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Distributed hierarchical control structure for voltage harmonic compensation and harmonic current sharing in isolated MicroGrids

Reza Ghanizadeh [a,*], Gevork B. Gharehpetian [b]

[a] Department of Electrical Engineering, Urmia Branch, Islamic Azad University, Urmia, Iran
[b] Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran

HIGHLIGHTS

- A distributed hierarchical control is proposed to use in islanded microgrids.
- A method is proposed for voltage harmonic compensation and sharing the compensation workload.
- A method is proposed for accurate harmonic current sharing among DGs.

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ABSTRACT

In this paper, a distributed hierarchical control structure is proposed for compensating voltage harmonics of Sensitive Load Bus (SLB) and sharing current harmonics of load current among Distributed Generation (DG) units in isolated MicroGrids (MGs). In this structure, each DG has primary and secondary controller implemented locally. In the primary control level, a method is proposed for voltage harmonic compensation at SLB and sharing the compensation workload, which is based on non-fundamental apparent power, and directly takes into account the rated capacity limitation of DG inverter. Furthermore, in this level, another method is proposed for accurate harmonic current sharing among DGs which is based on circulating currents. The proposed method is capable of removing harmonic current sharing error without using any knowledge about MG topology and also impedances of distribution lines and loading conditions. Moreover, the effect of the applying proposed method on the amplitude and quality of DG output voltage waveforms will be insignificant. The secondary control level transmits the reference control signals to the primary control level in order to decrease the voltage harmonics at SLB and share harmonic currents among DGs. Details of designing control system parameters are presented and simulation results are given to show the efficiency of the proposed structure.

1. Introduction

A MicrogGrid (MG) is an under-control network consisting of Distributed Generation (DG) units, energy storage systems and distributed loads that could be utilized in grid-connected mode or independently (isolated) [1,2]. DGs are usually connected to the network through a power electronic converter which is often a Voltage Source Inverter (VSI). The most important task of an interface inverter is to adjust the phase angle and the magnitude of the output voltage in order to control the active and reactive powers injected by the DG [3]. Moreover, based on proper control methods, this inverter can also be used for compensating power quality problems such as voltage harmonics [3–35].

In [4–16], controlling capabilities of DGs interface inverter have been used for voltage and current harmonic compensation. In [8], an approach has been presented based on imitating the resistive behavior at harmonic frequencies for compensation of DG output voltage harmonics in isolated MGs. In [9], it has been proposed to control MGs through dividing control operations in frequency domain. This can be done by centralized controlling of voltage and power sharing and locally controlling the power quality. In this approach, the main focus is on the presented structure, and the power quality control is limited to an extent that DG is responsible for keeping its own output voltage sinusoidal. In [10,11], an optimum control method based on Particle Swarm Optimization (PSO) has been used to improve the power quality indices of an isolated MG. In these references, PSO is responsible for real-time adjustment of control parameters of the system to satisfy the power quality needs, specially adjusting voltage and frequency. In [12], a decentralized method has been proposed for MGs, and

* Corresponding author.
E-mail address: r.ghanizadeh@iaurmia.ac.ir (R. Ghanizadeh).

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Nomenclature

MG	MicroGrid
DG	Distributed Generation
SLB	Sensitive Load Bus
VSI	Voltage Source Inverter
PSO	Particle Swarm Optimization
LB	Load Bus
NLB	Non-sensitive Load Bus
LBC	Low Bandwidth Communication
THD	Total Harmonic Distortion
D	Distortion power
h	Harmonic order
$C^h{}_{dq}$	hth order reference compensation signal of SLB voltage
$HD^h{}_{SLB}$	hth order harmonic distortion index of SLB voltage
$i^h{}_{odq,k}$	Actual output current of DG_k
h_k	Load distribution factor
$S_{0,k}$	Rated power of DG_k
S_T	Total power loading of DGs
$i^h{}_{Cir,k}$	Circulating current of harmonic component of kth inverter
Φ^*	Phase angle reference
Φ_0	Rated phase angle
m_{pp}, m_{ip}	Proportional and integral coefficients of the active power control
n_{PQ}	Proportional coefficient of the reactive power control
k_{pfV}, k_{phV}	Proportional coefficients of the fundamental and harmonic components of the voltage controllers
ω_c, ω_0	Cut-off frequency and the reference angular frequency of voltage controllers
S_n	Non-fundamental apparent power
$k^h{}_P$	Harmonic proportional controller
S_f	Fundamental power
S_{free}	Free capacity of DG for supplying the non-fundamental apparent power
S_{rem}	Remaining capacity of DG after supplying the non-fundamental apparent power
Ts	Sampling time
$G_{CL\text{-}f}(s)$, $G_{CL\text{-}h}(s)$	Closed-loop transfer functions of fundamental and harmonic components of voltage
$Z_0(s)$	Equivalent output impedance of the closed-loop system
$Z_v(s)$	Virtual impedance in the fundamental component
$Z'_o(s)$	Output impedance of the inverter

