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Two-step optimization algorithm for energy management and active-reactive power commands for real-time operation of hybrid microgrids

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Abstract. This paper proposes a two-step optimization algorithm for energy management and optimal control of active-reactive power commands in microgrids. The first step ensures an optimal energy management and provides the active power setpoints for power plants and energy storage. The second step calculates the voltage setpoints for power plants and reactive power flows whilst minimizing power transmission losses. This work focuses on the second step of the algorithm and the framework to combine both. A previous study introduces the first step based on a receding-horizon scheme. It is analysed and discussed the performance of the algorithm against two decentralized methods widely used in the literature. The results show that the proposed algorithm reduces power transmission losses by more than 20% compared to other methods.

Keywords. Microgrid, Reactive Power Sharing, Energy Storage Systems, Energy Management System.

1. Introduction

The growing share of Renewable Energy Sources (RES) for the decarbonization of the energy mix entails the replacement of conventional generation by distributed renewable generation and energy storage, which poses a challenge for traditional operation techniques. In this new scenario, Microgrids (MGs) have emerged as a solution due to their flexibility and proven ability to provide a reliable and resilient power supply.

The National Renewable Energy Laboratory (NREL) defines a microgrid as "a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid" [1], but in the literature a microgrid does not have a well-stablished definition. Many authors often agree that MGs should be able to work isolated, they should integrate RES and, in many cases, Energy Storage Systems (ESS) [2]–[4].

Integrating different generation technologies on islanded conditions requires flexibility and reliability that must be provided by a resilient Energy Management System (EMS). The control must be performed in several control layers (Primary, Secondary and/or Tertiary), with constant communication between the agents of the MG [5], [6].

Different approaches can be found in the literature to coordinate the reactive power sharing [6], [7]. A decentralized control is often considered, which relies on a primary control layer and leads to an inefficient distribution of both active and reactive power among generators [8]. To improve power distribution and frequency/voltage deviations caused by conventional droop primary control schemes, a centralized secondary control could be implemented [9].

Different approaches have been proposed based on centralised optimization techniques but they consider all distributed generation (DG) connected to a single bus bar, avoiding non-linear and non-convex optimization problems [10]. Therefore, power losses are not taken into consideration leading to a suboptimal distribution of active and reactive power in the MG. Other works include RES in the MGs, but do not consider Energy Storage Systems [11], which are very valuable devices in modern energy systems with high penetration of RES [12], [13].

A common constraint on MGs is to assume that they cannot operate with a 100% RES penetration, forcing the MG to have at least one conventional generator connected to regulate the frequency of the system. The use of power converters as uninterruptible voltage sources was introduced in [4], [14], and led to the appearance of the so-called Voltage Source Converters [15], [16], which easily operate not only in MGs with high RES penetration, but also on islanded MGs with no conventional generation [17], [18]. Grid forming recently emerges as a new concept of power converters that implements the necessary inertial response for the integration of RES in microgrids; they allow MGs to operate without any conventional generator connected [19].

This paper presents a centralised, rolling horizon-based, two-step optimization algorithm for the optimal active-reactive power sharing in hybrid MGs, minimizing power losses and integrating RES and ESS. The proposed algorithm is applied and evaluated in a MG whose components, PV production and demand are based on real data.

2. Description of the MG under study

The proposed algorithm is tested in a microgrid composed of 3 diesel generation units, 1 solar PV power plant and 1 battery energy storage system (BESS). Fig. 1 shows the topology of the microgrid where all the generation units, BESS, and load are connected to a grid with different line impedances.

Table I presents the technical data of the different components based on real data from the current operation of the microgrid. Solar PV production and load demand data are also taken from its operation. The maximum and minimum load demand in the year is 3418 kW and 1043 kW respectively, following a customary residential load profile.

