Electrical Power and Energy Systems 99 (2018) 11–27

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A new approach to voltage management in unbalanced low voltage networks using demand response and OLTC considering consumer preference

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ARTICLE INFO

Keywords:
Voltage unbalance
Demand response
On-load tap changers
Photovoltaics
Consumer comfort
Peak demand

ABSTRACT

Voltage unbalance and magnitude violations under normal operating conditions have become main power quality problems in many low voltage (LV) distribution networks. Maintaining the voltage level in an LV network within the standard limits is the main constraining factor in increasing the network hosting ability for rooftop photovoltaic (PV). This study presents a new effective method for voltage management in unbalanced distribution networks through the implementation of optimal residential demand response (DR) and on-load tap changers (OLTCs). The proposed method minimises the compensation costs of voltage management (cost of DR and network loss), while prioritises the consumer consumption preferences for minimising their comfort level violations. A modified particle swarm optimisation algorithm (MPSO) is utilised to identify the optimal switching combination of household appliances and OLTC tap positions for the network voltage management. The proposed method is comprehensively examined on a real three-phase four-wire Australian LV network with considerable unbalanced and distributed generations. Several scenarios are investigated for improving the network voltage magnitude and unbalance considering individual and coordinated operations of DR and OLTCs (three phase tap control and independent phase tap control). Simulation results show that the coordinated approach of DR and OLTC, especially, DR integrated with OLTC independent phase tap control effectively improves the network voltage and increases the PV hosting capacity.

1. Introduction

Many low voltage (LV) residential feeders are three-phase, four-wire systems and the majority of the houses have single-phase power supply [1]. In LV four-wire distribution networks, voltage magnitude and unbalance are the main power quality problems of concern to distribution system operators. The three-phase voltage near a strong supply is usually well balanced, however, it can become unbalanced at the consumer side due to many factors such as unequal system impedances, unequal distribution of single-phase loads and distributed generators [2]. The increasing penetration of rooftop photovoltaics (PVs) and new types of loads/appliances such as electric vehicles (EVs) into LV networks, introduce even more network voltage unbalance (VU) and magnitude violations. For instance, in Australia, the widespread installation of residential rooftop PVs have caused the overvoltage problems in the residential LV networks [3]. As distribution networks were not originally designed to accommodate such resources, the consequence is voltage violations in the network [4], which may cause the deterioration of the operating life of distribution system assets (e.g. transformers, voltage regulators, line, etc.) [5]. Furthermore, an unbalanced network can host less PV generation and loads without reaching the critical voltage limit.

Voltage unbalance occurs due to the asymmetry of voltage magnitude or phase angle at the fundamental frequency between the phases of a three-phase power system [6]. An unbalanced system will have voltage and current that have positive, negative and zero sequence components. The negative sequence component can flow through the network in a similar way to positive sequence currents, which causes energy losses and reduce the capacity of the transmission/distribution line. The zero-sequence current flowing through phase wires results in an extra current in the neutral wire and eddy current energy losses as well as overheating of transformer windings [7]. For a balanced system, both zero sequence and negative sequence components are absent. The presence of excessive levels of VU can result in overheating and derating of all induction motor loads such as squirrel cage induction motors (swimming pool pumps and air-conditioning compressors,

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https://doi.org/10.1016/j.ijepes.2017.12.034
Received 5 May 2017; Received in revised form 15 November 2017; Accepted 26 December 2017

Nomenclature

$A_{n(i,t)}$	switching control/status variable for the nth appliance of the ith candidate consumer at tth timeframe
OLTC_{dep}	three phase tap control
OLTC_{ind}	independent phase tap control
$ADR_{(i,t)}$	appliance disturbance ratio of the ith candidate consumer at tth timeframe
$P_{n(i,t)}$	rated kW demand of the nth appliance of the ith candidate at tth timeframe
$DR_{(i,t)}$	DR contribution in kW from the ith candidate consumer at tth timeframe
$price_{(i,t)}$	bid price ($/kW h) of the ith candidate consumer at tth timeframe
N_{DR}	total number of DR candidate consumers
$Network_{losses(t)}$	total network power loss (kW) at tth timeframe
$cost_{(t)}$	network power loss (kW) cost ($/kW) at tth timeframe
Δt	timeframe duration (hours) of a DR event
T	number of intervals for a DR event in a particular day
$VUF_{(j,t)}$	negative sequence voltage unbalance factor for jth bus at tth timeframe
$VUF_{Zero(j,t)}$	zero sequence voltage unbalance factor for jth bus at tth timeframe
$V_{(p,t)}$	pth phase voltage magnitude at tth timeframe
N_{bus}	number of buses
N_{line}	total number of lines
N_{phase}	total number of phases of all buses
$I_{(l,t)}$	lth line current at tth timeframe
$I_{\max(l)}$	maximum current limit of lth line
$N_{disturb(t)}$	total number of participated consumers with at least one $A_{n(i,t)} \neq 0$
$\text{Penalty}_{ADR(i,t)}$	penalty factor associated with $ADR_{(i,t)}$
$\text{Penalty}_{(VUF)}$	penalty factor for negative sequence voltage unbalance violation
$\text{Penalty}_{(VUF_{Zero})}$	penalty factor for zero sequence voltage unbalance violation
$\text{Penalty}_{(V)}$	penalty factor for the magnitude voltage violation
$\text{Penalty}_{(I)}$	penalty factor for the line thermal limit violation
$\text{Penalty}_{(OLTC)}(t)$	penalty factor for OLTC tap change at tth timeframe
$tap_{posi}(t)$	OLTC tap position at tth timeframe
C_{main}	estimated maintenance cost of OLTC
N_{change}	maximum allowable number of tap change of OLTC without maintenance
$tap_{chng/day}^{total}$	total tap changed per day
$tap_{chng/day}^{total}$	maximum allowable tap operation per day

