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*Published in:*
Proceedings of 2014 AEIT Annual Conference - From Research to Industry: The Need for a More Effective Technology Transfer

*DOI (link to publication from Publisher):*
10.1109/AEIT.2014.7002028

*Publication date:*
2014

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

Link to publication from Aalborg University

*Citation for published version (APA):*
Quang, N. N., Sanseverino, E. R., Di Silvestre, M. L., Madonia, A., Li, C., & Guerrero, J. M. (2014). Optimal power flow based on glow worm-swarm optimization for three-phase islanded microgrids. In *Proceedings of 2014 AEIT Annual Conference - From Research to Industry: The Need for a More Effective Technology Transfer* (pp. 1-6). IEEE Press. https://doi.org/10.1109/AEIT.2014.7002028

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# Optimal Power Flow based on Glow Worm-Swarm Optimization for Three-Phase Islanded Microgrids

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***Abstract*—This paper presents an application of the Glow-worm Swarm Optimization method (GSO) to solve the optimal power flow problem in three-phase islanded microgrids equipped with power electronics dc-ac inverter interfaced distributed generation units. In this system, the power injected by the distributed generation units and the droop control parameters are considered as variables to be adjusted by a superior level control. Two case studies with different optimized parameters have been carried out on a 6-bus test system. The obtained results showed the effectiveness of the proposed approach and overcomes the problem of OPF in islanded microgrids showing loads unbalance.**

***Index Terms*— Optimal power flow, three phase systems, islanded microgrid, glow-worm swarm optimization**

## I. Introduction

MICROGRIDS, that are low or medium voltage autonomous systems integrating large amount of Renewable Energy, to be operated in islanded mode require a hierarchical control architecture [1]. Such architecture is composed of three levels, the highest of which is called tertiary control provides functionalities such as real and reactive power dispatching, voltage regulation, contingency analysis, expandability, or reconfiguration, among others. Optimal power dispatching in particular must account for frequency and voltage dependency of generation and consumption units, especially in islanded mode operation. Indeed the optimized operating point of all sources strongly depends on these features whose values else than providing a minimum losses operating point, should also not overcome the rated ranges of variations. Therefore, the solution of three-phase Optimal Power Flow in islanded distribution systems is needed. The formulation of the problem accounts for the presence of inverter interfaced units with control laws specifically designed to compensate voltage and frequency deviations when sudden load variations occur. Power flow calculation in three-phase balanced and unbalanced islanded microgrids systems is concerned and studied recently. The work appearing in [2] proposes a model that reflects the important features of islanded power network operation. However this model can only be applied in three phase balanced power systems. A generalized three-phase power flow algorithm using a trust-region method to solve balanced and unbalanced three phase islanded microgrids is proposed in [3]. The authors in [4] use a Matlab solver (*fsolve*) function to calculate power flow in three-phase balanced and unbalanced islanded microgrids.

Optimal operation of electrical systems has been researched intensively in the last decades. Many optimization techiques have been used, such as “the steepest descent” method [5], particle swarm optimization (PSO) method [6], [7], fuzzy logic [8], [9], dynamic programming [10], semi-definite programming [11], globally optimization [16], [17], and so forth. Optimization methods have been progressively improved and applied in power flow problems on three-phase balanced [12], [13] and unbalanced systems [14]. In addition, optimization problems have been solved in for energy storage systems, which are critical in islanded microgrid systems [10], [18-23].

In the above mentioned research works, optimal power flow of three-phase balanced and unbalanced systems is usually applied on high voltage electrical systems or medium voltage microgrids, while the constraint variables are the generators injected real power. However, to the best knowledge of the authors, there is no paper concerning optimization power flow on islanded microgrids where generated and consumption powers depends on frequency and voltage levels. In these kind of systems no generator unit can be physically considered a slack bus, and reactive power management must also be considered as a variable to be controlled.

In this paper, a comprehensive optimal power flow formulation taking into account both active power-to-frequency and reactive power-to-voltage droop parameters is

considered. Since the problem cannot be solved in closed form using analytical methods, the problem is dealt with using a recent heuristic strategy, the Glow-worm Swarm Optimization (GSO) algorithm.

A number of tests have been done on 6-bus islanded microgrid systems in order to show the feasibility of the proposed technique.

