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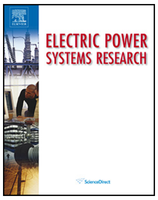

# A distributed constraint satisfaction approach for reactive power sharing in microgrids

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ABSTRACT

Decentralized droop-based control has gained enormous attention in the operation of islanded microgrids (IMGs) over the last decade due to its superiority over centralized control schemes. However, poor reactive power sharing has been identified as a major drawback that limits the implementation of the communicationless droop control in IMGs. In order to preserve the decentralized control structure in IMGs, distributed communication-based reactive power sharing has been recently mentioned as a complementary process for the decentralized droop control. This paper proposes a scalable and solid mathematical approach for distributed reactive power sharing in IMGs. First, the problem of reactive power sharing in IMGs has been formulated mathematically as a distributed constraint satisfaction problem in a multi-agent environment, where the local controller of each distributed generation is defined as a control agent. The proposed formulation aims to achieve the desired reactive power sharing among the control agents while ensuring the satisfaction of other IMG operation requirements including bus voltages limits and line current capacities. Second, an asynchronous weak commitment (AWC) technique has been proposed to solve the formulated distributed constraint satisfaction problem. The proposed technique tends to search for voltage droop parameter settings of the control agents based on an asynchronous peer-to-peer cooperative protocol. Several case studies have been carried out to validate the effectiveness of the proposed algorithm and test its performance and convergence characteristics. The results have shown that the proposed approach can achieve accurate reactive power sharing and satisfy the IMG operation constraints under different operating conditions. Further, the proposed algorithm has shown fast convergence properties.

## 1. Introduction

Droop control is defined as the most viable control scheme for the operation of islanded microgrids (IMG) dominated by inverter-based distributed generation units (DGs) [1–3]. The droop control parameters are usually designed to be pre-specified in order to share the IMG loads in proportion to the ratings of DGs [2–4]. Nonetheless, such settings are not able to achieve the desired reactive power sharing due to the different impedances seen by each DG inverter [1,2,4,5]. This might, in turn, lead to reactive power circulation [4,6–8]. Further, fixed settings of droop parameters might fall short in satisfying the IMG operation requirements such as bus voltage and line current capacity limits under all operating conditions. The work in Refs. [9,10] showed that fixed droop parameters setting might cause voltage regulation issues due to the variability associated with the output power of renewable DG units as well as the variability of the IMG load.

Various modified local control methods have been presented in the literature to enhance the accuracy of reactive power sharing in droop-controlled IMG systems [6,11]. The concept of virtual impedance has been proposed in Refs. [5,7,8,12,13] to mend the accuracy of reactive power sharing and improve the system control stability. Modified local droop control methods are capable of eliminating the mismatch of the output impedances of the DGs, thus enhancing the reactive power sharing accuracy. Yet, the reactive power sharing is still not exact, and the satisfaction of voltage regulation tolerance boundary with the entire IMG system is not ensured. To overcome the limitations of these methods, a secondary control layer with a low bandwidth communication has been widely presented in the literature [6,14–22]. Based on the communication system requirements, secondary control methods can be classified into (1) centralized secondary control, and (2)

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## Nomenclature

*Abbreviation*

| | |
|---|---|
| AWC | Asynchronous weak commitment |
| CSP | Constraint satisfaction problem |
| DG | Distributed generation |
| DGA | Distributed generation control agent |
| DisCS | Distributed constraint satisfaction |
| DisCSP | Distributed constraint satisfaction problem |
| EPS | Electric power system |
| IMG | Islanded microgrid |
| LV | Low voltage |
| MGCC | Microgrid central controller |
| MU | Measurement unit |
| PCC | Point of common coupling |
| PZC | Point of zones coupling |

*Indices*

| | |
|---|---|
| $d$ | Index of IMG/zone downstream bus |
| $Gj$ | Index of distributed generation number |
| $i, n$ | Index of branch and bus number |
| $l, j$ | Index of controlled agent number |
| $PZC$ | Point of zones coupling bus index |
| $u$ | Index of IMG/zone upstream bus |
| $z$ | Index of zone number |
| $z_{adj}$ | Index of adjacent zones number |
| $k$ | Index of the proposed action |

