**Marquette University**

**e-Publications@Marquette**

***Electrical and Computer Engineering Faculty Research and Publications/College of Engineering***

***This paper is NOT THE PUBLISHED VERSION*.**

Access the published version via the link in the citation below.

*2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, (October 11-15, 2020): 1343-1350. [DOI](https://doi.org/10.1109/ECCE44975.2020.9235988). This article is © Institute of Electrical and Electronics Engineers and permission has been granted for this version to appear in [e-Publications@Marquette](http://epublications.marquette.edu/). Institute of Electrical and Electronics Engineers does not grant permission for this article to be further copied/distributed or hosted elsewhere without the express permission from Institute of Electrical and Electronics Engineers.

Distributed Averaging Optimization-based Technique for Microgrid Secondary Control

Fahad Alshammari

Marquette University, Milwaukee, United States

Ayman El-Rafaie

Marquette University, Milwaukee, United States

# Abstract:

In this paper, we present a distributed averaging optimization-based controller for secondary control of islanded microgrid. In islanded mode, grid-forming units collaborate to maintain the voltage and frequency of the microgrid through droop control. However, traditional droop control suffers from poor reactive power sharing due to voltage drop in the lines. Therefore, secondary control interferes to improve power sharing in addition to restore the voltage and frequency errors produced by droop control. The proposed controller seeks minimum inconsistency of power sharing among units while keeping the frequency at its nominal value and the terminal voltage within allowable tolerance i.e. ±5% of its nominal value. The active and reactive power sharing are communicated through low frequency peer-to-peer communication channel and the average value is calculated locally. A convex optimization function is utilized to minimize the difference of power sharing among grid-forming units. The optimization function is implemented using CVX/CVXGEN and embedded in the control system in real-time on a discrete basis over a time horizon of one second. The controller is validated through simulation using MATLAB/SIMULINK. In addition, plug-and-play capability is tested for the proposed controller.

# SECTION I. INTRODUCTION

Microgrid is a group of interconnected loads and distributed energy resources (DERs) which can operate in grid-connected and island modes [1]. The control system of microgrid plays an important role in transition between modes and maintains proper operation in each mode. In both modes of operation, the critical load should be always supplied with appropriate power quality. However, islanded mode is a challenging mode of operation because microgrid controller should maintain the voltage and frequency to certain reference values and redispatch the real and reactive power among the distributed generations (DGs) and loads [2].

Microgrid can be islanded intentionally (e.g. scheduled maintenance) or unintentionally (e.g. fault in the main grid). In either case, the DG units are supposed to regulate frequency and voltage control. Grid-forming units are used to maintain the frequency and voltage in islanded microgrid through hierarchical control structure. In hierarchical control structure, primary control sustains the stability of the microgrid via droop control, secondary control compensates for the deviation of frequency and voltage caused by primary control, and the tertiary control is related to the global economic dispatch of DG units [3]. The control objective of this mechanism is to balance the power sharing among parallel units and restore the frequency and voltage to their nominal values [4].

In inductive grid, frequency can be controlled by controlling active power and voltage by controlling reactive power without prior knowledge of line parameters. However, frequency is a global variable while, voltage is a local variable due to line impedance effect causing intuitive tradeoff between voltage regulation and precise reactive power sharing among the heterogenous DG units in the microgrid [5]. Therefore, the secondary control is required to restore the frequency and voltage to their nominal values and ensure an acceptable reactive power sharing.

Several recent research activities focused on trying to solve the poor power sharing via secondary control level. Author in [5] proposed a distributed control mechanism based on a consensus protocol in which the tradeoff between voltage regulation and reactive power sharing can be tuned based on the designer requirements. In [6] distributed averaging control is used to restore the frequency and voltage as well as ensuring balanced reactive power sharing among DG units via distributed averaging technique. A review of the issues related to active and reactive power sharing was presented in [4].

This paper is organized as follow. In Section II, the role of grid-forming unit in islanded microgrid is identified in the context of hierarchical control structure in addition to the issue of poor reactive power sharing. Section III presents the implementation of the proposed distributed secondary control where the optimization function is derived, and the constraints are defined for islanded microgrid. The simulation results of the controller’s performance and a comparison with distributed averaging proportional-integral secondary control in [5] are presented in Section IV. Finally, Section V provides conclusions and future work for the proposed controller.

