link is fixed.

In Fig. 10 and 11 details of the dc link voltage approaching the minimum and maximum thresholds are reported. The battery voltage reaches the maximum and the minimum value without any overshoots.

The simulation results reported, as already said, have been performed using ideal controlled current sources to make the time simulation faster. Now, we can consider a shorter time simulation using switching converters to test the controller effectiveness also in the presence of real disturbances. Two shorter simulations have been performed.

In the first simulation, the power absorbed by the load is null while the power generated by the PV plant is equal to 2 kW. In this way, the battery starts to charge, as it is possible to see it in Fig. 12, converging to the maximum voltage. As noticeable, after the system reaches the maximum voltage, the ripple becomes more visible. This effect is because, in addition to the ripple due to the switching frequency, the 2 kW power of the PV plant is no longer flowing into the battery but it starts to flow into the grid. Therefore, the 100 Hz power oscillation of the ac side yields the same oscillation in the dc link voltage on the filtering capacity placed in parallel with the storage system.

In Fig. 13 the complete discharge of the storage is simulated. In this case, the power absorbed by the load is equal to 2 kW while the power generated by the PV plant is null. The battery starts to discharge and the power flowing to the ac side produces the 100 Hz oscillation. When the battery is fully discharged, the grid feeds all the power requested by the load. In this condition, the voltage of the dc link is kept constant at the minimum value. The dc–ac converter now is operating at no load, therefore the dc link voltage ripple is due only to the switching frequency.

Moreover, we can calculate the energy exchanged with the battery during one day. Integrating the module of the electric power exchanged with the battery and dividing it by 2, we obtain 5.6 kWh that is 93% of the battery pack capacity. This confirms the good size procedure of [2].

Furthermore, in [2], the solution with the optimum battery sizing and the one without the battery but considering the grid as storage service have been compared. From this comparison, it resulted that in Italy, the necessary incentive to be paid per exchanged kWh to make the storage convenient is €0.11/kWh. In that case, among the fixed costs, even the cost of the dedicated converter for the battery was considered. In the present work, without any dedicated battery converters, the updated incentive becomes €0.05/kWh. The latter has been calculated using the same cost procedure reported in [2].

4 Conclusion

In this paper, a simple battery control strategy for PV plants integration was proposed. The battery pack is sized with the

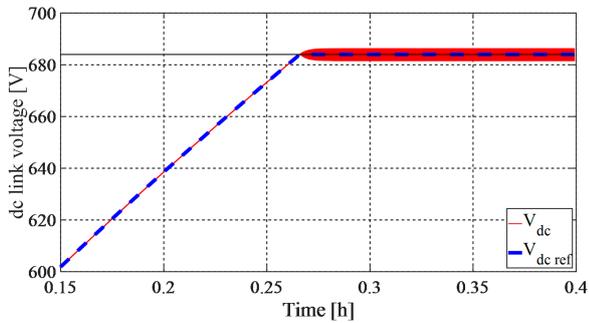


Fig. 12 Zoom of the dc link voltage in the upper limit with non-ideal dc-ac converter

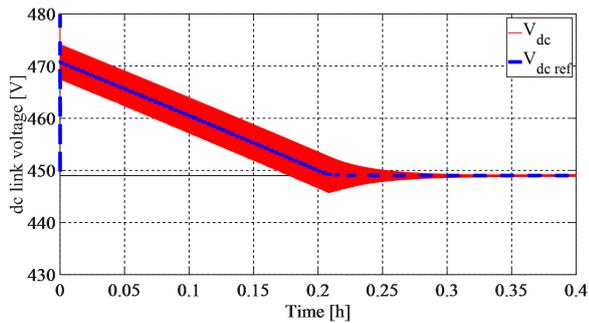


Fig. 13 Zoom of the dc link voltage in the lower limit with non-ideal dc-ac converter

procedure proposed in [2], and it is directly connected to the dc link of a system composed by one dc-dc converter and one dc-ac converter.

The proposed control strategy can charge/discharge the battery pack accordingly to the difference between the power generated by the PV plant and the one absorbed by the domestic load. If this power difference is positive, it is used to charge the battery until it is fully charged, after that, it is injected into the grid. Conversely, if

this power difference is negative, it is drawn from the battery until it is fully discharged, after that, it is drawn from the grid.

According to the simulation results, the proposed control strategy follows effectively both the battery current reference and the dc link voltage reference, which is the voltage of the battery pack.

Moreover, thanks to the absence of the dedicated battery converter, the incentive to be paid per exchanged kWh in order to make the storage system economically convenient is €0.05/kWh instead of €0.11/kWh as reported in [2] where also the cost of the battery converter was taken into account.

5 References

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