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Sanseverino, Eleonora Riva; T. T. Quynh, T.; Di Silvestre, Maria Luisa ; Zizzo, Gaetano; Quang, Ninh Nguyen; Hernández, Adriana Carolina Luna; Guerrero, Josep M.

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E. Riva Sanseverino, T.T.T. Quynh,
M. L. Di Silvestre and G. Zizzo
Department of Energy Engineering,
Information technology and Mathematical models
University of Palermo, Palermo, Italy
eleonora.rivasanseverino@unipa.it;
thituquynh.tran@unipa.it;
marialuisa.disilvestre@unipa.it; gaetano.zizzo@unipa.it

N.Q. Ninh
Institute of Energy Science, IES
Hanoi, Vietnam
nqninh@ies.vast.vn
A. C. Luna and J.M. Guerrero
Department of Energy Technology, Aalborg University,
Denmark
acl@et.aau.dk

Abstract — **This paper presents a combined optimal energy and power flow management for islanded microgrids. The highest control level in this case will provide a feasible and optimized operating point around the economic optimum. In order to account for both unbalanced and balanced loads, the optimal power flow is carried out using a Glow-worm Swarm Optimizer. The control level is organized into two different sub-levels, the highest of which accounts for minimum cost operation and the lowest one solving the optimal power flow and devising the set points of inverter interfaced generation units and rotating machines with a minimum power loss. A test has been carried out for 6 bus islanded microgrids to show the efficiency and feasibility of the proposed technique.**

Keywords—optimal power flow, glow-worm swarm optimization, microgrid, droop control.

I. INTRODUCTION

Although fossil sources still play a key role in supplying the energy needs of humanity, they are on the road to get exhausted and are largely the main cause of environmental pollution. Therefore, worldwide governments are trying to exploit alternative energy sources. This will not only help to diversify sources of energy but also contribute to diversify risks, strengthen and ensure national energy security.

One way to massively install Renewable Energy Sources, RES, is by means of the microgrids technology. These systems are flexible power distribution networks at small or medium scale. They can operate at low or medium voltage in grid-connected or islanded mode with many different types of power resources including RES and storage systems. In the future, these systems will be developed to take strong advantage of using clean and renewable energy sources. One of the main problems in these systems is to match production and consumption at the different time scales. For this reason, a hierarchical control architecture, in which each level deploys a different function, is usually adopted. The highest control level implements Optimal Power Flow, OPF, and Energy Management at minimum cost and minimum losses.

The latest research carried out optimal energy management in islanded microgrids is based on different methods to find out the minimum cost operation while analyzing the technical and economic time dependent constraints. In most papers, the economic issue is considered in great details [1-5], but only a few cases account for OPF issues such as power loss minimization, branch current limits and voltage drop control. The aim of this paper is to propose a complete control structure which comprises two sub-levels: Energy management and OPF, where not only economic objectives but also technical issues (power loss minimization, voltage, frequency and branch currents limitation) are considered.

The OPF problem is usually dealt with in the Distribution Management System (DMS) to find the optimal operating points in the electric power system in order to achieve the minimum operating costs as well as minimum power losses. The time scale for deploying such function range could last from minutes to tens of minutes. In this way, electricity demands are also met while ensuring security conditions. Therefore, the OPF solution in power systems as well as in microgrids is necessary.

Recently, many study have been done to calculate the OPF in microgrid systems. These studies generally consider the participation of inverter-based devices, which are designed, by means of lower control levels deployed between milliseconds and seconds, to compensate the voltage and frequency deviations.

Some recent research works concern the optimal power flow problem in islanded microgrids. In most cases, approaches rely on numeric solution approaches. In [6, 7], the authors use Newton-Raphson method to solve a set of nonlinear algebraic equation for power network. In [8], the Newton trust-region method is implemented to consider some case studies for both balanced and unbalanced microgrid test systems. Matlab's *fsolve* function has been used in [9] to calculate the power flow in three-phase balanced and unbalanced microgrids and supports the OPF solution based on an iterative strategy for non-linear optimization. Based on a quasi-Newton method, [10] also describes a methodology for unbalanced three-phase OPF for smart grid. But these solution approaches do not efficiently account for constraints.