## II. Power Stage Modeling of 3 phase Islanded Microgrid

In this Section, a comprehensive model of a three phase islanded microgrid system oriented to study unbalances is presented. The general model encompasses power lines, loads, generators, including their control loops such as droop characteristics and virtual impedance loops.

### A. Lines modeling

Line modeling [3] in this study is based on the dependency on frequency of the lines reactances.

Carson's equations are used for a three phase grounded four wire system. With a grid that is well grounded, reactance between the neutral potentials and the ground is assumed to be zero. The impedance matrix required to model the electromagnetic couplings between conductors and the ground, assumes the following form:

$$\left[Z_{ij}^{abcn}(f)\right] = \begin{bmatrix} Z_{ij}^{aa} & Z_{ij}^{ab} & Z_{ij}^{ac} & Z_{ij}^{an} \\ Z_{ij}^{ba} & Z_{ij}^{bb} & Z_{ij}^{bc} & Z_{ij}^{bn} \\ Z_{ij}^{ca} & Z_{ij}^{cb} & Z_{ij}^{cc} & Z_{ij}^{cn} \\ Z_{ij}^{na} & Z_{ij}^{nb} & Z_{ij}^{nc} & Z_{ij}^{nn} \end{bmatrix} \quad (1)$$

Kron's reduction [24] is applied to (1), and the line model including the effects of the neutral or ground wire and the impacts of the frequency in unbalanced systems can be attained:

$$\left[Z_{ij}^{abc}\right] = \begin{bmatrix} Z_{ij}^{aa-n} & Z_{ij}^{ab-n} & Z_{ij}^{ac-n} \\ Z_{ij}^{ba-n} & Z_{ij}^{bb-n} & Z_{ij}^{bc-n} \\ Z_{ij}^{ca-n} & Z_{ij}^{cb-n} & Z_{ij}^{cc-n} \end{bmatrix} \quad (2)$$

### B. Load modeling

The frequency and voltage dependency of the power supplied to the loads can be represented as follows:

$$P_{Li} = P_{0i}|V_i|^{\alpha}\left(1 + K_{pf}\Delta f\right) \quad (3)$$

$$Q_{Li} = Q_{0i}|V_i|^{\beta}(1 + K_{qf}\Delta f) \quad (4)$$

where $P_{0i}$ and $Q_{0i}$ are the rated real and reactive power operating points respectively; $\alpha$ and $\beta$ are the real and reactive power exponents. The values of $\alpha$ and $\beta$ for these kinds of loads are given in [25]. $\Delta f$ is the frequency deviation $(f\text{-}f_0)$; $K_{pf}$ ranges from 0 to 3.0, and $K_{qf}$ ranges from -2.0 to 0 [26].

### C. Distributed Generators modeling

The three phase injected real and reactive power from a Distributed Generator, DG, units with droop inverter interfaced generation can be expressed in the following equations:

$$P_{Gi} = -K_{Gi}(f - f_{0i}) \quad (5)$$

$$Q_{Gi} = -K_{di}(|V_i| - V_{0i}) \quad (6)$$

In these equations, the coefficients $K_{Gi}$ and $K_{di}$ as well as $V_{0i}$ and $f_{0i}$ characterize the droop regulators of distributed generators. The other generators that do not perform droop regulation are modeled as PQ buses.

### D. Mathematical model with virtual impedance

The mathematic model of our proposed power flow analysis can be obtained as follows:

$$\begin{cases} f_{0i} - f_{og} - K_{Pi}P_{Gi} + K_{Pg}P_{Gg} = 0 \\ |V_{G0i}| - \left|V_{Droopi}\right| - K_{Qi}Q_{Gi} = 0 \\ P_{Gi} - P_{Li} - P_i = 0 \\ Q_{Gi} - Q_{Li} - Q_i = 0 \end{cases} \quad (7)$$

where $V_{Droopi}$ is the voltage at $V_{Droop}$ bus $i$

## III. Optimal Power Flow Calculation

The Optimal Power Flow in this paper is carried out to minimize power losses by the MicroGrid Central Controller, MGCC in Fig. 1. The aim of this work is to find an efficient optimization method in order to devise new droop parameters for primary regulation and replace the secondary regulation level by finding an iso-frequency working condition for all units within admissible ranges. The results of the computations are sent to the individual inverter interfaced units, these being the optimized operating point and the optimized droop parameters, together with the unified working frequency.