Table I Characteristics of the MG

Diesel Generators (per unit)	Values
Rated Power	2000 kW
Technical Minimum Power	400 kW
Fuel Cost	197 (€/MWh)
Hourly wearing cost	100 (€/h)
PV Plant	**Values**
AC maximum output power	4000 kW
BESS	**Values**
Power	2000 kW
Capacity	2000 kWh
Roundtrip Efficiency	90%
Degradation Cost	20€/MWh

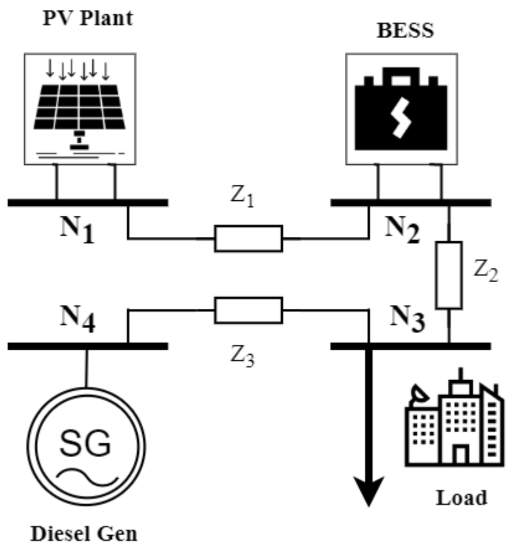

Fig. 1 Configuration of the MG

3. Optimization problem

Fig. 2 shows a flowchart with the complete process of the algorithm consisting of two steps. The first step optimizes the energy management of the system using the rolling horizon unit commitment algorithm based on the scheme presented in [19], providing the active power generation setpoint for power plants and BESS. The second part inputs the results of the first step and calculates the voltage commands for the power plant and BESS controllers to minimize transmission power losses in the MG.

The algorithm is a rolling horizon control scheme that runs every hour. The first step usually considers data for a 24-hour time frame, updating the forecast data for the next rolling horizon every hour.

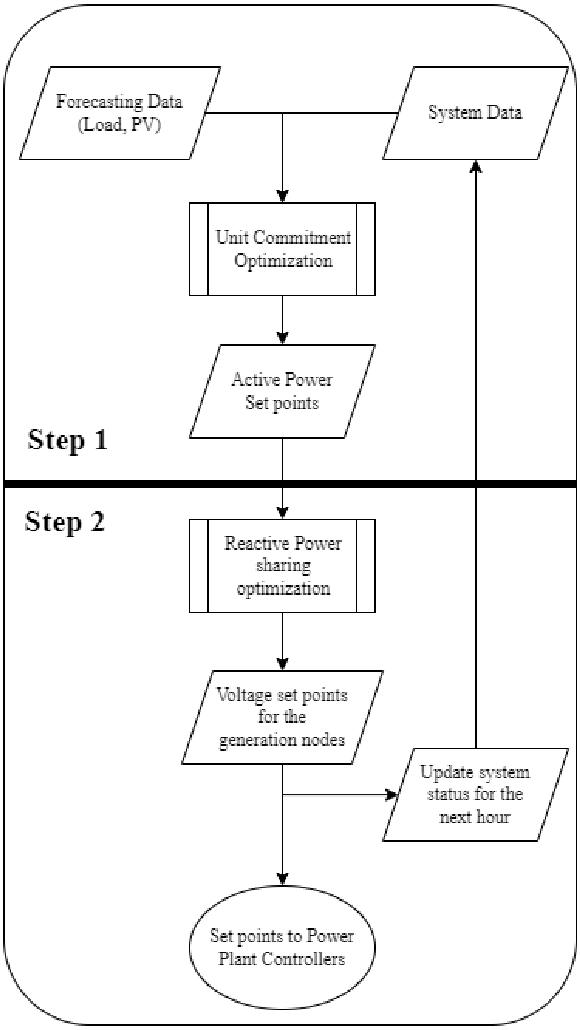

Fig. 2 Flowchart of the presented algorithm

A. Step 1: Optimal generation dispatch

The first step of the algorithm optimizes the energy management of the microgrid and provides the active power generation setpoints. To do this, the EMS inputs forecasting data such as load demand and PV resource.
A detailed description of the first step of the algorithm proposed by these authors can be found in [19], where the objective function minimizes the operation cost for a time horizon of K hours, according to

$$\boldsymbol{min}\sum_{t=1}^{K}\left(\begin{array}{c}((\boldsymbol{n}_{1,t}+\boldsymbol{n}_{2,t}+\boldsymbol{n}_{3,t})*\ \mathbf{H}^{\mathbf{COST}})+\\(\boldsymbol{p}_t^{\mathbf{GEN}}*\ \mathbf{F}^{\mathbf{C}})+(\boldsymbol{p}_t^{\mathbf{BAT}}*\mathbf{D}^{\mathbf{COST}})\end{array}\right) \quad (1)$$

Where $\mathrm{H}^{\mathrm{cost}}$ is the hourly wearing cost of the diesel generators, F^{C} is the fuel cost, p_t^{GEN} is the total power output of the diesel generators and $n_{i,t}$ indicates the status, on or off, of the diesel generators ($i = 1,2,3$) at each hour t. The variable p_t^{BAT} is the absolute value of the hourly power of the battery, charging or discharging, and $\mathrm{D}^{\mathrm{COST}}$ is the degradation cost of the BESS.
The constraints of this step of the algorithm are fully described in [19]. Fig. 3 shows an example of the output of the algorithm for the energy management of the MG for a 96-hour simulation.

