Analysis of performance criteria for an optimal PV system configuration

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Abstract

The main objective of this study is to offer an approach to analyze the performance of different three-phase four-wire residential rooftop photovoltaic system topologies. Among different photovoltaic system topologies, this work focuses on the two most used. These two photovoltaic topologies have different design regarding the neutral wire. The first topology includes a DC-link neutral point and the second one incorporates a Delta/Star grounded transformer. Authors conduct a comparative study of both topologies based on the following criteria and constraints: (1) the battery and the DC link capacitors lifetimes; (2) the impact of non linear load on the neutral current; (3) the power quality; (4) the cost of the photovoltaic system topology and (5) voltage and current total harmonic distortion. Analyses are supported by simulation results performed under PSIM software.

Keywords Photovoltaic system · Battery energy storage system · DC-link neutral point · Delta/Star transformer

1 Introduction

Currently, the market of PV power systems continues to grow at a high rate, about 47% per year according to the International Energy Agency (IEA), with a cumulative capacity of 609 GW by 2019.

Many advantages and benefits concerning environmental, social and economic sectors are offered by these systems [1–3]. The fluctuation of the meteorological data is considered among the most important difficulties for PV systems. One alternative to deal with this problem is the incorporation of battery energy storage system (BESS) [1] essentially for autonomous microgrids [1, 4, 5].

Rooftop photovoltaic systems in urban cities are generally installed in grid connected mode [5], but the autonomous mode is also feasible [6, 7].

The architecture of the microgrid based on PV system is a real concern for researchers. Some authors investigate

the single phase architecture [8, 9], but the problem with three phases architecture is more important. Indeed, the configuration of the system has a significant impact on several points, including the techno-economic feasibility, the power quality, the control efficiency and the storage devices lifetime [10–13].

Many topologies are presented in literature in order to obtain an optimum PV system architecture. In general, most of the authors focus on only one criteria, for example in [12], a hierarchical structure is proposed in order to reduce power losses, in [9, 14], the main concern is to improve the power quality via residential photovoltaic systems, in [15], the problem of harmonic distortions is discussed for the proposed architecture, in [16], authors aim to decrease power ramping of residential PV system in connected mode and in [17], the impact of non linear loads on PV systems is investigated. In [18] The influence of the Energy storage systems to support hosting capacity

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of (PV) systems is investigated. In [19] the objective is to balance the power between residential load and rooftop PV generation, an optimal configuration model is accomplished by mixing two-stage voltage control technique and the order of overall reduced PV generation.

In this paper authors propose an approach to analyze the performance of different photovoltaic residential microgrid architectures, in order to assist users and grid operators to choose the appropriate topology according to their custom criteria, two structures are presented but the study can be extended to other structures. Comparison criteria are power quality (PQ) and batteries as well as DC-link capacitors lifetime. In this work, linear and non linear residential loads are considered.

The paper is organized as follows, first, in Sect. 2, the two studied structures are described. Then, in Sect. 3, the control of each converter is detailed. In Sect. 4, a comparative analysis of the two structures is presented followed by simulation results. Finally, in Sect. 5, a discussion of the obtained results is given.

2 System description

Studied microgrid includes PV panels connected to a DC/DC converter in order to ensure maximum extracted power and a PV system linked to a DC bus in parallel with the storage system. A DC/AC converter is interfaced between DC and AC bus. Single and three phase linear and non linear residential loads are connected to the AC bus.

In this study, residential loads are grouped into two sets: linear and non linear loads. The linear and non linear loads are modeled by resistive load and a rectifier connected to a capacitive filter respectively. These models correspond well with the real residential loads [1, 20].

The problem of neutral current is evoked when different single phase loads are connected into dissimilar bus phases. In this case load harmonics generate a neutral current.

The two considered structures have different design regarding neutral wire. The first one with DC-link neutral point and the second one includes Delta/Star grounded transformer. In the following, both structures are described and detailed.

