An novel power dispatch optimization using linear programming and operating strategy in DC Microgrid

Jorge Mírez
IEEE Senior Member
Group of Mathematical Modeling and Numerical Simulation
Faculty of Oil, Gas and Petrochemical Engineering
Universidad Nacional de Ingeniería
Lima, Perú
jmirez@uni.edu.pe

Abstract— **This paper report the propose of an optimization process of power dispatch in a DC microgrid using principles of linear programming. The microgrid used has as microsources: a wind turbine, a solar PV plant, a battery bank, an electric load and an electrical interconnection point with utility network. The microgrid only allows the energy input from utility network. Additionally, every component is configured to offer/request a fixed nominal power of production/demand during periods of five minutes of duration; this is a new operating strategy: a constant power generation and consumption is defined in each microsources, loads and storages. To optimization process search the minimum cost of production, distributing adequate the demand between microsources and utility network under the proposed operating strategy. In this paper has been assumed that costs vary randomly in every period by each microsource and utility network. The optimization process has been development, implemented and compared with its equivalent in Matlab.**

Keywords— Energy management, microgrids, optimization, power generation dispatch.

I. INTRODUCTION

Electrical systems need to operate under several technical and economic conditions. Companies look for the minimum product cost and to maximize sales, while customers look at the minimum cost for supplied energy.

Traditionally, the economic aspect is based on measurements for the register of supplied energy in generation/transmission/distribution under a structure of centralized generation. Now, new trends as Distributed Generation (DG) [1], Actives Networks (AN), Smart Grids (SG) and Microgrids (MG) [2-5] have sources of generation and storage nearest to the loads, even inside the customer buildings; so economic operation changes substantially because of the appearance of these new elements, with multiples prime resource highly dependent of the environmental conditions. The attention in this paper is the Direct Current MG (DCMG), because its multiplier technical advantages in comparison to Alternating Current MG (ACMG) [6-8].

The technical aspects of MG’s operation are treated in several publications [2,8], where has been developed some ways to ensure the management of voltage and frequency [4] that have led to the creation and development of technologies, and the technics implemented in inverters [9], rectifiers [10], smart measurers, controllers of microsources and MGs. But is usual to find that the MGs have only one source of storage for the whole MG, that is, there is no temporary storage in microsources y loads.

There are many possible ways of business for MGs [2,4,5]. Usually, every so often is considered the energy quantity that had been dispatched [11,12]. Our scenario is that MG's have multiple owners, where each component has been implemented according to the owner’s specialization; microsource and storage ensure certain power with a fixed price during the next period of operation and the electric utility network (UN) will ensure delivery at a determined price as last backup source of the MG. All the prices will change in the time. Electrical demand, microsources and storage must have the needed of adequate configuration to ensure the power dispatch or supply.

The base times of optimization are in some cases one hour [5, 11-13], a month [14] and a year [15]. Only one study has considered each 3 minutes for realizing the calculus for the operation of the electric system but this MG is being fed from a PV plant. But is more usual to find that the optimization calculation time is every hour [8,14,16]. However, storage and generation micro-sources in MGs have variable costs defined by a random behavior over time of the powers involved; therefore, being desirable that constant or slightly variable powers are defined in microsources. This leads to propose that the microsources have temporary storage devices so that they can generate / consume constant power over a certain period of time (period); for example in [16] can be observed that utility network (UN) allow power contracts in intervals of 15 minutes.

Also, there are studies using several technics of optimization [12-14,16]; but the economic operation of MG is decided in only one component: a Central Controller (CC) [11]. In this paper, has been assumed that MG’s operation decisions are realized in each period by the CC under the premise that microsources/storage/load are designed to know their environment and the behavior of the power that these manipulate and with it: to ensure a demand/supply for the next period (a period duration time of 5 minutes has been assumed). Under this supposition, the system gets linear and many functions of prediction and control in microsources, storage and demand response strategies are derived to controllers. For this new operating strategy is that an optimization process to MGDC is too presented, which has with rules to improve the dispatch power at minimum cost and is explained in a mathematical model with two scenarios of study. A previous study [17] allows us to visualize that this new form of operation can serve for the interconnection operation between MGs.