# SECTION II. SECONDARY CONTROL IN ISLANDED MICROGRID

## A. Grid-forming Unit Control System

During islanded mode, grid-forming units operate to regulate frequency and voltage in the microgrid. Hierarchical control structure is used to perform those functionalities through primary and secondary control based on the following:

(1)

Where *ωi* and *Vi* are the angular frequency and terminal voltage of *ith* unit, *ωnom* and *Vnom* are the nominal angular frequency and terminal voltage, *Kpi* and *Kqi* are active and reactive power droop coefficients, *Pi* and *Qi* are measured active and reactive power of *ith* unit, and *δi–ω* and *δi–v* are the secondary control corrective terms, respectively [7].

A grid-forming unit employing hierarchical control structure as shown in Fig. 1. Local controller receives the reference voltage’s amplitude and frequency from primary control level and dispatches the connected unit to follow its reference through generating modulation index to pulse width modulation. Primary control produces reference voltage and frequency by mimicking the behavior of synchronous machine in inductive grid where the change in frequency is observed by change of the active power and change in voltage is detected by change of reactive power. The secondary control aims to restore the terminal voltage and frequency to their nominal values through generating error terms *δi–ω* and *δi–v* to the primary control in slower time scale. The timescale of those levels of control are detached to avoid interaction among control levels. In addition to terminal voltage and frequency restoration, secondary control is responsible for ensuring proper power sharing among units. Hence, there are three philosophies introduced in literature to deliver those functionalities [8].

[Figure 1. - 
Grid-forming unit in hierarchical control structure.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235988/alsha1-p8-alsha-large.gif)

**Figure 1.** Grid-forming unit in hierarchical control structure.

Decentralized secondary control restores the terminal voltage and frequency solely based on local measurements. However, the power sharing is poor due to voltage drop in the lines and low *X*/*R* ratio. Centralized secondary control depends on the Micro Grid Control Center (MGCC) to obtain the proper voltage and frequency reference values for secondary control. Nonetheless, intensive communication is required between the MGCC and grid-forming units. Furthermore, a computation burden can limit extendibility of the microgrid. Distributed secondary control is based on cooperation between all grid forming units to reach proper reference values ensuring proper restoration and power sharing among units. In distributed secondary control, the plug-and-play feature is preserved since disconnection and connection of units does not require a centralized controller to change its setting. The distributed secondary control, which is based on averaging technique, utilizes peer-to-peer communication mechanism to reach an average frequency and voltage errors as well as average reactive power sharing. Another type of distributed control uses consensus-based communication to reach proper values restoration and power sharing among units.

## B. Reactive Power Sharing

The droop coefficients identify the amount power sharing for each unit based on its rated power as shown in following.

(2)

Where ∆*ωmax* and ∆*Vmax* are maximum allowable change in angular frequency and terminal voltage and *Pi–rated* and *Qi–rated* are active and reactive rated power of each unit, respectively.

load is shared properly when all units compensate for the same amount of *KpiPi* and *KqiQi.* The condition under which the power sharing is satisfied is given as follows.

(3)

The frequency in the system is a global variable therefore, the active power sharing between units is satisfied in the primary level. However, the terminal voltage in each unit is affected by the line impedance hence, different voltage is observed in each unit. Secondary control is used to enhance reactive power sharing between units in addition to its functionality to restore frequency and voltage to their nominal values. Fig. 2 shows droop characteristics of two grid-forming units including frequency and voltage as a function of active and reactive power, respectively as treated in primary and secondary levels. For *P*-*ω* droop characteristics, two units with different droop coefficients converge onto a common steady state angular frequency *ωss* with active power (*P*1and *P*2) shared between them based on their droop coefficient values in the primary level. Then, the secondary control level restores the frequency to its nominal value *ω*∗ without affecting the active power sharing. However, the *Q*-*V* droop characteristics shows two units with similar droop coefficients converge onto different voltages in the primary level. In secondary control level, the voltages converge onto a common nominal voltage while the reactive power sharing is exacerbated.

[Figure 2. - 
Droop characteristics of two grid-forming units for a) P-ω droop with similar droop coefficients b) Q-V droop with similar droop coefficients [9].
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235988/alsha2-p8-alsha-large.gif)

**Figure 2.** Droop characteristics of two grid-forming units for a) *P*-*ω* droop with similar droop coefficients b) *Q*-*V* droop with similar droop coefficients [9].

## C. Senstivity Analysis

It is essential to study the per unit change in line parameter mismatch effect on the per unit change in reactive power mismatch. Considering the system composed of two units sharing a load through a line impedance as given in Fig. 3.

