# Supervisory Control for Real Time Reactive Power Flow Optimization in Islanded Microgrids

Milczarek, Adam; Vasquez, Juan Carlos; Malinowski, Mariusz; Guerrero, Josep M.; Graells, Moises

*Published in:*
Proceedings of the 23rd European Symposium on Computer Aided Process Engineering, ESCAPE

*DOI (link to publication from Publisher):*
10.1016/B978-0-444-63234-0.50055-5
10.1016/B978-0-444-63234-0.50055-5

*Publication date:*
2013

*Document Version*
Early version, also known as pre-print

Andrzej Kraslawski and Ilkka Turunen (Editors) Proceedings of the 23rd European Symposium on Computer Aided Process Engineering – ESCAPE 23 June 9-12, 2013, Lappeenranta, Finland,


# Supervisory Control for Real Time Reactive Power Flow Optimization in Islanded Microgrids

Adam Milczarek,[a] Juan C. Vasquez,[b] Mariusz Malinowski,[a] Josep M. Guerrero,[b] Moisès Graells[c]

[a] *Warsaw University of Technology, Institute of Control and Industrial Electronics Koszykowa 75, 00-662 Warsaw, Poland*
[b] *Aalborg University, Institute of Energy Technology, Pontoppidanstraede 101, DK-9220 Aalborg East, Denmark*
[c] *Universitat Politècnica de Catalunya Department of Chemical Engineering EUETIB, Comte d'Urgell, 187, 08036-Barcelona, Spain*

## Abstract

A microgrid (MG) is a local energy system consisting of a number of energy sources, energy storage units and loads that operate connected to the main electrical grid or autonomously. MGs include wind, solar or other renewable energy sources. MGs provide flexibility, reduce the main electricity grid dependence and contribute to change the large centralized production paradigm to local and distributed generation. However, such energy systems require complex management, advanced control and optimization. Interest on MGs hierarchical control has increased due to the availability of cheap on-line measurements. Similarly to any process system, MG hierarchical control is divided into three levels. However, an additional control algorithm is required to manage power transmission between sources and loads, maximizing efficiency and minimizing transmission losses. This real-time optimization problem is addressed to locally readjust converters operation to attain global efficiency.
An algorithm is presented by formulating and solving the power sharing optimization problem in a two-level approach. The objective function is the sum of the apparent power transferred, whose minimization reduces total power losses and energy costs. The performance of the approach proposed is validated on a simulated case study. Different scenarios are tested and the performance of the algorithm is compared and discussed. The power losses reduction obtained with the proposed approach are compared with those obtained by standard procedures (Equal Power Sharing - EPS), showing enhanced performance.

**Keywords**: real time optimization, supervisory control, energy systems, microgrid.

**Symbols**: *k* – converter number; *P[K]* – *K*-elements vector of active powers; $P_k$ - active power of *k* converter; *P1,Q1, P2, Q2, PL2, QL2* – auxilary parameters to total active and reactive power calculations in otpimization algorithm; *PL* – total load active power; *PLs* – sum of acitve powers for limited converters; $Ps_k$, $Qs_k$ – auxilary parameters for real-time optimization algorithm; $S_k$ – apparent power of *k* converter; *SN[K]* - *K*-elements vector of apparent powers; $SN_k$ – nominal apparent power of *k* converter; $Q_k$ - reactive power of *k* converter; *QL* – total reactive power; *QLine* – total line reactive power losses; *QLoad* – total load reactive power; *QLs* – sum of reactive power for limited converters; *QLnew* – sum of calculated total reactive power in optimization algorithm; $Qmax_k$ – maximum reactive power for converter; $Qopt_k$ – optimal reactive power for converter in unconstrained case; *Qref[K]* – *K*-elements vector of calculated optimal reactive powers; $Qref_k$ – calculated reactive power for $k$ converter; $\Delta Q_k$ – difference between optimal reactive power in unconstrained case and optimal reactive power in constrained case for $k$ converter.