elevators, etc.) in residential apartment complexes [1,8]. A small unbalance in the phase voltages can cause a disproportionately large unbalance in the phase currents. VU can cause network problems such as mal-operation of protection relays and voltage regulation equipment, and generate non-characteristic harmonics from power electronic loads [9]. Therefore, it is important to improve VU in LV distribution networks. In Australia, the distribution code allows for negative sequence voltage up to 1% on average and a maximum of 2% (can go over 2% for a maximum period of 5 min within each 30-min period) [10]. In the UK, VU limit in the whole network is 2% [11], and the max limit of VU is 3% at no-load conditions as per the ANSI standard [12].

1.1. Voltage control methods

Many different solutions are proposed in the literature to tackle Voltage unbalance and magnitude problems in LV feeders. Some conventional voltage improvement methods are feeder cross-section increase and manually switching the phases to improve the distribution of the loads across the three phases [1,13]. However, these practices are carried out only once and are very costly [14]. Another problem with the phase switching approach is to determine an optimum switching order that allows both reduction of power losses and balancing loads while increasing the renewable energy penetration capacity in the network [15]. Dynamic switching of residential loads from one phase to another using a static transfer switch is proposed in [16] to minimise the VU and network loss along a feeder. However, this approach is only suitable for three phase consumers, but, the majority of the houses in LV networks have a single-phase power supply.

In some situations, special balancing equipment such as the unified power quality conditioners (UPQC) [17] and the distribution static compensators (dSTATCOM) [18] can be useful solutions for improving voltage unbalance and magnitude at LV networks. However, these types of equipment require high installation costs in addition to associated operation and maintenance costs, and therefore, is mainly suitable for medium voltage (MV) networks. Existing MV network equipment such as the OLTC with different types of tap control (e.g. three phase tap control, independent phase tap control) are studied in [19] to improve the voltage in the LV network. The application of OLTC was conventionally limited to MV distribution transformers. As a result of the high growth of intermittent PV generations, recently, various studies [20,21] have proposed secondary distribution transformers with OLTC due to their capabilities and advantages to distribution networks. Nevertheless, they have mostly been studied in three-phase balanced LV distribution networks. One study [5] proposes a coordinated control of PV inverters with an individual phase tap control OLTC to balance the four-wire LV network. It claims that this types of OLTC can minimise the voltage unbalances at some degrees, however, without coordination it can worsen the voltage unbalances in some loading conditions due to the complex nature of positive and the negative sequence components of bus voltages. Furthermore, as the PV generation penetration level increases, OLTC operation might increase the total network losses [5].

Some local control strategies have been proposed using converter control of EVs [4,14] and PVs [2,22] to improve voltage quality in LV networks. One example is, a three-phase balancing PV inverter and EV charger are proposed consisting of three single-phase inverters for improving phase balance in distribution grids [4]. The main drawback of these proposed converter control methods are: the need to increase the capacity of the converter, require three-phase connection to consumers premises, less influence of reactive power compensation by the converter on LV network voltage control. Another drawback of this approach is the financial losses to PV owners due to curtailing active power generation and currently no incentive scheme available to consumers for supporting reactive power in the network. Recently, due to growing popularity of energy storage devices and vehicle to grid operations, researchers are focusing on improving the charging and discharging conditions of these devices for maintaining network constraints. For instance, authors in [23] present an approach for solving EVs charging coordination (EVCC) problem using Volt-VAr control, energy storage device (ESD) operation and dispatchable distributed generation (DG) in unbalanced distribution networks. An interactive energy management system for incorporating plug-in electric vehicles (PEVs) is developed in [4] to maintain voltage unbalance within acceptable limits. Furthermore, a two-stage control method is proposed in [6] using coordination of OLTC and vehicle-to-grid for voltage management in distribution system. Most of these studies (e.g. [4,6,23]) performed unbalance study on three-phase three-wire power networks, which may not provide actual network impacts on voltage management. Since LV networks are generally configured with four-wire cables/lines, the voltage management study including unbalance requires proper modeling of the network parameters as a four-wire