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Economic and environmental dispatch of power systems: Minimising CO_2 emissions by integrating renewable energy sources

Despacho económico y medioambiental de los sistemas eléctricos: Minimización de las emisiones de CO_2 mediante la integración de fuentes de energía renovables

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Abstract

This paper analyses the impact of the integration of renewable energy sources on the economic and environmental operation of power systems (PS). The models of renewable energy sources, as well as the generation cost function and Carbon Dioxide (CO_2) emissions are integrated in an Optimal Power Flow (OPF) formulation in order to obtain a non-linear multi-objective optimisation model, which considers economic and environmental aspects. This OPF model, having integrated the models of renewable energy sources, allows to evaluate the impact that these energy sources have on the minimisation of generation cost and CO_2 emissions. In this work, the multi-objective OPF problem is solved using weighting factors for the two functions considered in the global objective function. Several case studies are carried out to evaluate the effect of the integration of renewable energy sources on the economic and environmental operation of power systems. The results of the case studies show that renewable energy sources reduce generation cost and CO_2 emissions.

Renewable energy sources, Optimal generation dispatch, Power systems

Resumen

En este trabajo se analiza el impacto de la integración de las fuentes de energía renovable en la operación económica y ambiental de los sistemas eléctricos de potencia (SEP). Los modelos de las fuentes de energía renovable, así como la función de costo de generación y de emisiones de Dióxido de Carbono (CO_2) se integran en una formulación de Flujos de Potencia Óptimos (FPO) con la finalidad de obtener un modelo de optimización no lineal multi-objetivo, que considera aspectos económicos y ambientales. Este modelo de FPO, al tener integrados los modelos de las fuentes de energía renovable, permite evaluar el impacto que tienen estas fuentes de energía en la minimización del costo de generación y en las emisiones de CO_2. En este trabajo, el problema de FPO multi-objetivo se resuelve utilizando factores de ponderación para las dos funciones consideradas en la función objetivo global. Diversos casos de estudio se llevan a cabo para evaluar el efecto que tiene la integración de las fuentes de energía renovable en la operación económica y ambiental de los SEP. Los resultados de los casos de estudio muestran que las fuentes de energía renovable reducen el costo de generación y las emisiones de CO_2.

Fuentes de energía renovable, Despacho óptimo de generación, Sistemas eléctricos de potencia

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Introduction

In recent years, care for the environment has become increasingly important in the daily and productive activities of society around the world. Therefore, it is of great importance nowadays to carry out such activities with minimal impact on the environment and to ensure environmental sustainability. Virtually all productive activities, especially those carried out at the industrial level, produce large amounts of pollutant gas emissions, known as greenhouse gases. Of all productive activities, in developed countries, electricity generation represents one of the main sources of environmental pollution through the emission of polluting gases into the atmosphere [Stott, 1979]. The greenhouse gases that power plants emit into the atmosphere in the greatest quantity are carbon monoxide, sulphur dioxide, nitrogen oxides and carbon dioxide, the latter being considered the greenhouse gas that contributes most to global warming, as it is the gas that is emitted in the greatest quantity by industry around the world [Atten et al, 2004; Demirel, 2004; Oceana, 2008; Rodríguez et al, 2013].

Mexico is one of the countries that, within the framework of the United Nations (UN) Paris Agreement [United Nations, 2015], have made specific commitments to curb global warming and climate change. The Nationally Determined Contributions (NDCs), together with the Special Climate Change Programme (SCCP), are Mexico's climate policy instruments, in which specific targets have been set to reduce 22% of its Greenhouse Gas (GHG) emissions, as well as to generate 35% of electricity through clean energy sources by 2024 and 43% by 2030, such generation to include renewable energy, cogeneration with natural gas and thermoelectric plants with CO_2 capture [CEMDA, s. f.; SEMARNAT, 2015].

For this reason, the integration of renewable energy sources into the active power generation system is of great importance, as it offers clean energy without greenhouse gas emissions, thus contributing to meeting the electrical energy demand of the power system with a decrease in GHG emissions, which reduces the carbon footprint that would occur if the demand were met solely by thermoelectric power plants.

As in the case of Mexico, policies, procedures and methods have been implemented around the world to minimise the effect of GHGs on air pollution. Policies and procedures include financial penalties for violation of permitted emission limits or green certificates to encourage the integration of clean energy sources in power systems. On the other hand, some of the common methods to reduce GHG gases are to reduce emissions from thermal power plants by using fuels with lower emission potential, installing post-combustion cleaning systems or dispatching generating units in such a way that emissions of polluting gases are minimised [Kulkarni et al, 2000; Song et al, 1997].

The analysis of Optimal Power Flows (OPF) allows the optimisation of an objective function subject to different equality and inequality constraints, thus determining the optimal steady-state operation of the power system. The objective functions can consider economic, safety or environmental aspects of the power system [Acha et al, 2004]. The objective function of the OPF problem can consider two aspects to be minimised simultaneously, obtaining a multi-objective OPF model, whose functions and constraints are non-linear.