II. MATHEMATICAL MODEL AND SIMULATIONS

A. *Microgrids and Linear Programming.*

MG is an integrated energy system consisting of distributed energy resources and multiple electrical loads operating as a single, autonomous grid either in parallel to or islanded from the existing utility power grid. MG can be viewed as the building blocks of the SG or as an alternative path to "Super Grid" [18] - a similar concept is Multi-MG [2]. Also, one of the main characteristic of MGs is that it can interchange until 10 MVA with the UN. According to [19] a linear programming (LP) problem has standard form if (a) the objective is to minimize, (b) all constraints are of equality type and (c) all variable are non-negative.

B. *Mathematical Model.*

For the model of optimization of the MG, has been used [19], where a linear program is specified in the following form: Minimize $f^T x$ and is subject to $Ax \le b$; $A_{eq} x = b_{eq}$ and $l_b \le x \le u_b$ where f is a vector that represents the cost coefficients of the objective function with that the value of x is calculated and is assumed that constraints are grouped according to inequality constraints: $Ax \le b$ represents inequality constraints; $A_{eq} x = b_{eq}$ represents the equality constraints, and $l_b \le x \le u_b$ represents the lower and upper bounds on the decision variables. So, A , A_{eq} are matrices and defined by their own characteristics of the problem; b , b_{eq} , l_b and u_b are vectors.

The CC every 5 minutes makes the monitoring of the system and decides the energy buy/sell for next 5 minutes. Has been considered 8 hours as total simulation time; taking into consideration that noon is the time base, which divided this study time in equal hours before (4 hours) and after (4 hours) of the solar noon. Therefore, the time can be discretized as an amount of "m" states. Moreover, is considered that MG have "n" microsources, so, it needs "n" cost coefficients of objective function for every state "m" and additionally, each state "m" has loads for supply b_{eq} described in Eq. (1).

$$\left.\begin{array}{cccccccc}
\textbf{State} & & & f & & & b_{eq} \\
1 & f_{1(1)} & f_{2(1)} & f_{3(1)} & \cdots & f_{n(1)} & b_{eq(1)} \\
2 & f_{1(2)} & f_{2(2)} & f_{3(2)} & \cdots & f_{n(2)} & b_{eq(2)} \\
3 & f_{1(3)} & f_{2(3)} & f_{3(3)} & \cdots & f_{n(3)} & b_{eq(3)} \\
\cdots & & & \cdots & & & \cdots \\
m & f_{1(m)} & f_{2(m)} & f_{3(m)} & \cdots & f_{n(m)} & b_{eq(m)}
\end{array}\right\} \quad (1)$$

The Eq. (1) show relations between several sources of generation and storage, as well as the UN and to be contain inside the optimize software, which after processing data of *x* and *f* give back the values of *x* according to Eq. (2).

$$\left.\begin{array}{cccccccc}
\textbf{State} & & & x & & & f_{val} \\
1 & x_{1(1)} & x_{2(1)} & x_{3(1)} & \cdots & x_{n(1)} & f_{val(1)} \\
2 & x_{1(2)} & x_{2(2)} & x_{3(2)} & \cdots & x_{n(2)} & f_{val(2)} \\
3 & x_{1(3)} & x_{2(3)} & x_{3(3)} & \cdots & x_{n(3)} & f_{val(3)} \\
\cdots & & & \cdots & & & \cdots \\
m & x_{1(m)} & x_{2(m)} & x_{3(m)} & \cdots & x_{n(m)} & f_{val(m)}
\end{array}\right\} \quad (2)$$

Is assumed random prices which emulate its behavior and additionally it allows us to evaluate the optimizer considering also that the electrical loads have a random behavior also. A general schema of the simulations realized is presented in Fig. 1 where and *fval* that is the value of minimum cost and is shown that we need a generator of states, costs, electrical charge and the optimizer.

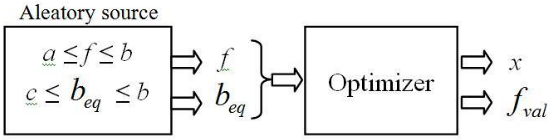

Fig. 1. Flow of information toward Optimizer and results.