B. Step 2: Reactive power sharing

The second step of the algorithm optimizes the reactive power sharing, minimizing the transmission power losses in the system. The optimization problem consists of the objective function (2) subject to constraints (3)-(6). The objective function (2) minimizes transmission power losses p^{LOSS}:

$$\boldsymbol{min}(\boldsymbol{f}) = \boldsymbol{p}^{\boldsymbol{LOSS}} \quad (2)$$

Constraints (3) and (4) calculate the bus voltages and the active-reactive power flows in the MG considering the power transmission losses and the inputs of the first step of the algorithm:

$$\mathbf{P}_k^{\mathbf{PV}}+\mathbf{P}_k^{\mathbf{GEN}}+\mathbf{P}_k^{\mathbf{BAT}}-\mathbf{P}_k^{\mathbf{LOAD}}+\boldsymbol{p}^{\mathbf{LOSS}} = \boldsymbol{v}_k\sum_{n=1}^{\mathbf{N}}\mathbf{Y}_{kn}\,\boldsymbol{v}_n\boldsymbol{cos}(\boldsymbol{\delta}_k-\boldsymbol{\delta}_n-\boldsymbol{\theta}_{kn}),\quad \boldsymbol{k}=\mathbf{1},\mathbf{2},\dots,\mathbf{N} \quad (3)$$

$$\boldsymbol{q}_k^{\mathbf{PV}}+\boldsymbol{q}_k^{\mathbf{GEN}}+\boldsymbol{q}_k^{\mathbf{BAT}}-\mathbf{Q}_k^{\mathbf{LOAD}} = \boldsymbol{v}_k\sum_{n=1}^{\mathbf{N}}\mathbf{Y}_{kn}\,\boldsymbol{v}_n\boldsymbol{sin}(\boldsymbol{\delta}_k-\boldsymbol{\delta}_n-\boldsymbol{\theta}_{kn}),\quad \boldsymbol{k}=\mathbf{1},\mathbf{2},\dots,\mathbf{N} \quad (4)$$