In this work, the reduction of CO_2 emissions and the cost of active power generation are considered as objectives. It should be mentioned that the simultaneous reduction of CO_2 emissions and generation cost is a topic widely studied by utilities and researchers [Demirel, 2004; Dhillon et al, 1993; King, 1995; Kulkarni et al, 2000; Song et al, 1997]. However, the determination of the impact of renewable energies on the reduction of GHG emissions is not a common topic, since the mathematical modelling is complex and difficult to solve, due to the need to integrate the models of renewable energy sources in the formulation of multi-objective OPF, whose model is a highly non-linear optimisation problem with functional and variable constraints. This paper presents an analysis of the impact of the integration of renewable energy source models on the economic and environmental operation of power systems. The structure of the paper is as follows: The first section consists of the introduction and a review of the state of the art of the topic analysed in the paper, then in the next two sections the theoretical framework related to renewable energy sources and the multi-objective OPF problem is presented respectively.

In the case studies section, several cases with a test power system are shown to evaluate the impact of renewable energy sources on the economic and environmental operation of the system. Finally, the penultimate and last section presents the conclusions obtained from the work and the bibliographical references, respectively.

Power generation from renewable energy sources

The renewable energy sources currently used to generate electricity are geothermal, ocean, bioenergy, hydro, solar and wind. Of these, wind and solar energy are the most prevalent in the world's electric power systems [Naciones Unidas, n. d.]. For this reason, these sources are the ones considered in this work.

A. Power generation by wind energy

In general, wind energy is produced by wind turbines or windmills. The kinetic energy in the moving air causes the turbine blades to rotate, whereby the kinetic energy is converted into mechanical energy, which in turn is converted into electrical energy by an electric generator, whose operation is based on an induction motor with negative torque, also known as an induction generator [Chapman, 2012]. The turbine-generator set is known as a wind turbine. The available power that is converted by the wind turbine is [Mahaboob et al, 2021],

$$P_W = 0.5\,\rho\,A\,v^3\,C_P \tag{1}$$

Where ρ is the wind density with a value of 1,221 kg/m^3, A is the swept area of the wind turbine blades in m^2 and v is the wind speed in m/s. The C_P term is the Betz constant or power coefficient, whose value is equal to 59.3% [Ackerman, 2005].

B. Power generation by solar energy

Solar energy is the most abundant energy on the planet, does not generate emissions that pollute the environment, requires less maintenance and has a long duration time. One of the important points for solar power generation is the sun's radiation, which is captured by a photovoltaic panel that is used to convert the sun's radiation into electrical energy.

A typical PV panel consists of a P-N junction semiconductor diode [Patel, 1999], which works on the principle of the photovoltaic effect, since when radiation strikes the diode, the P-N junction absorbs light and produces electric current. The power output generated by a P_S solar plant can be calculated, in kW, as follows [Mahaboob et al, 2005], only in case the solar irradiation is known.

$$P_S = PR\ GHI\ \eta_{PV}\ A_S\ S_Z \tag{2}$$

Where, the PR term is the performance ratio, whose value is dimensionless and lies between 0.5 and 0.9, the default value normally considered for this parameter is 0.75. The GHI term is the global horizontal irradiation in kW/m^2, A_S is the surface area of the solar panel in m^2, η_{PV} is the efficiency of the solar panel whose value is around 0.15 and S_Z is the number of solar panels contained in the solar plant.

Multi-objective OPF formulation considering renewable energy sources

The two objective functions to be minimised in the multi-objective OPF are the cost of active power generation and CO_2 emissions, both of which are minimised simultaneously. The mathematical formulation of this OPF problem considering the integration of solar and wind renewable energy sources is described below.

A. Mathematical model of the multi-objective OPF problem

1) Objective Function

The cost of active power generation involves maintenance costs, fixed costs, labour, fuel, among others, and is given by the following objective function,

$$F_C = \sum_{i=1}^{N_g}\left(a_i + b_i P_{g,i} + c_i P_{g,i}{}^2\right) \tag{3}$$

In the above expression, it is clear that the function is non-linear. The terms a_i, b_i and c_i are the coefficients of the cost curves of the generators and $P_{g,i}$ is the power generated by each power plant connected to node i.

Similarly, the total CO_2 emissions from the combustion of thermal power plants can be modelled by the quadratic function given by (4).

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$$F_E = \sum_{i=1}^{N_g} \left(d_i + e_i P_{g,i} + f_i P_{g,i}^{\ 2} \right) \tag{4}$$

In the above equation, the terms d_i, e_i and f_i are the coefficients of the curves representing carbon dioxide emissions to the atmosphere. The valve points are not considered in this work [Demirel, 2004; Dhillon et al, 1993; King, 1995; Kulkarni et al, 2000; Song et al, 1997]. In both objective functions N_g is the number of generators installed in the power system.As mentioned, the sum of the generation cost function F_C and the emissions function F_E gives rise to the global multi-objective function [Demirel, 2004; Kulkarni et al, 2000], which is the new function to minimise in the OPF problem and is given as follows,

$$F_T\left(P_{g,i}\right) = w_C F_C(P_{g,i}) - w_E h F_E(P_{g,i}) \tag{5}$$

The terms w_C and w_E are the weighting coefficients for the cost and emissions functions, respectively, while the term h is the penalty factor that allows combining both objective functions into an overall function.

$$h_i = \frac{F_{Ci}\left(P_{gi}^{\max}\right) / P_{gi}^{\max}}{F_{Ei}\left(P_{gi}^{\max}\right) / P_{gi}^{\max}} \tag{6}$$

Where P_{gi}^{max} is the maximum power of generator i, so that the cost and emission functions, F_{Ci} and F_{Ei}, are evaluated at this value of the power generated at the *i-th* generator.