also a load compensator has been used in addition to a power droop controller and inner voltage and current control loops. The main goal of designing this compensator is to limit harmonic currents and prevent resonance at harmonic frequencies. In [13,14], to control the active and reactive powers, decrease harmonic currents and improve system unbalance, an improved current control strategy has been presented under asymmetric and nonlinear load conditions. In [15], a structure has been presented for voltage and current harmonics compensation in a grid-connected MG, which consists of one DG with two inverters. The first inverter is used for voltage harmonic compensation of local load and the latter is used for compensation of network current harmonics. In [16], a scheme has been presented for voltage harmonic compensation and voltage support in a grid-connected network. The voltage is supported through reactive power compensation which can decrease the over/under voltage problem. The presented methods are able to locally improve voltage quality at the DG output while voltage quality is usually of higher importance at the Sensitive Load Bus (SLB). Furthermore, if DGs try to locally compensate voltage harmonics at their outputs, harmonic distortion at other buses of system (including the SLB) might significantly increase. This phenomenon is known as "*whack-a-mole*" [17].

In an MG with severe nonlinearity, common droop controllers exhibit weak harmonic current sharing and cannot directly overcome the problem of harmonic currents among DGs. Thus, in previous researches several techniques have been presented for load sharing among interface inverters of DGs. In [18–23], several methods based on combinational and modified droop techniques have been presented for load sharing among DGs. The concepts of virtual active/reactive power and virtual voltage/frequency have been proposed for improving the stability of the droop controllers and performance of isolated MGs in [20] and [21], respectively. However, these concepts can hardly improve both decoupling of powers and accuracy of power sharing simultaneously. In [22], in order to improve the reactive power sharing, the output voltage of each DG has been changed by adding two terms; term for decreasing sharing error and the other one for voltage restoration. The voltage restoration term has been applied for compensating the voltage drop caused by the term added for decreasing the sharing error. Nevertheless, in this kind of strategies it is difficult to adjust the coefficients of terms under different rated power conditions of DGs and generalize it to harmonic current sharing. In [23], a high-frequency harmonic voltage has been injected to the reference output voltage of each DG in order to decrease reactive power sharing error and improve the accuracy of harmonic current sharing. By applying this signal, an accurate power sharing has been obtained through adjusting the closed-loop output impedance of each inverter by changing bandwidth of control loop. In [24], a method has been proposed for improving distortion power (D) sharing among DGs by adjusting the voltage control bandwidth through increasing D, which in turn increases the voltage control gain, and this improves nonlinear load sharing. It is worth noting that this method decreases the voltage control stability [25]. In [4–7,26–30], harmonic virtual impedance schemes have been used to improve harmonic current sharing. Harmonic virtual impedances have been adjusted through modifying the reference output voltage of the DG inverter using a load current feed-forward loop. However, harmonic load current sharing has been realized through virtual impedance schemes at the cost of the voltage drop and increase in voltage harmonic distortions. Another important issue, which has not been properly studied in aforementioned researches, is the effectiveness of the solutions in decreasing circulating currents which in turn causes improper load sharing among DGs.

In [31–34], the solutions, based on hierarchical structure consisting of primary and secondary levels, have been proposed to compensate voltage harmonics and improve load sharing in MGs. In [32], a hierarchical control structure consisting of several control loops has been presented for solving the problems related to unequal power sharing in isolated MGs. The main idea similar to that of [7]. In [33], a hierarchical control structure has been presented for coordination of DG interface inverters and active power filters in order to compensate voltage harmonics in MGs. The advantage of this structure is that it can be used in spite of rated power limitations of interface inverter or too much distortions in output voltage of DGs (due to participation in compensating power quality problems). In these methods, the secondary control has been implemented as centralized manner system for all DGs. The main problem of centralized system is that if there is a fault in the central controller or communication link between the primary and the secondary control, the operation of DGs will encounter problems.

In this paper, in order to compensate voltage harmonics of SLB and properly share harmonic currents among DGs, a distributed