## 1. Introduction

Currently, real-time optimization algorithms (RTO) for many industrial applications have become increasingly accepted. The basic limitation of traditional RTO is a steady-state wait time, regardless of the degree of rigor used [1]. Unfortunately, shorter optimization times may be required. Control algorithms have to be fast, with high dynamic response. Thus, a global solution approach is using many control units in a distributed system, and executing many partial optimization runs at the same time within a hierarchical multilevel control system (e.g. according to ANSI/ISA-95 or ISA-95 standard). In this solution each level provides supervisory control for lower-level systems [2]. The optimization algorithm can be split into two, three or more levels, in order to speed up online calculations.

This work proposes a new on-line optimization approach, divided between primary and secondary control levels. It has been applied for reactive power flow optimization in distributed generation systems such as islanded microgrids (MG), which require fast solution for the dynamic changes of the system parameters.

### *1.1. Islanded microgrid – reactive power sharing*

MGs are becoming more important since they can manage energy generation, storage and demand as well as reduce dependence on the main grid for local customers. Islanded MG is a distributed generation (DG) system working autonomously at low voltage (< 1kV), independently of the main electricity grid. MGs performance is specified according to IEEE 1547.4. Islanded MGs are complex systems requiring advanced control and optimization strategies to manage power transmission between source and loads, and efficiently minimize transmission losses. The most popular solution is a hierarchical control, which is usually divided into three levels [3]:

- primary control (level 1): droop control and virtual impedances,
- secondary control (level 2): adjustment of frequency and amplitudes as well as improvement of power quality in the microgrid,
- tertiary control (level 3): adjustment of power flow between the MG and the main electricity grid.

The primary control is autonomous, allowing DG units to work independently. On the other hand, secondary and tertiary controls are placed in the MG central controller and needs communications infrastructure. Depending on the energy source and converter type, active power is fixed by the maximum power point, so active power sharing is not so interesting for that kind of applications. The main problem is reactive power injected or absorbed by the DG, which is limited and depends on nominal apparent power and the active power delivered by each DG unit. Energy converters are interfaces between energy sources and the local or main grid. They allow to set voltage and current parameters, indirect cause of active and reactive power flow control. For each converter $k$ (power supply), active ($P_k$), reactive ($Q_k$) and apparent power ($S_k$) are related by:

$$S_k^2 = P_k^2 + Q_k^2 \tag{1}$$

The problem is voltage drop and power losses in the transmission local line. Energy sources may be 2-5 km away from local loads and transmission losses cannot be neglected [4].

## 2. Supervisory control - real-time optimization algorithm

For the optimal reactive power sharing, the objective function to be minimized is established as the sum of apparent power $S_k$, transferred from all supplies to loads:

$$min \sum_{k=1}^{K} S_k = \sum_{k=1}^{K} \sqrt{P_k^2 + Q_k^2} \tag{3}$$

Given the set of $P_k$ to be met, the set of control variables $Qref_k$ have to be obtained (set-points). The constraints are total reactive power produced, which has to be equal to total load reactive power, including line impedances:

$$\sum_{k=1}^{I} Qref_k = QLoad + QLine = QL \tag{4}$$

and apparent power $S_k$ cannot exceed its nominal apparent power $SN_k$ :

$$S_k \leq SN_k \quad \forall k \tag{5}$$

The optimization problem this way formulated can be solved by the assignment algorithm proposed (fig. 1), whose graphical interpretation is given later on (section 3).

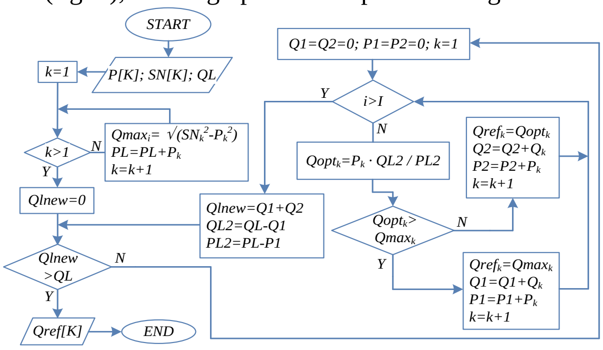


Fig. 1. Block scheme of algorithm for optimal reactive power sharing.