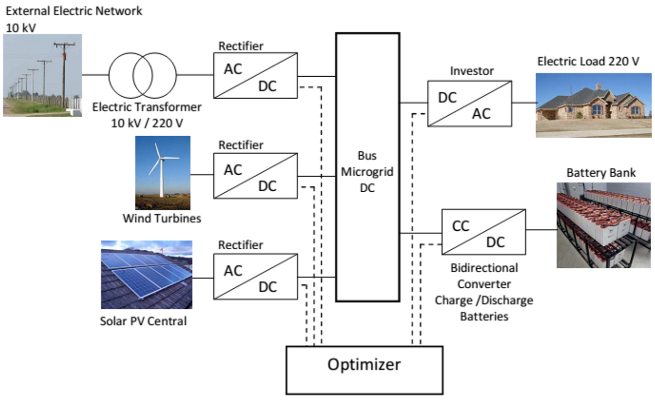

Fig. 2. MG squeme studied with Optimizer containing hardware, software and communications with converters for data and control.

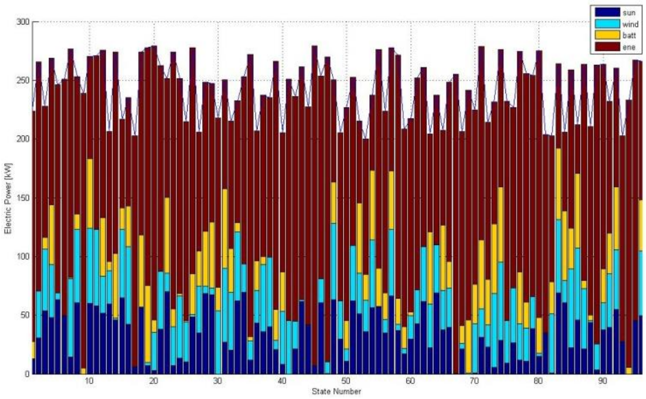

Fig. 3. Flow of information toward Optimizer and results.

The MG shown in Fig. 2 has been the study case, where the Optimizer interacts with converters for data collection, action of command and control over power flow. The DCMG-bus of unlimited capacity has been considered. MG is formed by wind central, solar PV central, battery bank, electrical load and interconnection with UN through of a transformer-inverter arrangement. Nominal capacities of equipment are assumed according to scenarios of analyzed study. Temporal storage in microsources had been assumed that it was implemented to ensure supply of nominal power during every period "m". Then, is deduced that "*n = 4*", being f_1 is the price of solar energy, f_2 the cost of wind energy, f_3 the cost of battery energy and f_4 the cost of energy that enter from UN. There are 4 components which give 24 possible ways of supply energy to electrical load represented by b_{eq}; from all of them, when A_{eq} have next expression $A_{eq} = [1 \quad 1 \quad 1 \quad 1]$ is the more favorable condition; where, $A_{eq}(1,1)$ represents the photovoltaic solar source, $A_{eq}(1,2)$ the wind, $A_{eq}(1,3)$ the power coming from batteries and $A_{eq}(1,4)$ the power that enter from UN. l_b and u_b represents the minimum (0 in every case) and maximum value of the power offered by every source.

According to [11], the following prices per energy source have been assumed: Sun, $f_1 = 0.10 \pm 0.2$ US$/kW-h; wind, $f_2 = 0.15 \pm 0.2$ US$/kW-h; battery, $f_3 = 0.20 \pm 0.2$ US$/kW-h and UN, $f_4 = 0.25 \pm 0.2$ US$/kW-h. With these data are analyzed using two study scenarios.

C. Scenario 1: Criteries implemented in Matlab.

The power demand of loads has been assumed: $200 \pm 80 \times rand()$ kW; where *rand()* create a random value uniformly distributed between 0 and 1 for every state "m"; the supplied power from each microsource is $70 \times rand()$ for every state "m" (different random number is are created for every microsource) and supply capacity from UN is 300 kW for every case. The command *linprog* [20] is used to implement this model and Fig. 3 shows results for 8 hours of simulation time (to 12 states by hour with 5 minutes of duration each state).

The total cost associated to every state "m" is shown in Fig. 4 and the big capacity of support of UN is shown in Fig. 5.