Meanwhile, the heuristic solution approaches can overcome the weaknesses of the numeric solutions. In [11], a novel load flow analysis (LFA) and Particle Swarm Optimization are used to optimize the power sharing among

sources in a microgrid. In another research [12], a fuzzy based Modified Artificial Bee Colony (MABC) algorithm is presented for solving the OPF problem. Recently, an Adaptive Multi Objective Harmony Search Algorithm is used in [13] to decrease power losses and improve load ability in islanded microgrids. In [14, 15], the Glow-worm Swarm Optimization method is implemented to solve the OPF problem accounting for frequency [15] and line impedance constraints of the system [14,15]. Also some works focus on energy storage systems management [16,17] which are critical for energy and power balance.

All these studies above do not account for the economic and technical problems at the same time. In order to account for both issues, in this paper the control structure is divided into 2 sub-levels considering the economic and technical constraints more comprehensively, strengthening the security and stability of energy power system. The authors use the Energy Management System's output to define the variables boundaries to run the Optimal Power Flow. The latter is executed to account for perfect matching between generation and consumption also accounting for frequency and voltage constraints by GSO technique. The optimized power set points of generators are found around the given economic set point on an hour by hour basis. The new set points still keep frequency within required boundaries, voltage drops below given threshold and branch currents below ampacities. A test has been carried out for 6 bus islanded microgrid to show the efficiency and feasibility of the proposed two level technique.

II. PROBLEM FORMULATION

In this problem, a new layer in hierarchical microgrids control structure is proposed, including two different sub-levels: the energy management (EM) and optimal power flow (OPF). The organization of the new layer is shown in Fig. 1 below [5]:
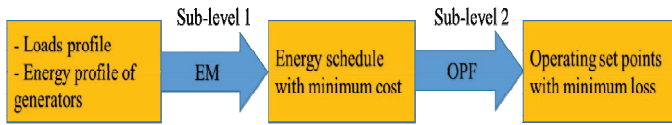

Fig. 1. Control levels for microgrids

- The first sub-level provides a feasible and minimum cost operating point.

- The second sub-level solves the optimal power flow, devising the set points of inverter interfaced generation units and rotating machines with a minimum power loss in a point which is nearby the minimum cost optimum.

The element time interval for scheduling is 15 minutes or one hour. In this case, the paper assumes a time slot (h) of one hour. The solution method used by the Energy Management sub-level relies on a Linear Programming approach.

A. Energy Management sub-level

In this sub-level, the cost of energy supplied by the j unit can described by the following equation:

$$Cost = \sum_{j=1}^{n_{G1}} \sum_{h=1}^{24} (C_{G1\_j} . E_{G1\_j}(h)) + \sum_{j=1}^{n_{G2}} \sum_{h=1}^{24} (C_{G2\_j} . E_{G1\_j}(h)) \qquad (1)$$
$$+ \sum_{j=1}^{n_{G3}} \sum_{h=1}^{24} (C_{G3\_j} . E_{G1\_j}(h))$$

Where C_{G1_j}, C_{G2_j}, C_{G3_j} are the unitary cost energy supplied at each time slot h by the j unit of type 1- the generator providing base load with slow ramping times, type 2 – the generator providing the regulation service with fast ramping time and type 3- the generator providing both services, respectively; E_{G1_j}, E_{G2_j}, E_{G3_j} are the generated energy at each time slot h by the j generator of type 1, type 2 and type 3, correspondingly.

This problem is subjected to constraints about energy balance between loads and generation and the constraints on the power supplied by different kinds of generators.

To solve problem in this sub-level, the Mixed Integer Linear Programming is used, the model is implemented in The General Algebraic Modeling System (GAMS). The results of problem are the range of variation of the generation units in 24 hours.

B. Optimal Power Flow sub-level

The power generated from DG unit with droop inverter interfaced generation can be expressed by the following equations:

$$P_{Gi} = - K_{Gi}(f - f_{0i}) \qquad (2)$$
$$Q_{Gi} = - K_{di}(|V_i| - V_{0i}) \qquad (3)$$

Where:

K_{Gi} and K_{di} are optimization variables of inverter interfaced units. V_{0i} and f_{0i} are rated values of voltage and frequency.