*Variables and parameters*

| | |
|---|---|
| $\Delta V_{Gj}^{*}$ | DG $j$ variable, change of no-load reference voltage |
| $\Delta V_{Gj}$ | DG unit $j$ dependent variable, change of PCC voltage |
| $\Delta Q_{Gj}$ | DG $j$ dependent variable, change of reactive power generation |
| $P_{Gj}$ | DG $j$ injected active power at the PCC |
| $m_{pj}$ | Static droop coefficients of DG $j$ active power |
| $\omega$ | The system steady-state frequency |
| $\omega_j^{*}$ | DG unit $j$ pre-specified output frequency at no-load condition |
| $Q_{Gj}$ | DG $j$ injected reactive power at the PCC |
| $n_{qj}$ | Static droop coefficients of DG $j$ reactive power |
| $V_{Gj}$ | DG unit $j$ PCC voltage magnitude |
| $V_{Gj}^{*}$ | DG unit $j$ pre-specified voltage magnitude at no-load condition |
| $P_i$ | Active power flow from any node $i$ |
| $Q_i$ | Reactive power flow from any node $i$ |
| $P_{L,n}$ | Active power demand at node $n$ |
| $Q_{L,n}$ | Reactive power demand at node $n$ |
| $V_i$ | Voltage magnitude at bus $i$ |
| $\Delta V_i$ | Voltage change of bus $i$ |
| $r_n$ | Resistance model of branch $n$ |
| $x_n$ | Reactance model of branch $n$ |
| $P_n$ | Line active power at branch $n$ |
| $Q_n$ | Line reactive power at branch $n$ |
| $X_{i,j}$ | Feeder reactance between DG $j$ and node $i$ |
| $X_{PZC,j}$ | Feeder reactance between DG $j$ and the DG PZC |
| $\mathbb{N}$ | Feeder impedance mismatch factor |
| $S_{max,j}$ | DG $j$ capacity limit |
| $n_{DG}$ | Number of distributed generation |
| $V_{lb}^{*}$ | Lower bound of the CSP domain range |
| $V_{ub}^{*}$ | Upper bound of the CSP domain range |
| $Q_{Gj}^{A}$ | DG $j$ generated reactive power at droop control operation point $A$ |
| $\Delta Q_{Gj}^{(A,A^*)}$ | DG $j$ required reactive power change to move from steady state operation point $A$ to a new operation point $A^*$ ($Q_{Gj}^{A^*}$) |
| $V_{ub}$ | Nodes voltage upper acceptable limits |
| $V_{lb}$ | Nodes voltage lower acceptable limits |
| $I_i$ | Current flows through branch $i$ |
| $I_{max}$ | Branch current capacity limit |
| $h_j$ | Designed reactive power sharing ratio of DG $j$ |
| $Q_{sh,j}$ | Average reactive power generation per sharing unit calculated by DGA $j$ |
| $q_{sh}^{av}$ | Overall reactive power generation per sharing unit |
| $\Lambda_{jl}$ | element of the directed graph adjacency matrix of size $n_{DG} \times n_{DG}$ |
| $h_{Tj}$ | Total reactive power shares calculated by DGA $j$ |
| $\rho^{j}$ | Priority order of DGA $j$ |
| $CSP_z$ | Zone z CSP |
| $D_{Gj}$ | DG $j$ domain range |
| $\Delta V_{z,i}^{(A,A^*)}$ | Voltage change required at the location of the maximum voltage deviation within the zone $z$ |
| $V_{PZC}^{z,z_{adj}}$ | PZC voltage between zone $z$ and its adjacent zone |
| $\varepsilon$ | Acceptable bandwidth of voltage deviation |
| $SF_j$ | DG $j$ local sensitivity factor |
| $\Delta V_{Gj}^{Spec}$ | Specified voltage change at the DG PCC |

*Sets*

| | |
|---|---|
| $B_{droop}$ | Set of all droop buses |
| $B_{droop}^{Z}$ | Location of the droop-controlled DG unit in zone $z$ |
| $\mathbb{X}$ | Set of finite control variables |
| $\mathbb{D}$ | Set of non-empty solution domain |
| $\mathbb{C}$ | Set of constraints |
| $C_z$ | Set of zone constraints |
| $C_s$ | Set of system constraint |

two-way communication based distributed secondary control. In Refs. [14,15,23], the authors used the centralized secondary control to improve the accuracy of reactive power sharing via harmonic injection with consideration of the virtual impedance to adjust the output voltage. Nonetheless, the harmonic current sharing mechanism may degrade the system stability. The work in Ref. [16] utilized a centralized secondary control, in which a microgrid central controller (MGCC) receives continuous measurements from the DGs and updates the reactive power generation set point at the DGs inverter feedback controller. Centralized secondary control methods can notably enhance the reactive power sharing accuracy by taking the line impedance mismatch into consideration. They can also be utilized to restore the voltage at the point of common coupling (PCC) of the drooped DGs. Centralized algorithms, however, may face issues related to the scalability and reliability of the IMG system due to the complex communication requirements and the single point-of-failure [17]. Further, allocating an MGCC for each defined microgrid in large-scale distribution systems seems to be costly and impractical [18,24]. Consequently, utilizing distributed algorithms with minimal data exchange requirement is a critical requirement for smart grids [25,26].

The concept of distributed control aligns with the trend of the smart grid structure, which is mainly clustered into microgrids with DG owners having different preferences [24,27]. Numerous distributed secondary control schemes have been recently proposed to mitigate the limitations of centralized control methods [28].