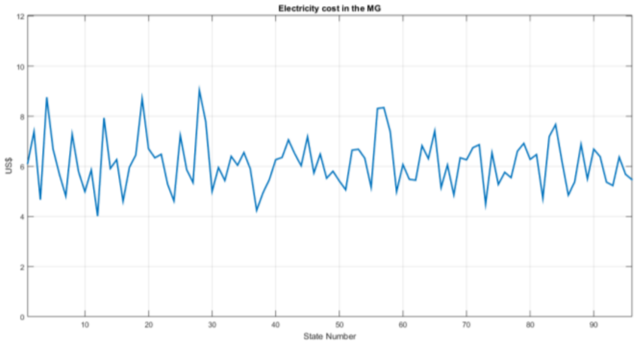

Fig. 4. Evolutión of the electricity cost in MG according to state number.

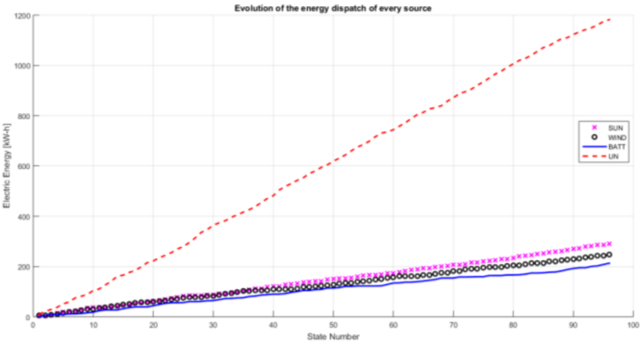

Fig. 5. Example of evolutíon of the energy dispatch of every source in MG according to state number.

D. Scenario 2: Alternative method of optimization process.

During MG operation, is possible that requested power won't be available by the cheaper source and another source will be needed more expensive; it means: If source 1 which is cheaper do not have enough power to supply the demand, the system supplies this deficiency complementing with another source 2, which is a little more expensive, in a way that adding both source the demand will be attended. So, the alternative optimization process order for every state, the prices of energy from the cheaper towards the expensive according to the supply source linking at the same time its own power availability to supplied. The software chooses the source to supply the demand even when the prices are random. For this scenario, a new flow diagram with the news considerations is shown in Fig. 6 with its respective inputs and outputs.

The Fig. 6 shows an algorithm consisting of three stages: A first stage called *Optimizer* uses the technic detailed in Scenario 1 with the premise that the sources (microsources, UN) have unlimited capacity of supply and that inside alternative method it will allow us rescue those states where only one source can supply the demand using the rule $x > pd_s$ where pd_s is the supply power of the source in each state. In a second stage, a *Technical Optimizer* order from lowest to highest price of the sources and distribution of the power according to the availability of each source for the states where only one source cannot supply the demand. And another third stage makes the union (*U* symbol in Fig. 6) of all answers of every state to give as a final result the matrix *x''* and the *fval''* vector (*fval''* is the cost of MG's operation y *x''* is the distribution of the demand in every microsource, storage and UN). A comparison between both methods is shown in Fig. 7 and Fig. 8.

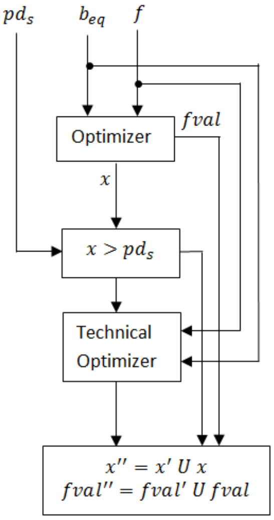

Fig. 6. Schematic diagram of complete optimization process.

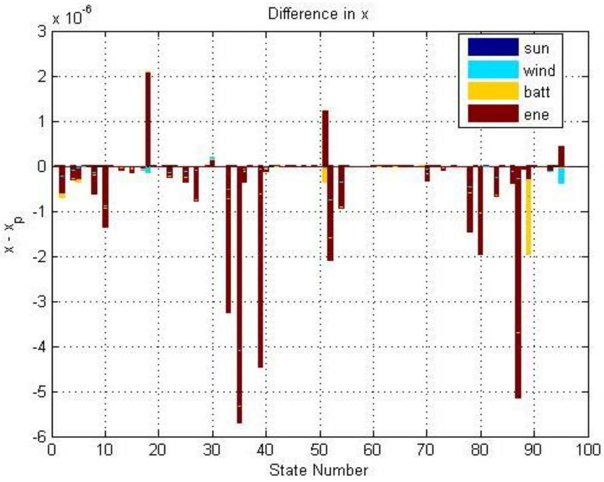

Fig. 7. Difference of supply power in each source of MG.