The generic power injection at bus i can be expressed by the function below:

$$P_{i(K_G,K_d)}(h) = \sum_{j=1}^{n_{br}} |V_{i\_h}||V_{j\_h}||Y_{ij}|\cos(\theta_{ij\_h} - \delta_{i\_h} + \delta_{j\_h}) \qquad (4)$$

Where:

V_{i_h} and V_{j_h} are the voltages at buses i and bus *j*, depending on K_d and K_G at droop buses.

δ_{i_h} and δ_{j_h} are the phase angles of the voltages at bus i and bus *j*, depending on K_d and K_g at droop buses.

Y_{ij} is the admittance of branch ij

θ_{ij} is the phase angle of Y_{ij}

n_{br} is the number of branches connected to bus i

K_G is optimization variable which are the parameters of inverter interfaced units. It is a coefficient in the linear function generated real powers and frequency.

Then, the total real power loss of the system or OF for a three-phase system can be calculated as follows:

$$OF_{(K_G,K_d)}(h) = P_{\text{Loss}}(h) = \sum_{i=1}^{n_{\text{bus}}} P_{i(K_G,K_d)}(h) \qquad (5)$$

Where n_{bus} is the number of buses in the system.

The above funtions must satisfy the equality constraints about the balance between generated power and total demands plus losses in the system and inequalty constraints about admissible ranges of K_G, admissible range of variation of the frequency Δf, and current in every branch below $I_{\text{branch\_i}}$:

$$K_{Gmini} \leq K_{Gi} \leq K_{Gmaxi}, \, i=1 \text{ to } n_g \qquad (6)$$

$$\Delta f = f_0 - f \leq 0.02 \qquad (7)$$

$$I_{\text{branch\_i}} \leq I_{\text{maxbranch\_i}}, \, i=1 \text{ to } n_{br} \qquad (8)$$

$$V_{imin} \leq V_i \leq V_{imax} \qquad (9)$$

Where:

K_{Gmini}, K_{Gmaxi} are the boundary values of the droop paremeters for P-f droop generators

Δf is the operating frequency deviation

$I_{\text{branch\_i}}$ is the current of branch i-th

$I_{\text{maxbranch\_i}}$ is the maximum curent of branch i-th

n_g is the number of generations.

III. SOLUTION METHOD

The minimization of the OPF is in this paper carried out by means of a heuristic technique. In this paper the Glow-worm Swarm Optimization (GSO) method was chosen, due to its ability to fully explore the search space and find local optima. The GSO is a relatively new heuristic method proposed by K.N. Krishnanad and D. Ghose [18]. In GSO, agents are initially randomly deployed in the objective function space. Each agent in the swarm decides the 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 glow worm which is used to attract mates or prey. The brighter the glow, the more is the attraction. And the best will be chosen as the solution of problem.

In (4), the variable K_G don't appear in the equation but they still have an impact on the results of equation through the components V_i, V_j, δ_i, δ_j. Hence, to solve a complex nonlinear like OF, conventional methods such as Lagrange or Linear programing can't be used. In this case, a global optimizer and heuristic like GSO can be a good solution, even if the problems have unbalanced loads. However, it is difficult to know the result attained at a given iteration is the best solution or not when applying GSO is the choice of the Termination Condition. A number of iterations (n) which is previously given as Termination Condition can be risen until results with no more improvements or negligible improvements are attained.

Pseudocode of GSO algorithm is shown in Fig. 2.

Initialize a population Archive A randomly, population has m glow-worms, m is archive size
*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)) **considering constraints***
  *Step 3: **recombination***
 END m
 *Step 4: create **new population (replace A)***
END.