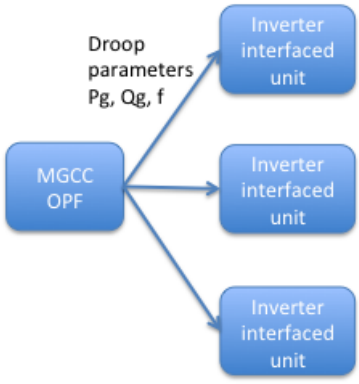


Fig. 1. The 6_bus test system.

It has been shown in [4] that the power losses term is of course connected to the droop parameters values and thus such choice influences the steady state operation of the microgrids. Moreover sharing power among units so as to get a minimum loss operation will lead also to stable operation as proved in [27].

### A. Variables

In this paper, the considered variables, both for P-f droop generation units and for Q-V droop generation units, are the parameters of inverter interfaced units $K_G$ and $K_d$

$$K_G = \left(K_{G1}, K_{G2} \dots, K_{Gn_{gr}}\right) \quad (8)$$

$$K_d = \left(K_{d1}, K_{d2} \dots, K_{dn_{gr}}\right) \quad (9)$$

where $n_{gr}$ is the number of generators.

### B. Objective functions (OF)

Let $P_i$ denote the calculated three phase real power injected into the microgrid at bus *i*. The formulation to calculate $P_i$ can be expressed, as follow:

$$P_{i(Kg,Kd)} = \sum_{j=1}^{n_{br}} |V_i||V_j||Y_{ij}| cos\left(\theta_{ij} - \delta_i + \delta_j\right) \quad (10)$$

where:

$V_i$ and $V_j$ are the voltages at bus $i$ and bus $j$, depending on $Kg$ and $Kd$ at droop buses.

$\delta_i$ and $\delta_j$ are the phase angles of the voltages at bus $i$ and bus $j$, depending on $Kg$ and $Kd$ at droop buses.

$Y_{ij}$ is the admittance of branch $ij$

$\theta_{ij}$ is the phase angle of $Y_{ij}$

$n_{br}$ is the number of branch connected into bus $i$

So the total real power loss of the system or OF for three phases balanced system can be calculated as follow:

$$O_{1(Kg,Kd)} = P_{Loss} = \sum_{i=1}^{n_{bus}} \left(P_{i(Kg,Kd)}\right) \quad (11)$$

where $n_{bus}$ is the number of bus in system.

### C. Constraints

The optimal dispatch problem is thus that to find the set of droop parameters ($K_{Gi}$) and ($K_{di}$) and relevant operating frequency and bus voltages minimizing the function expressed in (9), subject to the constraint that generation should equal total demands plus losses

$$\sum_{i=1}^{n_{gr}} P_{Gri} = \sum_{i=1}^{n_d} P_{Li} + P_{Loss} \quad (12)$$

where $P_{Gri}$ is the real power of generator *i*; $P_{Li}$ is the real power of load bus *i* and $n_d$ is the number of load bus.

Satisfying the inequality constraints, expressed as follows:

$$K_{Gimin} \leq K_{Gi} \leq K_{Gimax}, i = 1 \text{ to } n_{gr} \quad (13)$$

$$K_{dimin} \leq K_{di} \leq K_{dimax}, i = 1 \text{ to } n_{gr} \quad (14)$$

### D. Proposed method

From (11) we can see that the OF is highly nonlinear because the variables ($K_G$ and $K_d$) do not appear in the equation. So we could not use classical optimization methods, such as Lagrange or linear programming in this case.

When OF is highly nonlinear, the search space is typically multimodal. With Complex nonlinear models, we typically do not know if the model is multimodal (i.e. has many local minima) or unimodal. Hence to analyze a complex model we need to search for a global minimum even if we do not know if it is multimodal. The global optimization capability is important when dealing with complex nonlinear models. In these cases, we need a global optimizer and heuristics can be a good choice.

Glow-worm Swarm Optimization (GSO) [28] is a relatively recent heuristics method. In GSO, agents are initially randomly deployed in the objective function space. Each agent in the swarm decides its direction of movement by the strength of the signal picked up from its neighbors. This is somewhat similar to the luciferin induced glow of a glowworm which is used to attract mates or prey. The brighter the glow, the more is the attraction. Therefore, we use the glowworm metaphor to represent the underlying principles of this optimization approach. Pseudocode of the GSO algorithm is shown in Fig. 2.