In Fig. 7, the variable *x* is the distribution of power by source that has been determined by the command *linprog* [20], and; *xp* is the answer equivalent given by the alternative method. In Fig. 8, *fval* is the total cost for state calculated by the command *linprog*, and; *fvalp* is the equivalent deducted by the alternative method. There is a remarkable accuracy of the result that both methods give for the power and price values.

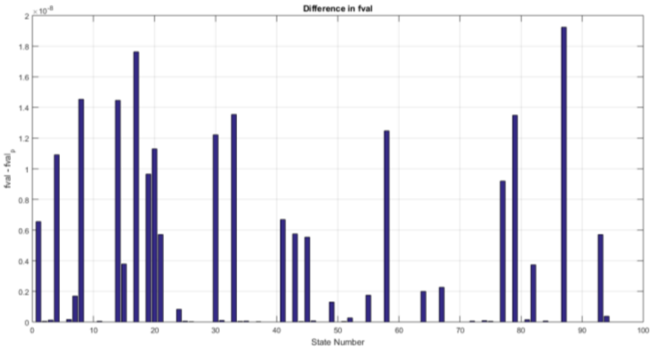

Fig. 8. Porcentual difference of electricity total cost in MG between two study scenarios.

III. DISCUSSION

Five minutes has been proposal as a period for optimization calculation for this MG where microsources, storage, customers, manufacturers and UN have greater benefit; it allows ensure electricity at best price and it foments the development and implementation of multiples specialized technologies: electronic power equipment, storage, communications and more, because the sources and loads should have a temporal storage. This length of period can reduce o extend according to electric system inertia or also can be variable, which is subject for further studies that can refine this period length, but a general criterion is that the duration of period could be extended in case there is bigger capacity nominal by installed and/or major capacity in temporal storage in each microsource and/or battery bank. It is reduced only if there is PV plant as a main source or is a high percentage of the self-generation of the MG.

In case that power from microsources and storage is bigger than the demand, the rest of power which generally corresponds to the expensive source, can be injected to UN or to other MG with a bigger price because implies a right of step using MG-bus, with this, is ensure that MG customers have a cheaper price. Including the sources with adequate temporary storage will be able to operate at their maximum efficiency and profitability, compared to what exists now, in that what is generated is transported by the MG-bus to the storage, which causes random power flows in the electrical circuits of the MG.

IV. CONCLUSSIONS

An optimization process had been developed, implemented and tested under the premise of priority of electric dispatch ordering the random price of sources from lowest to highest value in every state and distribute the demand at minimum possible cost for the customer. To achieve this, has been used principles of linear optimization and proposed a new strategy of operation for MG: that all the components of MG ensure a power of supply/demand during a determined time (periods of 5 minutes of duration as example in this paper), and this time duration for each state, constitutes a reference for the contractual part of the electric market between auto-generators, loads and UN. Likewise, a better management of generation and dispatch and the power flow in the electrical circuits that make up the MG-bus is achieved. The method had been validated comparing the results that give the *linprog* command of Matlab. Also, has been obtained the excess of power in every source (with potential for temporal storage in each source) and the reserve of supply of UN in PCC. The developed software allow to configurator the inputs (price, power) and operating conditions of each source, demand curve of loads, calculate prices of sales, excess of power and determine where to send this surplus energy. Therefore, this proposal for optimization and operation strategy for the MG reinforces the potential of being applied in the interconnection of multi-MGs.

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REFERENCES

[1] Hans Larsen, “The Future Energy System – Distributed Production and Use,” Roskilde, Denmark, Risø DTU National Laboratoty, Rep. Riso Energy Report 4, Oct. 2005.

[2] Nikos Hatziargyriou, “Microgrids Architectures and Control”. Chichester, UK: Wiley, 2014.