2.1 Structure with DC-link neutral point

The structure with DC-link neutral point is shown in Fig. 1. In this structure, the PV system is connected to 4 wires distribution system and the neutral wire is connected to the DC-link neutral point via two identical capacitors.

Fig. 1 Structure with DC-link neutral point

Fig. 2 Structure with Δ/Y transformer

2.2 Structure with Δ/Y transformer

The structure with transformer is illustrated in Fig. 2. It is composed of three DC/AC converter wire and a Delta/Star transformer that ensures the fourth wire.

3 Power converters control strategies

3.1 BESS DC/DC converter control

The BESS converter regulates the power flow of the battery in both directions. It regulates the DC voltage to ensure a constant voltage V_{dc} with respect to voltage reference value. According to the battery mode charge or discharge, just one of the two switches C_1 and C_2 is controlled. In discharging mode, the switch C_2 is controlled and in charging mode, the switch C_1 is controlled. The BESS DC/DC control is illustrated in Fig. 3. It is based on cascade control. The external loop is devoted to the regulation of the DC voltage V_{dc} and the internal one regulates the battery current I_{bat} .

3.2 PV DC/DC converter control

Several topologies of power converter that interface PV systems and AC bus are presented in literature. In this study, the approach of two stage power conversion is adopted. This structure is generally privileged in the most of the PV systems [21] (Fig. 4). The V_{dc} control is done by the battery energy storage system. The PV DC/DC converter ensures the photovoltaic Maximum Power Point Tracking (MPPT) [22]. The used algorithm is the Perturbation and Observation (P&O). This algorithm is based on the notion that when the power and

Fig. 4 Control of the PV DC/DC converter

the voltage increase, a step is added to the duty cycle towards the maximum point. More details are given in a previous work [23]. Perturbation and Observation algorithm flowchart is given by Fig. 5 [24].

3.3 DC/AC converter control

In case of standalone mode, the DC/AC converter ensures the alternative voltage with adequate magnitude and frequency in the AC Bus (Fig. 6). In case of connected mode, it guarantees the injection of the PV power into the grid.

Fig. 3 Control of the BESS DC/DC converter

Fig. 5 P&O algorithm based MPPT flowchart

Fig. 6 Control of the DC/AC converter in standalone

Fig. 7 Total generated power, resistive load power and non linear load power

4 Comparative analysis of the two configurations

The test scenarios are done with resistive load of 6 kW and non linear load of 2 kW. To reproduce the residential home load profile, a step variation is applied at 0.2 s corresponding to the activation of the non linear load. Figure 7 shows the total generated power and those consumed by each load.

The first test assumes that there is no solar radiance so no PV production, as the system is in autonomous mode, all consumed power is supplied by batteries. Figure 8 presents the current generated by the batteries with both system structures. It is shown that when neutral current configuration is applied, battery current

Fig. 8 Battery current

Fig. 9 Neutral current

has a faster transient response than with transformer structure. It is to note that batteries can support rapid variation as they are characterized by an important power density, but the best option for fast transients are supercapacitors according to Ragon diagram [24]. So, for the criterion of battery lifetime, the structure based on transformer is the most appropriate. Figure 9 presented the total current and the resulted neutral current for both cases. For this test, a single phase nonlinear load is activated at 0.3 s. As shown in this figure, transformer configuration presents a slightly higher neutral current harmonics than neutral point structure. The neutral current THD are equal to 30% and 26%, respectively.

Time and frequency analyzes of AC output voltage are illustrated in Figs. 10 and 11, respectively. The neutral point and the transformer structures present tolerable and comparable harmonic distortion, the THD are equal to 3% and 2.25% respectively. According to several standards such as SSEN50160 and IEEE standard 519-2014, the voltage THD must not exceed 8% for voltage less than 1 kV [25].

