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A three-phase community microgrid comprised of single-phase energy resources with an uneven scattering amongst phases

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ABSTRACT

This paper considers a three-phase, low voltage community network with both grid-connected and autonomous modes of operation, which is composed of a group of residential houses and some single-phase, converter-interfaced distributed energy resources (DER) with equal and arbitrarily scattering of the DERs among the phases. The vigorous operation of such a microgrid system is examined with the proposed management techniques. In such a network, it is highly probable for one phase to have a high generation capacity while the other phases experience a higher demand; a technically challenging problem for a network operating in autonomous mode. In this paper, it is proposed for the single-phase DERs of such a system to operate under a droop-based voltage control technique while an appropriate technique is proposed to facilitate the transmission of the excess power from one phase to other phases. The proposals are validated by extensive digital simulations in PSCAD/EMTDC for several scenarios to demonstrate the feasibility of operating such a system and the efficacy of the proposed techniques.
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1. Introduction

The ever growing energy demand, the ecological concerns, the requirement of lessening electricity generation costs and increasing the reliability of electric systems are the major motivation for the fast proliferation of the distributed energy resources (DERs) in electric networks in the last few years [1,2]. With this trend, it is expected that in near future, the majority of households will have some sort of DERs, which is anticipated to be mostly a single-phase, grid-connected photovoltaic, wind, fuel cell or battery type. If the generation capacity of a DER is large enough, it can supply the household demand fully and thereby not only it can result in a net-zero energy trade for their owners but can also help them to permanently leave the grid [3–6]. Alternatively, it is more beneficial if a cluster of neighboring households formulate a low voltage (LV) network in which not only they can consume the generated power of their own DER but they can also share the generated power of their neighbours' DERs [7]. Such a network can operate in autonomous mode and is denoted in this paper by community network. This community network appears as a microgrid (MG) and should be a single controllable unit that responds promptly to the demand variations in its network [8]. The single-phase DERs in these community networks not only need to supply the demand of the network but should also regulate the voltage and frequency within the acceptable limits, when it is operating in autonomous mode [9,10].

The MG concept is well-established and ample of literature is available on power management and control in MGs [11,12]. In grid-connected mode, the voltage and frequency of the MG is dictated by the grid; however, in autonomous mode, it depends on the network demand and generation balance, and the DERs and the MG central controller are in charge of regulating them. The control and power sharing of three-phase DERs in the MGs are extensively studied in [13,14]. It is suggested for the DERs to operate in constant PQ control during the grid-connected mode of operation of the MG and in droop control during the autonomous mode of operation, assuming a decentralized control principle which is most probably due to the lack of proper data communication systems. In [15], the performance of DER converters is demonstrated in the presence of balanced, unbalanced and nonlinear loads in the MG. The converters of the DERs can operate in current-controlled [16] or voltage-controlled mode [17]. Their performance is compared in [17] and it is shown that voltage-controlled converters have less computation complexity in the output reference generations. A review of the central control systems and energy management systems for MGs is presented in [18,19] while a fast backup technique to regulate the voltage and frequency of the MG in autonomous mode is presented in [20].

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The carried out studies on the MGs are mostly focused on three-phase ac MGs [9–20], dc MGs [21,22] or their hybrid combinations [23–25]. So far, not enough research is carried out on the operation of single-phase DERs within three-phase MGs, specifically when the MG is operating in autonomous mode. Due to the traditional mechanism of designing and operating LV networks by the utilities in which all three-phases are distributed in the streets [26] (except in the North American countries [27]), this is the most probable case if neighboring households form a network. Thus, the network will be in the form of a three-phase, four-wire system while the DERs will be single-phase. The operation of single-phase DERs in a grid-connected MG is discussed in [28,29]; however, such an operation is not complicated as they operate in constant PQ mode and the grid dictates the voltage and frequency. In [30], the autonomous operation of single-phase DERs is discussed; however, it is assumed that the three-phase network falls into three separate single-phase MGs and the loads in each phase are only supplied by the DERs of the same phase. This requires a matching generation capacity in the DERs of each phase with the demand of that phase as well as a hierarchical control system among them, such as the one proposed in [31] for such systems. However, the utilities around the world usually do not use a systematic method for connecting the households evenly among the phases. The households are normally connected arbitrarily [32] and corrections for changing the phases are carried out only if periodic measurements (every few years) illustrate a significant unbalance in the phases. The autonomous operation of a three-phase MG consisting of single-phase DERs, with different generation capacities and unequal scattering among the phases has not been analyzed before. This is the knowledge gap that is targeted in this research and is the main research scope of this paper.