In first step the algorithm calculates a maximum value of reactive power for each converter $Qmax_k$ (basic on eq. 1 and ineq. 5). After that as long as auxilary parameter $Qlnew$ is smaller than $QL$ the optimal solution for all converters is calculating as it is shown on fig. 1. The basic equation for optimal reactive power calculations is described as:

$$Qopt_k = P_k \frac{QL}{PL} \tag{6}$$

Usual calculations in microcontroller have to be executed in less than 0.5 ms, depending on the switching frequency of the converters (microcontroller interruptions) and the applications. To use this algorithm on-line, its implementation is split between primary and secondary control levels (fig. 2). First, $Qopt_k$ is calculated (eq. 6) as the optimal solution for the unconstrained case ($SN_k \rightarrow \infty$, $\forall k$), as well as reactive power limit for converter $Qmax_k$ (eq. 7). Simultaneously, the secondary control module (common for all the MG) calculates four parameters ($PL$, $QL$, $PLs$, $QLs$), as a sum of input signals, ensuring the fulfillment of the first of constraint (4). The calculation process is very fast, even with transmission delay. In a second step, in the primary control module checks the second constraint (eq. 5), and calculates auxiliary parameters $Ps_k$ and $Qs_k$ (eqns. 8-9). Finally, the optimal values $Qref_k$ (eq. 11) are given by the sum of unconstrained optimal values $Qf_k$ and $\Delta Q_k$ (eq.10), thus taking into account all constraints.

$$Qmax_k = \sqrt{SN_k^2 - P_k^2} \tag{7}$$

$$Qs_k = \begin{cases} Qref_k & if\ Qref_k = Qmax_k \\ 0 & otherwise \end{cases} \tag{8}$$

$$Ps_k = \begin{cases} P_k & if\ Qref_k = Qmax_k \\ 0 & otherwise \end{cases} \tag{9}$$

$$\Delta Q_k = \begin{cases} \left(\frac{P_k}{PL-PLs} \cdot (QL - QLs) - Qf_k\right) & if\ Qf_k \neq Qs_k \\ 0 & otherwise \end{cases} \tag{10}$$

$$Qref_k = Qf_k + \Delta Q_k \tag{11}$$

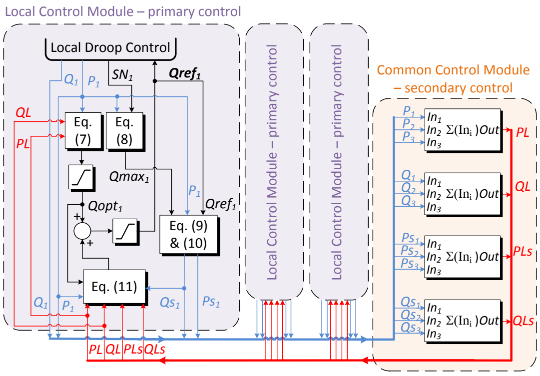


Fig. 2. Block scheme of real-time implementation of reactive power flow optimization algorithm

## 3. Case study

*3.1. Preliminary analysis of optimization algorithm*

An illustrative example of twelve renewable sources is solved in MS Excel-VBA. Two cases are addressed. The first case is the unconstrained situation for which the optimal reactive power values $Qref_k$ are straightforward (eq. 6), while the second includes active constraints for apparent power. The parameters of performed analysis are shown in Table I. Figure 3 plots the results for both cases with the graphical interpretation of the solution. The sum of active and reactive powers on P and Q axis shows the unconstrained optimal solution given by a straight line, while the optimal constrained solution is represented by the broken line made of the feasible segments, which shows the gap between both solutions.