Fig. 2. Pseudocode of GSO algorithm

IV. CASE STUDY

A test has been carried out for 6 bus islanded microgrids, shown in Fig. 3. DG1 and DG3 are microturbines with power supply capacities of 10kW to 30kW, DG2 comprises a PV generator and a storage system which has generation capacity of 40kWh.
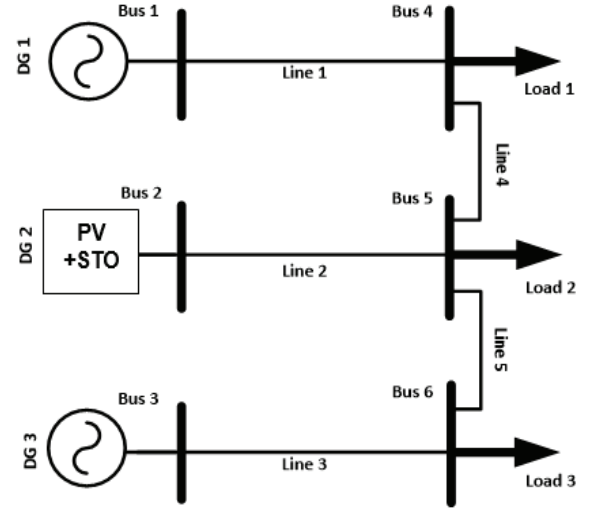

Fig. 3. 6-bus test system

The line data is shown in the below table:

TABLE I. LINE DATA OF 6 BUS TEST SYSTEM

Bus nl	Bus nr	R(pu)	X(pu)	Imax(pu)
4	5	0,08128544	0,022662	0,4
4	1	0,05671078	0,024943	0,5
5	2	0,05671078	0,024943	0,5
5	6	0,08128544	0,022662	0,4
6	3	0,05671078	0,024943	0,5

The results after performing Energy management level every hour from [5] are shown in Fig. 4 and Fig. 5.
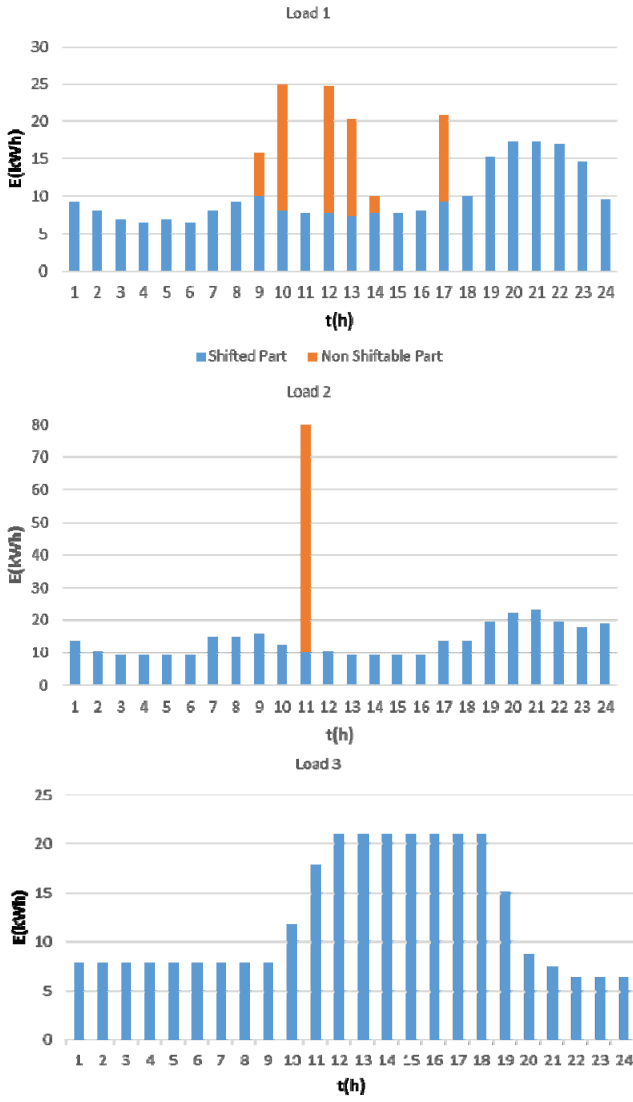
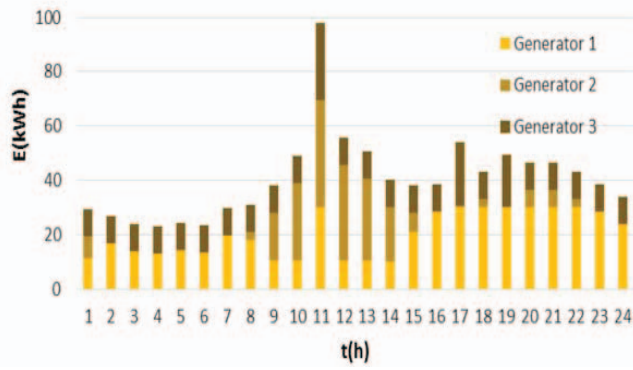Fig. 4. Scheduling of loads after performing Energy management level