In this paper, a voltage droop control-based operation is proposed for the converters of the single-phase DERs, when the community network is in autonomous mode while they operate in constant PQ mode when it is grid-connected. The network is controlled such that the voltage and frequency is maintained within the acceptable limits with minimum number of load-shedding in the network, regardless of the number and ratings of the available single-phase DERs in each phase. By adopting the proposed and developed control strategies, the DERs are controlled to operate as dispatchable DERs. It is to be noted that the dynamic characteristics of the DERs are beyond the research scope of this paper and are not discussed. Also, in this study, it is assumed that the DERs are capable of supplying the required demand (i.e., the instantaneous power demands are within the instantaneous capacities of the DERs depending on the environmental conditions or their state of charge).

To realize the above system, an appropriate mechanism for interphase power circulation, i.e., transferring the excess power from the single-phase DERs, located in one phase, to the loads in the other phase(s). This can be realized by different approaches, one is proposed in [33] in which a back-to-back converter is located between every two phases of the system. This technique is very costly as it requires 6 single-phase voltage source converters (VSCs) and filters, and three dc link capacitors and. The authors have proposed another technique using three, single-phase VSCs and one, three-phase VSC in [34,35]. On top of them, this paper discusses another technique for the necessary interphase power circulation which uses the existing equipment of the network and does not need further investments in terms of purchasing and installing new equipment; however, some rewiring of the existing circuit breakers and protective devices may be necessary.

In summary, the main contribution of this research is proposing an appropriate operational mechanism for a three-phase community network which is supplied by single-phase DERs, with uneven and unknown scattering amongst the phases, and can operate autonomously. The chief application of the presented control mechanism is for residential-level photovoltaic, wind, fuel cell, and battery type DERs that are connected to the feeder through a single-phase VSC.

The rest of the paper is organized as follows: The system under consideration is introduced in details in Section 2. Section 3 presents the proposed control strategies for the single-phase DERs of the system while the techniques by which an interphase power circulation may be realized are discussed in Section 4. Through several digital computer simulation studies in PSCAD/EMTDC, the vigorous operation of the considered three-phase MG, composed of single-phase DERs with unequal scattering amongst phases, is evaluated under different operation scenarios in Section 5. The main findings and highlights of the research are summarized in Section 6. In addition, more detailed information on the considered VSC and filter system for the DERs and its closed-loop control system as well as the considered technical parameters for the simulation studies are provided in the appendices.

2. System under consideration and assumptions

Let us assume that a group of neighboring residential households with enough generation capacity in their DERs have formulated two communities, namely community-1 and community-2, as shown in Fig. 1a. All considered households are thought to have single-phase LV supply systems, except a few houses (approximately 10% in this study) which have a three-phase supply. Only a portion of the households are thought to have converter-interfaced DERs. Both communities are coupled to the upstream medium voltage feeder through three-phase, delta/wye-grounded distribution transformers (DT). Each community network is a three-phase, four-wire, multiple earthed neutral (MEN)-type network [36] in which the neutral wire is earthed at the secondary side of the DT and also at each customer's premises. All above assumptions are valid and the common practice in the Australian urban LV networks [26]. Only the beginning section of the LV feeder of each community is shown in Fig. 1a (for simpler presentation of the figure). This figure also illustrates the assumed number of households connected to each phase within the communities in addition to the assumed number, types, and ratings of the DERs. Each community acts as a three-phase MG and can operate in either grid-connected or autonomous modes. It is thought that each community may connect to or disconnect from the upstream medium voltage feeder through a static transfer switch, installed at the upstream of the DT (represented by CB_2 and CB_3 in Fig. 1a), and referred to as the main switch in the rest of this paper. The communities are also thought to be capable of being interconnected to each other to support the demand of the neighboring community temporarily, as proposed in [12] as a solution to minimize the load-shedding and improve the self-healing in autonomous MGs.

It is assumed that 33% of the houses in community-1 (i.e., 4 houses) are equipped with single-phase DERs where all of them are running in voltage-control mode. It is also assumed that 46% of the houses in community-2 (i.e., 7 houses) have DERs, where 57% (i.e., four) of them are single-phase voltage-controlled, 28% (i.e., two) of them are single-phase current-controlled, and 15% (i.e., one) of them is a three-phase voltage-controlled. All DERs are assumed to have energy storages with sufficient capacity that can smoothen the generated dc voltage in case of sudden changes in the ambient conditions (such as clouding or temperature change).

A distribution static compensator (DSTATCOM) is also assumed to be installed at the secondary side of each DT. The main function of the DSTATCOM is to guarantee a three-phase, balanced voltage

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