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Impact comparison of PV system integration into rural and urban feeders

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Abstract

This paper is directed to evaluate the impact that the future widespread use of photovoltaic grid connected systems (PVGCSs) will have on feeder operation. With a view to achieve a global vision of this impact, the present work investigates representative feeders located in different latitudes. Actual rural and urban distribution feeders belonging to the Spanish electric utility have been selected and analyzed in both northern and southern latitudes.

The analysis identifies the operating variables to assess the PV impact in the different feeders. These critical variables are related to the design and performance characteristics of the feeder. Meteorological conditions at the installation site, load patterns, PV allocation and penetration are the main factors affecting this PV impact.

Keywords: Photovoltaic power systems; Power distribution planning; Rural area; Urban area

1. Introduction

Most of the newest PV systems installed nowadays are PVGCSs. In the urban environment, small and medium building integrated photovoltaics (BIPVs) are the main application, while in suburban and rural environments, centralized PV power plants may be erected as well. Small PVGCSs (1–5 kWp) are connected to low voltage (LV) networks linked to (medium voltage) MV feeders. Medium PVGCSs (10–250 kWp) not only are connected to LV networks but also directly to MV distribution feeders. Lastly, large PVGCSs (0.5–5 MWp) are connected either to high voltage (HV) or MV systems.

As the PV penetration level increases gradually in a specific area, it is felt that PV generation and the resulting overall impact in the concerned MV feeder may become very significant. The impact, with both technical and economical implications, includes both feeder operation and the planning/security practices of electric utilities. A number of studies have analyzed some of the above issues. Most of them have focused on studying the change of some operating variables of a specific case (feeder with a PVGCSs allocation and penetration) throughout only a few days [1–8]. The importance of the assessment of the short and long term feeder performance is introduced in Ref. [9]. In addition, Pregelj pinpoints the significance of the PV allocation/penetration [10]. The PV impact is even different on different feeders due to their specific design and performance characteristics. To highlight this idea, a more comprehensive study was carried out in Ref. [11], where the PV impact on feeders and the allowed PV penetration levels was analyzed over different feeder types located at two latitudes. However, there is still a lack of knowledge on characterizing which are the necessary feeder operating variables to assess the PV impact on different feeders. Once such critical variables are determined in representative feeders, the assessment of PV impact or acceptable PV penetration in a particular feeder may be performed more reliably.

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The global assessment of the impact of PVGCSs on MV distribution feeder operation is a comprehensive and complex task where many variables are involved. On one hand, the feeders should be divided into different classes in relation to the significant operating variables that are modified by this PV integration because of their own characteristics of design and performance. Rural and urban feeders may be classified into a wide but suitable category. On the other hand, the PV impact also depends on the PV performance in relation to the environment (rural and urban) and the latitude. Lastly, a variety of potential spatial allocations and penetration levels of PVGCSs expands the analysis further. At this point, to achieve representative outcomes, it is advisable that the global assessment should become a clustering assessment. The clustering assessment reduces the potential cases by grouping similar inputs into groups. Thus, a later qualitative and quantitative analysis of the enhanced feeder operation with PVGCSs in each group allows finding useful particular conclusions for feeder planning and operating purposes.

In this context, this paper covers the above knowledge gap, through analysis of the impact of PVGCSs on two actual representative feeders, rural and urban, located at two latitudes (Jaén, Spain, 36°N and Helsinki, Finland, 60°N). First, it contrasts the optimal PVGCSs solution in technical and economical terms for both feeders. These results are important not only for the optimal solution but also because it allows us to know how other potential candidates depart from the optimal one in each type of feeder. Then, the enhanced operation of the two feeders with their optimal PVGCSs is examined. This comparison highlights the behavior of the critical feeder operation variables in each type of feeder.

For the analysis, the methodology presented in Ref. [12] has been used. This earlier method has been enhanced to include the differences of feeder operation and PVGCSs performance in rural and urban environments.

The present work starts by describing the significant differences in performance and design terms of rural and urban feeders. The specific PVGCSs performance and their constraints in urban and rural areas are detailed as well. The enhanced methodology of optimal allocation of PVGCSs and evaluation of their impact is presented. At last, the results allow obtaining a detailed overall view of the impact of high PV penetration on feeders.

2. Rural and urban feeders

2.1. Design characteristics

Rural distribution feeders are set up in sparsely populated areas, where only a small fraction, usually less than 2%, has any load. A representative rural load density may be up to 0.2–2.5 $\mathrm{MVA/km^2}$ [13,14]. Customer load densities as applied to urban areas are higher. A typical city would have load densities in the outer areas in the order of 5 $\mathrm{MVA/km^2}$ or less, rising to 60 $\mathrm{MVA/km^2}$ or more in the dense central areas.

The topology of rural feeders is radial with a primary main feeder and various laterals. The large distances between customers prohibit the looped configuration and translate into a longer main feeder. Urban distribution feeders are structurally meshed to provide added system reliability but radially operated.

In the rural environment, lines are not only overhead, but also might be underground close to urban centers where they are always underground.

A three phase feeder is the general practice for rural and urban feeders in European countries. This practice applies to urban areas in the US but not to rural ones where single phase–three phase systems are also used.

In urban areas, with a three phase LV, the economic maximum supply area is around 0.25 $\mathrm{km^2}$. Accepting that locations of substations can never be ideal, a minimum of five substations are required per $\mathrm{km^2}$. High urban load densities justify the use of large transformers (400–1000 kVA) in the MV substations. Typically, smaller transformers (15–250 kVA) serve rural areas. Fewer customers (typically no more than four, and often only one) are served by each transformer. European rural feeders locate larger transformers to multiple customers than the US.

The load of a distribution feeder is more unbalanced in rural than in urban areas because of the large number of unequal single phase loads that must be served.

Spain works within an internationally agreed framework that sets a typical $4 \times 150\ \mathrm{mm^2}$ (or 240 and 400) aluminum conductor for urban feeders. Conductors used in rural primary main feeders are type LA-180/LA-110 with type LA-110/LA-56 for laterals.

2.2. Performance characteristics

Operating variables for a feeder functioning in normal conditions closer to their respective limits may be called critical variables. Different critical variables are linked to each feeder depending on its design characteristics. Critical operating variables for rural and urban feeders are recognized.

In rural feeders, one of the mayor problems identified for power quality is voltage profile [15,16]. It is due to the high impedances of long distribution lines. Just the opposite occurs in urban feeders where the voltage profile is far from both the standard limit and voltage collapse. Therefore, while the viable voltage limit is regulated to within 10% or 7% of the nominal values [17,18], this limit also ranges as a compromise of rural (5–15%) and urban (0.5–2%) feeder operation [19]. The used indices to evaluate proximity to the above limits may be the loading margin to viable, standard, voltage (λ_v) and to voltage collapse (λ_c) as defined in Ref. [12].

Likewise, as a result of the aforesaid difference, in rural feeders, losses are in the range of 2–5%, while in urban feeders, they sometimes do not exceed 1%.