Fig. 5. Scheduling of the energy generated by generation units after performing Energy management level

The variables of the OPF are determined based on the following points of economic operating:

TABLE II.   THE SCHEDULED ENERGY GENERATIONS FROM ENERGY MANAGEMENT LEVEL

Time	E1(kWh)	E2(kWh)	E3(kWh)
1	11,2261	8,0000	10,0000
2	16,6547	0,0000	10,0000
3	14,0833	0,0000	10,0000
4	13,0547	0,0000	10,0000
5	14,2975	0,0000	10,0000
6	13,3119	0,0000	10,0000
7	19,6547	0,0000	10,0000
8	18,0588	2,9531	10,0000
9	10,7392	17,5583	10,0000
10	10,5992	28,3889	10,0000
11	30,0000	46,6728	28,3772
12	10,4141	35,2954	10,0000
13	10,5542	30,1483	10,0000
14	10,1256	20,1672	10,0000
15	21,0004	6,9496	10,0000
16	28,4881	0,0000	10,0000
17	30,0000	0,7120	23,4641
18	30,0000	3,1309	10,0000
19	30,0000	0,0000	19,4405
20	30,0000	6,6239	10,0000
21	30,0000	6,5000	10,0000
22	30,0000	3,0333	10,0000
23	28,4047	0,0000	10,0000
24	24,0333	0,0000	10,0000

In this case, the OPF will get a new operation set point for DG2 which is an inverter interfaced unit. The range of variation of each of them is assumed 20% greater and 20% smaller than the economic optimum. As an example, at the slot time h=1, $E_{2scheduled}$=8 kWh, the range of variation of DG2 will be from 6,4kWh to 9,6kWh. The PV and storage system is the main regulator. However, this generator has only some hours of work, it generates negligibly electricity power in remaining hours and is not able to provide enough energy for regulation. To meet the requirements of the balance between the power of generation and total demands plus losses, the OPF will also get a new operation set point for DG1 and DG3 with the smaller range of variation compared to the main controller generation DG2, within 10% around the economic optimum point. And these variations must also satisfy the power supply capacities of all generations above. Example, at the slot time h=12, $E_{2scheduled}$ = 35,29kWh, the range of variation of DG2 will be from 28,24kWh to 42,35kWh, but the generation capacity of DG2 is 40kWh, so the range will be from 28,24kWh to 40kWh. Similar calculations are carried out for the other cases. Another observation concerns the constraint about energy balance in 24 hours concerning the storage and possible uncertainties deriving from the environmental changes as compared to forecasted weather conditions. In this case, the EMS will run again the economic optimum, as a large variation from the solution outputted from the EMS is sensed by the measuring systems. After calculating optimized GSO solution for the OPF problem, the range of variations for all generators is showed in the following figures:
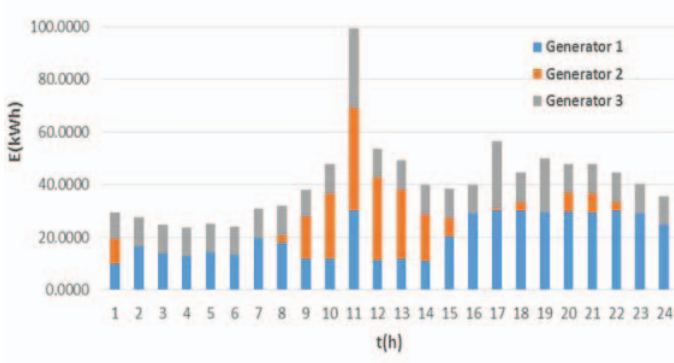
Fig. 6. Scheduling of the energy generated by generation units after performing optimized power flow