*3.2. Simulation and validation*

*3.2.1. Simulation model description*

The Equal Power Sharing (EPS) [5]- classical control method and the real-time optimization algorithm proposed were implemented in simulation model using Matlab/Simulink. The EPS control method assumes equal distribution of reactive power between converters in MG. Figure 4 shows the topology of MG, where all transmission lines are connected in parallel to common couple point (PCC) with energy loads. Both approaches were compared in five cases: three having different active power and the same nominal apparent power for unconstraint situation, a fourth having different $P_k$ and $SN_k$, and the fifth showing constraint case of MG optimization. The simulations were run for 4-km of low-voltage transmission with appropriate impedances (R=0.642 Ω/km, X=0.083 Ω/km).

Table I Case study of optimal reactive power sharing in preliminary analysis of MG

| | | | Unconstrained case | | | Constrained case | | |
|---|---|---|---|---|---|---|---|---|
| k | $P_k$ | $Qf_k$ | $SN_k$ | $Q_k$ | $S_k$ | $SN_k$ | $Q_k$ | $S_k$ |
| 1 | 1500 | 480 | 5000 | 480 | 1575 | 1800 | 837 | 1718 |
| 2 | 800 | 256 | 2000 | 256 | 840 | 1000 | 447 | 916 |
| 3 | 500 | 160 | 2000 | 160 | 525 | 1000 | 279 | 573 |
| 4 | 2000 | 640 | 4000 | 640 | 2100 | 2100 | 640 | 2100 |
| 5 | 1400 | 448 | 2000 | 448 | 1470 | 1500 | 539 | 1500 |
| 6 | 4000 | 1280 | 10000 | 1280 | 4200 | 4100 | 900 | 4100 |
| 7 | 1000 | 320 | 3000 | 320 | 1050 | 1100 | 458 | 1100 |
| 8 | 6000 | 1920 | 10000 | 1920 | 6300 | 6200 | 1562 | 6200 |
| 9 | 400 | 128 | 1000 | 128 | 420 | 1000 | 223 | 458 |
| 10 | 2400 | 768 | 5000 | 768 | 2520 | 2500 | 700 | 2500 |
| 11 | 1800 | 576 | 5000 | 576 | 1890 | 1900 | 608 | 1900 |
| 12 | 3200 | 1024 | 6000 | 1024 | 3360 | 3300 | 806 | 3300 |
| PL: | 25000 | | QL: | 8000 | | QL: | 8000 | |

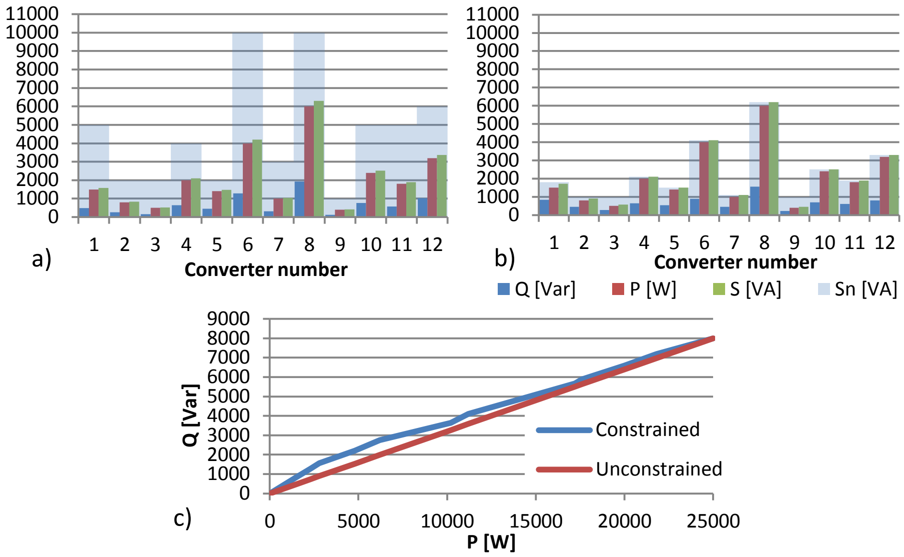


Fig. 3. Reactive power sharing for the illustrative MG case – a) unconstrained b) constrained c) Graphical comparison of unconstrained and constrained cases.