*Initialize Archive A*
  *Repeat Until* ***Termination Condition***
    *Do m times*
      *Step 1: deterministic* ***choice (selection)*** *of the base vector*
      *Step 2: probabilistic* ***choice (selection)*** *of the target vector (Roulette Wheel technique based on l(t))*
      *Step 3:* ***recombination***
    *END m*
    *Step 4: create* ***new population (replace A)***
  *END*
***A= archive***
***m=archive size***

Fig. 2. Pseudocode of the GSO algorithm.

One issue we usually face when applying GSO is Termination Condition. It is difficult to know if the result we get is the best solution. To resolve this issue, we can previously give a number of iterations (*n*) as Termination Condition. And *n* can be increased until we get the results with no more improvements or negligible improvements.

## IV. Applications

### A. Optimizing Kgs on a 6_bus balanced test system

An application of GSO Heuristic method, optimizing Kgs is done in this section on a 6_bus three phase balanced system (Fig. 3). The features of the system and the limits of Kgs are shown in Table I, II, III of appendix, respectively. In this case, the Kd parameters cannot be optimized and the values are reported in the table sabove, while the reactive powers injections are derived from the linear control law of the droop regulators.

The results of GSO method are shown in Table I.

TABLE I - RESULT OF OPTIMAL LOAD FLOW ON 6_BUS SYSTEM BY GSO HEURISTIC METHOD TAKING INTO ACCOUNT KGS, PU

| Random | KG1 | KG2 | KG3 | Plossmin | f |
|---|---|---|---|---|---|
| 1 | 17.8094 | 8.5080 | 21.2252 | 0.0178565 | 1.0507 |
| 2 | 18.0566 | 8.5681 | 21.5628 | 0.0178565 | 1.0509 |

### B. An application taking into account both KGs and Kds on 6_bus balanced test system

In this section, an application of GSO Heuristic method, taking into account both KGs and Kds, is shown on 6_bus test system. The parameters of 6_bus test system are shown in Table IV and V of appendix. The limits of KGs, Kds are

shown in Table II. The results after 2 random cases are shown in Table VI of appendix.

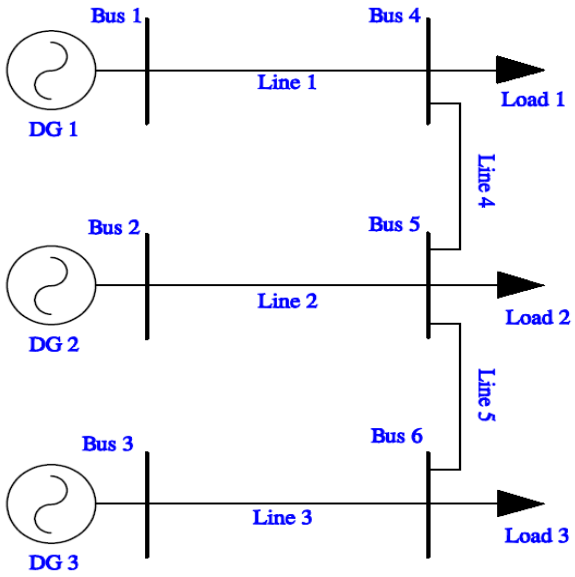


Fig. 3. The 6_bus test system

TABLE II. LIMIT OF KGS AND KDS ON 6_BUS BALANCED TEST SYSTEM TAKING INTO ACCOUNT KGS AND KDS, PU

| Generators | KGmin | KGmax | Kdmin | Kdmax |
|---|---|---|---|---|
| G1 | 6 | 18 | 6 | 18 |
| G2 | 3 | 10 | 3 | 10 |
| G3 | 6 | 18 | 6 | 18 |

The results obtained with the GSO in both cases are expressed as average and it is a very stable value as zero deviation was observed over a sample of 10 runs. So the results of the heuristic for this problem could be considered reliable and repeatable. Nonetheless, the sets of parameters attained are different. This means that the OF is multimodal and there are some local maxima at the close values.

## V. CONCLUSIONS

This paper introduces an application of Glow-worm Swarm Optimization method (GSO) to solve the issue of Optimal Power Flow in three-phase islanded microgrids with inverter interfaced units. Both of KGs (the P-f droops parameters) and Kds (the Q-V droops parameters) in the droop controllers are taken into account as variables. Some tests are executed on 6_bus balanced systems to prove the efficiency of the proposed approach.