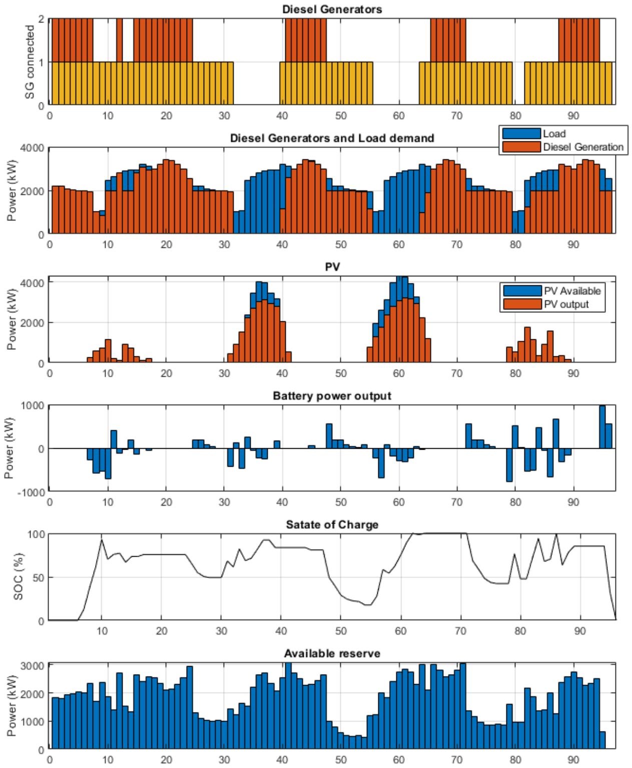

Fig. 3 Output of the step 1 after a 96-hour simulation

where v_k and δ_k are the modulus and angle of the voltage at bus k, respectively. The parameters Y_{kn} and θ_{kn} correspond to the modulus and angle of the element (k,n) of the network admittance matrix. The parameters $\mathrm{P}^{\mathrm{PV}}, \mathrm{P}^{\mathrm{LOAD}}, \mathrm{P}^{\mathrm{GEN}}$ and $\mathrm{P}^{\mathrm{BAT}}$ are determined by the previous optimization step. The variable q_k represents the injection of reactive power by the different elements, while $\mathrm{Q}^{\mathrm{LOAD}}$ corresponds to the reactive power consumed by the load.
Power transmission losses considered in this step affect the output power of the power plant and BESS. This variation in the output power is considered in the next iteration of the algorithm to update the state of the system.
Node voltages limits are included according to:

$$\mathbf{V}^{\mathbf{MIN}} < \boldsymbol{v}_n < \mathbf{V}^{\mathbf{MAX}} \quad (2)$$

Node voltage angle limits are also included; otherwise, there would be unlimited solutions to the optimization problem, so considering the angles in radians:

$$-\boldsymbol{pi} < \boldsymbol{\delta}_n < \boldsymbol{pi} \quad (3)$$

The Power Plant Controllers (PPC) of each generator now adjust the output active power and voltage setpoints sent by the centralised controller.
The active power values obtained in the first step of the optimization ensures an optimal dispatch. Then, the output of the second step corresponds to the voltage setpoints for each generator that provide an optimal reactive power sharing minimizing power transmission losses.

4. Simulation results and discussion

This section compares the strategy proposed here with two others widely used: 1) a decentralized strategy based on equal sharing of reactive power, and 2) a strategy based on node-voltage control. The three study cases are:

Strategy 1: Equal sharing of Q. This case distributes the reactive power equally between the two generating plants of the system and the battery, maintaining the voltage limits on the system bars and emulating a decentralized strategy.

Strategy 2: Node-Voltage Control. This case is based on a decentralised strategy of node-voltage control to maintain each bus voltage at ~1.0 p.u. The power plants and BESS only have information from their node.

Strategy 3: Optimization strategy. It corresponds to the proposed strategy in this paper, as the step 2 of the optimization problem. A centralised algorithm calculates the optimal reactive power setpoint for generators and BESS to minimizes power transmission losses.

The three study cases receive the active power commands from the first optimization step. Table II shows the active power setpoints used, obtained from a representative hour of the microgrid. The load that has a power factor of 0.95, consuming 0,9 MVAr.

Table II Active power setpoints from the step 1 of the algorithm and load data

GENERATOR	**ACTIVE POWER SETPOINT**
PV	2.10 MW
DIESEL GEN.	1.18 MW
BESS	-0.38 MW
LOAD	2.90 MW (P.F.=0.95)

Table III shows the results obtained in the comparison between the three different strategies presented. From the results, it can be seen that the widely used strategies 1 and 2 significantly increase the transmission power losses by 22.2% and 24.5% compared to the optimization strategy, respectively. The proposed optimization algorithm improves performance compared to other strategies in terms of power losses, while ensuring and optimal and secure operation of the MG.

Table III Results for the presented case study

	Equally sharing Q	**Node- Voltage Control**	**Optimization Strategy**
Reactive Power [kVAr]			
PV	377	-280	36.2
BESS	377	1866	827.4
Load	900	900	900
Diesel Gen.	377	-441	215.1
Voltage Profile [pu]			
N1	0.9628	1.00	1.0792
N2	0.9208	1.00	1.0514
N3	0.9018	0.9630	1.0338
N4	0.9816	1.00	1.1000
Losses			
Total [kW]	**211**	**216**	**163**
Diff. [%]	**+22.2%**	**+24.5**	**-**

5. Conclusion

This work proposes a two-step optimization algorithm to command active and reactive power setpoints for real operation of MGs. This paper focuses on the calculation of node-voltage setpoints which ensure optimal distribution of reactive power between power plants and BESS, and minimum power transmission losses.
The proposed strategy shows a significant reduction in power losses compared to two decentralised strategies commonly found in the literature, demonstrating the potential of strategies based on centralized algorithms for the operation of MGs.

Appendix

Table IV Transmission line parameters

Line, Bus to bus	*R [pu]*	*X [pu]*
1-2	0.02	0.08
2-3	0.002	0.008
3-4	0.04	0.16

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