### *3.2.2. Simulation results*

The results of simulation for three converters and two different algorithms were compared, in order to show that the idea of real-time optimization algorithm split between different levels of control is working properly. Moreover, the simulation results show the reducing of transmission power losses, as it was founded behind. Table II shows transmission power losses for all converters and compare it. Notice that power losses are reduced even 16-17% for optimized algorithm.

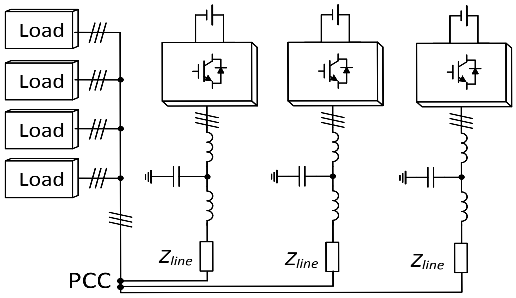


Fig. 4. Block scheme of MG with parallel transmission lines

Table II. Transmission power loses for and reduction of power losses. Results obtained with the proposed approach (OPT) are compared with the standard EPS approach.

| Case No. | | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|---|
| Total transmission power losses in MG [W] | EPS | 23,4 | 175,5 | 451,8 | 28,2 | 206,7 |
| | OPT | 23,1 | 164,7 | 428,4 | 23,4 | 174 |
| Reduction of losses | | 1% | 6% | 5% | 17% | 16% |

## 4. Conclusions

Reactive power sharing in MG has been addressed in order to minimize energy losses in real-time. A novel real-time optimization scheme, split between primary and secondary control levels has been proposed. Using parallel calculations in the primary control units the execution time of the optimization process is reduced and only calculations of global parameters are executed at the secondary level. The validation in a simulated scenario of the approach presented demonstrated a clear reduction of the total power losses with respect standard approaches (EPS), which in turn decreases the cost of energy transfer. These promising results envisage good opportunities for real-time adaptation of energy systems to flexible scenarios

## References

[1] Mark L. Darby, Michael Nikolaou, James Jones, Doug Nicholson, July 2011, RTO: An overview and assessment of current practice. Review Article, Journal of Process Control, Volume 21, Issue 6, Pages 874-884

[2] Josep M. Guerrero, Juan C. Vasquez, Jose Matas, Luis Garcia de Vicuna, Miguel Castilla, January 2011, Hierarchical Control of Droop-Controlled AC and DC Microgrids – A General Approach Toward Standardization, IEEE Transaction on Industrail Electronics, Volume 58, No. 1, Pages 158 - 172

[3] Juan C. Vasquez , Josep M. Guerrero, Jaume Miret, Miguel Castilla, Luis Garcia de Vicuna, December 2010, Hierarchical Control of Intelligent Microgrids, IEEE Industrial Electronics Magazine, Volume 4, No. 4, Pages 23 – 29

[4] C. Marinescu, A. Deaconu, E. Ciurea, Daniela Marinescu, May 2010, From Microgrids to Smart Grids: Modeling and Simulation using Graphs. Part II Optimization of Reactive Power Flow, 12th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), Pages 1251 - 1256

[5] A. Micallef, M. Apap and C. Spiteri Staines, J.M. Guerrero Zapata, Secondary Control for Reactive Power Sharing and Voltage Amplitude Restoration in Droop-Controlled Islanded MicroGrids, 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG) 2012, Pages 492 - 498