[Figure 3. - 
Two units supplying a common load.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235988/alsha3-p8-alsha-large.gif)

**Figure 3.** Two units supplying a common load.

The reactive power generated by each unit is given as:

(4)

The reactive power sharing mismatch is given as a function of the line impedance mismatch is given by:

(5)

Assuming the line 1 impedance (*Xl1*)vary from 100% to 200% of the value of line 2 impedance (*Xl2*) which is assumed to be 0.0389 *pu.* The amount of reactive power mismatch in *pu* is observed in Fig. 4. The reactive power mismatch rises as the line impedance mismatch increases.

[Figure 4: - 
Sensitivty analysis of line impedance mismatch to the reactive power mismatch.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235988/alsha4-p8-alsha-large.gif)

**Figure 4:** Sensitivity analysis of line impedance mismatch to the reactive power mismatch.

# SECTION III. Proposed Distributed Averaging Based Optimization Control

The secondary control terms *δi–ω* and *δi–V* in (1) are what constitute the functionalities of secondary control. Those terms are dispatched in order to restore the frequency and terminal voltage of each unit to their nominal values as well as guarantee power sharing among the units. Rearranging equation (1), the secondary control terms are represented as.

(6)

In inductive grid, the coupling between active and reactive power is ignored (in this paper, a physical coupling impedance is used for this purpose). The controller design procedure is to first model the active power sharing and frequency restoration. Then, the reactive power sharing and voltage restoration equations are derived. Finally, an optimization function to minimize the difference between power sharing among units is applied.

## A. Active Power Sharing and Frequency Restoration

Let the average active power sharing for all N units be given as.

(7)

Each unit should align its active power sharing with *x* in order to maintain a balanced sharing among units as:

(8)

Using (1) to substitute for *Pi* in (8), we obtain.

(9)

According to (9), the active power sharing can be easily obtained since the frequency measurements are global (i.e. all units observe common frequency). Hence, for an inductive grid where the frequency is related to the measured active power via droop control, the change of the load’s active power is detected globally.

For frequency restoration, the angular frequency in each unit *ωi* should be equal to its nominal value *ωnom* to avoid circulating current [9]. By using (6), the secondary control term becomes:

(10)

## B. Reactive Power sharing and Voltage Restoration

Similar procedure for reactive power is performed to obtain the average reactive power sharing given as.

(11)

For balanced reactive power sharing, the reactive power sharing of all units should be aligned with the average reactive power sharing given in (11) and that is given as:

(12)

Substituting (1) in (12) and rearranging we obtain.

(13)

As indicated in (13), when the terminal voltage *Vi* is dissimilar in each unit, poor reactive power sharing is observed. Hence, the proposed controller’s objective is to achieve a minimum difference in reactive power sharing while keeping the terminal voltage within acceptable tolerance. This constraint is given as:

(14)

## C. Minimization Algorithm

A time-invariant optimization function is used to minimize the difference in power sharing among grid-forming units while keeping the angular frequency at its nominal value and terminal voltage within its accepted tolerance. The optimization function generates optimal values of secondary control correction terms satisfying the following conditions; *i)* angular frequency of each units ωi is restored to its nominal value as in (10) *ii)* the terminal voltage at each unit Vi is within its tolerance as in (14) *iii)* the active power sharing given in equation (9) is satisfied *iv)* the reactive power sharing given in equation (13) is minimized. The quadratic minimization function is given as.

(15)

The proposed secondary control is shown in Fig. 5. The controller obtains the average power sharing data through low bandwidth communication and measures its terminal voltage and frequency. Those data are processed in a convex optimization function to obtain the minimum power sharing difference between units while keeping constraints satisfied. The output of the secondary control represents the optimal voltage and frequency error terms that feed into the primary control. The error terms are optimal in terms of minimizing difference in average power sharing. The optimization function minimizes a convex objective function over convex constraints. Therefore, the obtained minimum value is guaranteed to be the global optimal solution for the convex set [9].

[Figure 5. - 
Proposed distributed secondary control.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235988/alsha5-p8-alsha-large.gif)

**Figure 5.** Proposed distributed secondary control.

# SECTION IV. Simulation result and discussion

The proposed controller is applied to a test system given in Fig. 6 which represents the test model of a microgrid. Also, Table I shows the system specification of the DG units, lines, and loads. In this section, the controller performance is compared with distributed-averaging proportional-integral (DAPI) secondary controller presented in [5] with the objective to restore voltage at buses to their nominal values without considering reactive power sharing. In addition, plug-and-play capability is validated through simulation of the proposed controller.