[3] Clark W. Gellings, The Smart Grid. Lilburn, GA: CRC Press, 2009.

[4] S. Chowdhury, S. P. Chowdhury, P. Crossley, Microgrids and Active Distribution Networks. London, UK: The Institution of Engineering and Technology, 2009.

[5] Christine Schwaeger, “DG3&DG4 Report on the technical, social, economic, and environmental benefits provided by Microgrids on power system operation,” Erlangen, Germany, Siemens AG, Rep. STREP Project, Dec. 2009.

[6] Dong Chen, Lie Xu, “DC Microgrid with Variable Generations and Energy Storage,” in IET Conference on Renewable Power Generation 2011(RPG 2011). Sept 6-8, 2011.

[7] N. R. Rahmanov, N. M. Tabatabaei, K. Dursun, "Combined AC-DC Microgrids: Case Study - Network Development and Simulation," International Journal on Technical and Physical Problems of Engineering, issue 12, vol 4, no 3, Sep. 2012, pp: 157-161.

[8] Ji-Heon Lee, Hyun-Jun Kim, Byung-Moon Han, Yu-Seok Jeong, Hyo-Sik Yang, "DC Micro-Grid Operational Analysis with a Detailed Simulation Model for Distributed Generation," Journal of Power Electronics, vol. 11, no. 3, May 2011, pp: 350-359

[9] Alberto Andrés Bretón Schuwirth, “Design and Construction of a Multi-phase Inverter Four Stages Harmonic and Reactive Compensation,” Pregrade dissertation, Dept. Engineering. Pontifica Universidad Católica de Chile, Santiago de Chile, Chile. 2003.

[10] Miguel Villablanca, “Tryristor-based AC/DC Rectifiers with High-quality Waveforms,” Ingeniare. Revista Chilena de Ingeniería, vol. 18, no 1, pp. 132.143, 2010

[11] Sudipta [11] Chakraborty, Manoja D. Weiss, M. Godoy Simöes, "Distributed Intelligent Energy Management System for a Single-Phase High-Frequency AC Microgrid," IEEE Trans. Ind. Electron. Vol. 54, No. 1, Feb. 2007, pp: 1-13.

[12] In-Su Bae, "Phasor Discrete Particle Swarm Optimization Algorithm to Configure Micro-grids," J. Electrical Eng & Tech., vol. 7, no.1, pp. 9 -16, 2012, pp: 9-16, Jan 2012.

[13] René Martínez. “Renewable-Driven Microgrids in Isolated Communites,” M.S. dissertation, Electrical Eng. Departament, University of Puerto Rico, Puerto Rico, 2009.

[14] Francisco Goiana. “Design Optimization of Stand-Alone Hybrid Energy Sytems,” M.S. dissertation, Facultade de Engenharia, Universidade do Porto, Porto, Portugal, 2010.

[15] Richard W. Wies, Ron A. Johnson and Tyler J. Chubb, "Simulink Model for Economic Analysis and Environmental Impacts of a PV With Diesel-Battery System for Remote Villages," IEEE Trans. on Power Syst., vol. 20, no. 2, pp: 692-700, May 2005.

[16] Arto Niinistö, “Simulation of the Management of a Microgrid with Wind, Solar and Gas Generators,” M.S. dissertation, Faculty of Electronics, Communications and Automation, Aalto University, Espoo, Finland, 2009.

[17] Jorge Mírez. “A modeling and simulation of optimized interconnection between DC microgrids with novel strategies of voltage, power and control”. 2017 IEEE Second International Conference on DC Microgrids (ICDCM). DOI: 10.1109/ICDCM.2017.8001098

[18] Peter Asmus. “Microgrids: Islanded Power Grids and Distributed Generation for Community, Commercial, and Institutional Applications,” 2009. Pike ResearchLLChttp://www.missioncriticalmagazine.com/ext/resources/MC/Home/Files/PDFs/WP-MICROPike_Research-ExecutiveSummary.pdf.

[19] Roy H. Kwon, Introduction to Linear Optimization and Extensions with MATLAB. Boca Raton, FL: CRC Press, 2014.

[20] MathWorks Inc. “Matlab” Available in: https://la.mathworks.com/