Fig. 10 Phase voltage V_a for both structures

Fig. 11 FFT of the phase voltage V_a for both structures

Fig. 12 DC-link voltage V_{dc} for both structures

Regarding DC-link voltage (Fig. 12), the neutral point structure ensure more balanced steady state profile than with transformer structure. But as shown in Fig. 13, the DC-link capacitors report an unbalanced voltage which can affect their lifetime.

Generated single phase current for both structures are presented in Figs. 14 and 15. In these figures are shown

Fig. 13 DC-link capacitor voltages for neutral point structure

Fig. 14 Total current I_{tot} and different load currents with the structure integrating the transformer (I_R is a resistive load current and I_{NL} is a non linear load current)

Fig. 15 Total current I_{tot} and different load currents with the structure integrating the DC-link neutral point (I_R is a resistive load current and I_{NL} is a non linear load current)

Fig. 16 Zoom of the system output currents for both structures

Fig. 17 FFT of the system output currents with the structure integrating the transformer

the total current I_{tot} , the current of the resistive load I_R and the non linear load current I_{NL} which is activated at 0.3 s. At 0.2, the total current increases due to the activation of an additional three phase non linear load. The zoom of the current curves are shown in Fig. 16. It is to note that the total current with DC-link neutral point topology is more affected by the non linear harmonics than for the structure with transformer. The THD value for both cases is given by Figs. 17 and 18.

5 Discussion

To reach the optimum PV system architecture, several criteria should be considered. This study investigates a comparison approach according to selected criteria. This approach is summarized in the flowchart of Fig. 19. The difference with other researches is that power quality

Fig. 18 FFT of the system output currents with the structure integrating the DC-link neutral point

Fig. 19 Flowchart of the comparison approach

and techno economic criteria are considered together to help making an optimum decision regarding the PV system architecture. To apply this approach, two PV system topologies are studied: structure with DC-link neutral point and structure with transformer. The first issue concerns the battery and DC link capacitors lifetimes. Indeed, the transient due to load sudden activation is supported by batteries, which induce the reduction of their lifetime, because they are usually characterized by low power density [26]. It is to note that the transformer is better for operational constraints imposed on the battery. In that case, the load peak current is smaller of about 15%. With regard to DC link capacitors, their lifetime depends on several reasons like temperature, humidity, voltage and current ripples, in addition to charging and discharging cycles [27, 28]. The voltage fluctuation is addressed by this study. In fact, the structure with DC-link neutral point is the more concerned with this point as it solicits both capacitors of the DC

link, so this presents a disadvantage for this topology compared to structure with transformer. The second investigated criterion is the quality of the output AC voltage. Voltage THD is measured to evaluate both structures. The results are comparable and in compliance with standards. This is due to high performance of the DC/AC converter control. The third criterion is the impact of non linear load on neutral current according to chosen topology. The principal result of the connection of non linear loads is the generation of the odd multiples of the third harmonic. These harmonics provoke the neutral overloading [29, 30]. Concerning this point, results presented in Fig. 17 and Fig. 18 show that the topology with transformer is a little better than the topology with DC-link neutral point. The THD of the total current are 8.8% and 11.4%, respectively, which induce more harmonics in the generated neutral current for the DC-link neutral point structure. It is to note also, that the principal harmonics in the neutral current is the third harmonic. Indeed, as it is shown in Figs. 17 and 18, the third harmonic presented in the FFT of non linear load, does not appear in the FFT of the total current because this component of the current is injected into the neutral current. It is to note that even if the transformer based structure presents better results for many comparison criteria, it remains the most expensive. Adding to that the negative impact of non sinusoidal current on transformer losses which reduce the transformer efficiency and reduce its lifetime [31].

6 Conclusion

Due to the fast expansion in energy consumption, the rooftop photovoltaic systems have become an interesting alternative, for standalone and connected cases. These systems present a multitude of configurations. This paper investigates the comparison of two 4 wires configuration, the first one is connected to AC via a bus DC-link neutral point and the second is connected throw a Delta/Star transformer the consequences of single phase and non linear loads are studied, via several comparison criteria.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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