[Figure 6. - 
The microgrid test system single-line diagram.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235988/alsha6-p8-alsha-large.gif)

**Figure 6.** The microgrid test system single-line diagram.

**TABLE I:**SPECIFICATIONS OF TEST SYSTEM

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| System | parameter | value | parameter | value |
|  |  | 220V |  | 10khz |
|  |  | 700V |  | 50hz |
| DGs | parameter | DG 1&2 | DG 3&4 | Unit |
|  |  | 49 | 125 |  |
|  |  | 2 | 2 |  |
|  |  | 0.1 | 0.1 |  |
|  |  | 1.35 | 1.35 |  |
|  |  | 50 | 50 |  |
|  |  | 30 | 30 |  |
|  |  | 0.35 | 0.35 |  |
| Lines | parameter | Value |  | Unit |
|  |  | 0.23+j0.318 |  |  |
|  |  | 0.35+j1.847 |  |  |
|  |  | 0.23+j0.318 |  |  |
| Loads |  | 12 |  |  |
|  |  | 12 |  |  |
|  |  | 15 |  |  |
|  |  | 12 |  |  |

## A. Controller Performance

To validate the controller’s performance, the system is implemented based on given parameters in Table I. Initially, the primary control is running up to *t=3s* then, the secondary control is activated. A similar scenario is applied for DAPI secondary controller tuned for pure voltage regulation in order to compare the performance of both controllers. The optimization-based secondary control is discretized over one second. Figs. 7 & 8 show the frequency and terminal voltage of all units under the above-mentioned scenario with corresponding active and reactive power output.

At primary control level, controller is capable to stabilize the system and provide the required active and reactive power. However, voltage and frequency deviate from their nominal values. When the secondary control level is activated for DAPI controller as shown in Fig. 7, the frequency and voltage are returned to their nominal values. However, the reactive power sharing among units has deteriorated due to voltage drops across line impedances. In comparison, the distributed averaging-based optimization secondary controller is shown in Fig. 8. The frequency is restored to its nominal value with proper active power sharing among units. However, the terminal voltages of units are within allowable limits to allow minimum difference of reactive power sharing. In optimization-based secondary controller, units 1 & 3, where the loads are connected, inject lower reactive power as compared to DAPI secondary control. Whereas, units 2 & 4 increase their reactive power injection minimizing the reactive power sharing mismatch among units.

[Figure 7. - 
Frequency, voltage, active, and reactive power of DAPI secondary control.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235988/alsha7-p8-alsha-large.gif)

**Figure 7.** Frequency, voltage, active, and reactive power of DAPI secondary control.

Figure 8. - 
Frequency, voltage, active, and reactive power of distributed averaging-based optimization secondary control.


**Figure 8.** Frequency, voltage, active, and reactive power of distributed averaging-based optimization secondary control.

The active and reactive power sharing mismatch among units is shown in Figs. 9&10 as given in equations(8) and (12) for both controllers in addition to the average active and reactive power sharing as given in equations (7) and (11). Those values represent the amount of voltage and angular frequency shared by each unit to supply the required active and reactive power. In Fig. 9, The DAPI controller is shown where the secondary control deteriorates the reactive power sharing among units. On the other hand, the optimization-based secondary control follows the average active power sharing and minimizes the difference in the average reactive power sharing as shown in Fig 10.

[Figure 9. - 
Active and reactive power sharing for DAPI secondary control with the average power sharing between units
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235988/alsha9-p8-alsha-large.gif)

**Figure 9.** Active and reactive power sharing for DAPI secondary control with the average power sharing between units

[Figure 10: - 
Active and reactive power sharing for optimization-based secondary controller with the average power sharing between units.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235988/alsha10-p8-alsha-large.gif)

**Figure 10:** Active and reactive power sharing for optimization-based secondary controller with the average power sharing between units.

Table II summaries a peer-to-peer comparison between DAPI controller and the proposed controller in term of steady state values of per-unit voltage, reactive power, and voltage sharing. For DAPI controller, the voltage limits are kept at nominal values while the reactive power sharing are varies based on the measured voltage at unit’s terminals. However, the proposed controller minimizes the reactive power sharing among units by allowing the voltage at unit’s terminals to be varies within a specific limit. In addition, the amount of voltage sharing in per unit to supply the required reactive power shows a reduction in the sharing mismatch among units.