Further research will be oriented towards the implementation of the same approach for unbalanced distribution systems, since the conclusions that have been drawn can be generalized.

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# APPENDIX

TABLE I. BUS DATAS OF 6_BUS BALANCED TEST SYSTEM, TAKING INTO ACCOUNT KGS

| Bus number | Type generator | Load, pu | | Generator, pu | | | Exponent of Loads | |
|---|---|---|---|---|---|---|---|---|
| | | P | Q | Kdi | VG0i | f0i/pu | Alpha | Beta |
| 1 | Droop | 0.000000000 | 0.000000000 | 5 | 1.07 | 1.07 | 0 | 0 |
| 2 | Droop | 0.000000000 | 0.000000000 | 5 | 1.07 | 1.07 | 0 | 0 |
| 3 | Droop | 0.000000000 | 0.000000000 | 5 | 1.07 | 1.07 | 0 | 0 |
| 4 | | 0.529334489 | 0.350297754 | | 0.00 | 1.00 | 2.00 | 2.00 |
| 5 | | 0.000000000 | 0.000000000 | | - | - | - | - |
| 6 | | 0.351794954 | 0.248636718 | | 0.00 | 1.00 | 2.00 | 2.00 |

TABLE II. LINES DATAS OF 6_BUS BALANCED TEST SYSTEM, TAKING INTO ACCOUNT KGS

| Bus nl | Bus nr | R, pu | X, pu |
|---|---|---|---|
| 4 | 5 | 0.08128544 | 0.02266228 |
| 4 | 1 | 0.05671078 | 0.02494276 |
| 5 | 2 | 0.03780718 | 0.01781626 |
| 5 | 6 | 0.02835539 | 0.13134145 |
| 6 | 3 | 0.00945180 | 0.00356325 |

TABLE III. LIMIT OF KGS ON 6_BUS BALANCED TEST SYSTEM, TAKING INTO ACCOUNT KGS

| Generators | KGmin,pu | KGmax,pu |
|---|---|---|
| G1 | 1 | 25 |
| G2 | 1 | 25 |
| G3 | 1 | 25 |

# APPENDIX

TABLE IV. BUS DATAS OF 6_BUS BALANCED TEST SYSTEM, TAKING INTO ACCOUNT KGS AND KDS

| Bus number | Type generator | Load, pu | | Generator, pu | | Exponent of Loads | |
|---|---|---|---|---|---|---|---|
| | | P | Q | VG0i | f0i/pu | Alpha | Beta |
| 1 | Droop | 0.000000000 | 0.000000000 | 0.9877 | 1 | 0 | 0 |
| 2 | Droop | 0.000000000 | 0.000000000 | 0.9877 | 1 | 0 | 0 |
| 3 | Droop | 0.000000000 | 0.000000000 | 0.9877 | 1 | 0 | 0 |
| 4 | | 0.052900000 | 0.000000000 | 0 | 1 | 2 | 2 |
| 5 | | 0.052900000 | 0.000000000 | 0 | 1 | 2 | 2 |
| 6 | | 0.027872043 | 0.026411745 | 0 | 1 | 2 | 2 |

TABLE V. LINES DATAS OF 6_BUS BALANCED TEST SYSTEM, TAKING INTO ACCOUNT KGS AND KDS

| Bus nl | Bus nr | R, pu | X, pu |
|---|---|---|---|
| 4 | 5 | 0.08128544 | 0.02266228 |
| 4 | 1 | 0.05671078 | 0.02494276 |
| 5 | 2 | 0.03780718 | 0.01781626 |
| 5 | 6 | 0.02835539 | 0.13134145 |
| 6 | 3 | 0.00945180 | 0.00356325 |

TABLE VI. RESULT OF OPTIMAL LOAD FLOW ON 6_BUS SYSTEM, TAKING INTO ACCOUNT KGS AND KDS, PU

| Random | KG1 | KG2 | KG3 | Kd1 | Kd2 | Kd3 | Plossmin | f |
|---|---|---|---|---|---|---|---|---|
| 1 | 10.7587 | 9.9105 | 7.89 | 6.0087 | 6.2293 | 17.0326 | 0.0001813 | 0.9954 |
| 2 | 10.6981 | 9.8547 | 7.8456 | 5.9749 | 6.1942 | 16.9367 | 0.0001813 | 0.9954 |