The data on Fig. 6 and Fig. 7 illustrate the electricity power which is generated from generation units in each hour of the day. It was found that the power output of generators after the implementation of optimal power flow has not been changed significantly compared to the results of the EMS problem and ensured the economic optimality within technical limit.
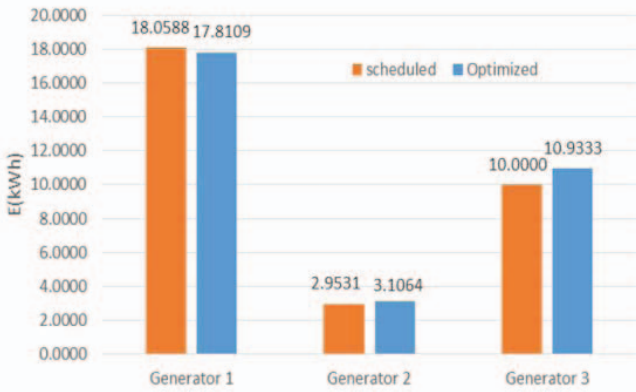

Fig. 7. Comparison of change of the energy generated by generation units after performing optimized power flow

Fig. 8 and Fig. 9 demonstrate the frequency and voltage of the system are still in the permissible limit, while satisfying branches ampacity constraints. At 11 am, the voltage of nodes at this time is lower than in the other times, because this time is a peak hour and the load demand is a lot greater.
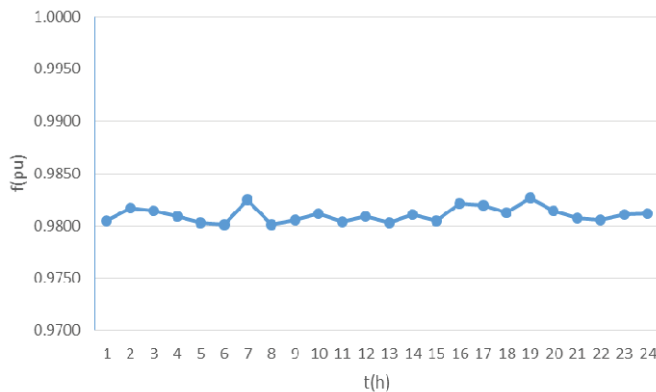

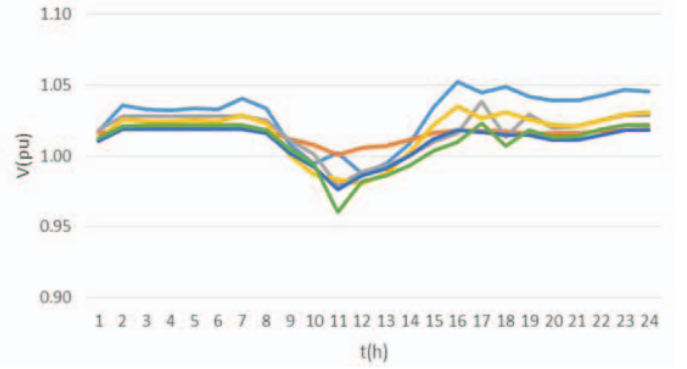Fig. 8. The frequency of system in 24 hours after performing optimized power flow

Fig. 9. The voltage of 6-bus of the system in 24 hours after performing optimized power flow

V. CONCLUSION

In this paper, a mix control level of OPF and EMS has been described and implemented. The problem is to provide a complete two sub-levels architecture for management and control of islanded microgrids. By GSO method, based on the economic set point, the OPF process is performed to find a new feasible and optimized operation point which minimizes production costs and power losses for an islanded microgrid during 24 hours of operation. Branch currents, frequency and bus voltages are kept within bounds. In particular, the methodology is tested on a small system and the result are shown.

Further studies will investigate the possibility to have different generators with different speed of response. In this case, some generators will be considered with constant output power others will be variable and will take part to the OPF because speed of response is higher and can follow loads change or sudden power generation variations. Also, a rolling horizon approach for the whole architecture needs to be considered in order to compensate possible weather changes or loads requests. Finally, the price of electricity from the PV and storage system have not been considered, although for the battery a cost can be considered due to the Dept of discharge issue and the number of operations producing a reduction of their lifetime.

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