**TABLE II:**COMPARISON OF STEADY STATE VALUES OF VOLTAGE, REACTIVE POWER, AND VOLTAGE SHARING.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Unit** | **DAPI Controller** |  |  | **Proposed Controller** |  |  |
|  | **Voltage (*pu*)** | **Reactive Power (kVAR)** | **Voltage sharing (*pu*)** | **Voltage (*pu*)** | **Reactive Power (kVAR)** | **Voltage sharing (*pu*)** |
| **1** | 1 | 20.15 | 0.1237 | 1 | 20.03 | 0.1310 |
| **2** | 1 | 14.4 | 0.1727 | 1.07 | 17.73 | 0.1482 |
| **3** | 1 | 26.87 | 0.0926 | 0.98 | 23.09 | 0.1139 |
| **4** | 1 | 19.25 | 0.1297 | 0.99 | 20.39 | 0.1287 |

## B. Plug-and-Play Capability

Plug-and-play capability is a significant feature of modern control system of microgrid [10]. It enables units to seamlessly integrate with the rest of the grid [11]. Plug-andplay capability for the proposed controller is tested by disconnecting unit 3 at *t=3s* and reconnecting it at *t=7s.* The number of units of average power sharing in equations (7) & (11) is changed to three units instead of four during disconnection. Fig. 11 shows the parameters of the system under plug-and-play operation. The controller is capable of maintaining the voltage and frequency regulation within acceptable range while optimizing the power sharing between the units. After reconnection of unit 3, the parameters are restored to their optimal values before unit 3 disconnection. During disconnection, the remaining units satisfy to compensate the additional active and reactive power emerge due to disconnection of unit 3. An appropriate optimal solution for reactive power sharing is computed for the other three units as well as a suitable voltage level is considered for the existing state.

[Figure 11. - 
Optimization-based secondary controller under plug-and-play operation.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235988/alsha11-p8-alsha-large.gif)

**Figure 11.** Optimization-based secondary controller under plug-and-play operation.

# SECTION V. CONCLUSIONS

In this paper, a distributed averaging-based optimization control is applied to secondary control of islanded microgrid. The function of the controller is to restore the frequency to its nominal value while keeping the active power sharing difference among units at a minimum as well as keeping terminal voltage deviation within allowable limits (i.e. ±5%) and maintaining minimum disparity of reactive power sharing. A real-time quadratic convex optimization function is implemented by CVX/CVXGEN and embedded to a simulation model using MATLAB/SIMULINK. The basic controller’s performance is validated through simulation. The proposed controller efficiently keeps the voltage and frequency levels within allowable limits and the power sharing difference at a minimum under line parameters mismatch. Plug-and-play operation has been verified during disconnection and reconnection of a unit.

For future work, Time-varying convex optimization is preferred to improve optimal tracking of the system and dynamic response of secondary control. Moreover, consensus based distributed optimization methods such Alternating Direction Method of Multipliers (ADMM) will be explored to potentially relax the communication channel.

# References

1. D. T. Ton and M. A. Smith, "The U.S. Department of Energy’s Microgrid Initiative", *Electricity Journal*, vol. 25, no. 8, pp. 84-94, 2012.
2. F. Guo, C. Wen, J. Mao and Y.-D. Song, "Distributed Secondary Voltage and Frequency Restoration Control of Droop-Controlled Inverter-Based Microgrids", *IEEE Transactions on Industrial Electronics*, vol. 62, no. 7, pp. 4355-4364, Jul. 2015.
3. J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuña and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids - A general approach toward standardization", *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158-172, 2011.
4. Y. Han, H. Li, P. Shen, E. A. A. Coelho and J. M. Guerrero, "Review of Active and Reactive Power Sharing Strategies in Hierarchical Controlled Microgrids", *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 2427-2451, Mar. 2017.
5. J. W. Simpson-Porco, Q. Shafiee, F. Dorfler, J. C. Vasquez, J. M. Guerrero and F. Bullo, "Secondary Frequency and Voltage Control of Islanded Microgrids via Distributed Averaging", *IEEE Transactions on Industrial Electronics*, vol. 62, no. 11, pp. 7025-7038, 2015.
6. Q. Shafiee, J. M. Guerrero and J. C. Vasquez, "Distributed secondary control for islanded microgrids-a novel approach", *IEEE Transactions on Power Electronics*, vol. 29, no. 2, pp. 1018-1031, 2014.
7. F. Alshammari and A. El-Refaie, "Functions of Microgrid Hierarchal Control Structure", *Proceedings of 2019 the 7th International Conference on Smart Energy Grid Engineering SEGE 2019*, 2019.
8. Y. Khayat et al., "On the Secondary Control Architectures of AC Microgrids: An Overview", *IEEE Transactions on Power Electronics*, vol. 35, no. 6, pp. 6482-6500, Jun. 2020.
9. S. Boyd and L. Vandenberghe, Convex Optimization., Cambridge University Press, 2004.
10. A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system", *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1963-1976, 2012.
11. T. Strasser et al., "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems", *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2424-2438, Apr. 2015.