2) Equality Constraints

The equality constraints that allow modelling the active power balance at node k considering the renewable energy sources are given as follows,

$$P_{g,k} + \sum_{i=1}^{N} P_{RES,i} - P_{D,k} - \sum_{k=1}^{Nb} P_{iny,k} = 0 \tag{7}$$

$$Q_{g,k} - Q_{D,k} - \sum_{m=1}^{Nb} Q_{iny,k} = 0 \tag{8}$$

Where $\{P_{g,k}, Q_{g,k}\}$, $\{P_{D,k}, Q_{D,k}\}$ and $\{P_{iny,k}, Q_{iny,k}\}$ are the active and reactive power generated, demanded and injected at node k, respectively. The term $P_{RES}=\{P_S, P_W\}$ represents the active power generated by the N renewable energy sources connected at node i. P_S is the power generated by photovoltaic power plants and P_W is the power generated by wind power plants.

3) Inequality constraints

Inequality constraints allow modelling the physical and operational limits of the power system, these limits are usually applied to the variables and sometimes to the functions that depend on the variables that determine the operating state of the power system. These limits are modelled by means of the following inequality constraints.

$$\delta_k^{\min} < \delta_k < \delta_k^{\max} \tag{9}$$

$$V_k^{\min} < V_k < V_k^{\max} \tag{10}$$

$$P_{g,i}^{\min} < P_{g,i} < P_{g,i}^{\max} \tag{11}$$

$$Q_{g,i}^{\min} < Q_{g,i} < Q_{g,i}^{\max} \tag{12}$$

$$P_W = \begin{cases} 0 & \text{if} \quad v < v_{\min} \\ 0.5\rho A v^3 & \text{if} \quad v_{\min} < v < v_{\max} \\ P_r & \text{if} \quad v > v_{\max} \end{cases} \tag{13}$$

$$P_S = \begin{cases} 0 & \text{if} \quad GHI < GHI_{\min} \\ PR\, A_S\, S_Z\, \eta & \text{if} \quad GHI > GHI_{\min} \end{cases} \tag{14}$$

It should be noted that all the above expressions are inequality constraints to variables, except constraint (12), which is an inequality constraint to function, since reactive power depends on voltage. On the other hand, inequality constraints (13) and (14) correspond to renewable energy sources [Mahaboob et al, 2021]. The variable P_r is the rated power of the wind turbine, v_{min} is the minimum wind speed of 3.5 m/s and v_{max} is the maximum wind speed of 20 m/s. It should be mentioned that the nominal wind speed given in the literature is 11 m/s. The variable GHI_{min} is the minimum irradiance from the sun whose average value is 5.5 kW/m^2 [Deloitte, 2019].

Study cases

In this section, several study cases are presented to analyse the effect of integrating renewable energy source models on CO_2 emissions and the cost of active power generation of a power system.

The 9-node test power system [Sauer, 1997] is used in the study cases presented his coefficients of both the generation cost functions and carbon dioxide emissions of the generators used in the case studies of this power system are shown in Table 1.

Generation cost coefficients			
Gen	**a ($/hr)**	**b ($/MWhr)**	**c ($/MW²hr)**
1	140	2.0	0.0060
2	120	1.5	0.0075
3	80	1.8	0.0070
CO_2 emission coefficients			
Gen	**d (lb/hr)**	**e (lb/MWhr)**	**F (lb/MW²hr)**
1	137.3701	-1.2488	0.0138
2	137.3701	-1.2488	0.0138
3	363.7048	0.8051	0.0077

Tabla 1 Coefficients of the cost and emission functions of the 9-node power system

The voltage limits used in the study cases presented with this power system are 0.95 pu for the lower limits and 1.05 pu for the upper limits. While the limits used for active and reactive power for generator 1 are, respectively, $0 \leq P_{G1} \leq 200$ MW and $-100 \leq Q_{G1} \leq 150$ MVAR; for generator of $0 \leq P_{G2} \leq 150$ MW and $-100 \leq Q_{G2} \leq 300$ MVAR; and for generator 3 of $0 \leq P_{G3} \leq 100$ MW and $-100 \leq Q_{G3} \leq 300$ MVAR. The initial conditions of the voltage phase angles are 0°.

First, the multi-objective OPF is solved to determine the economic and environmental dispatch of the 9-node power system without considering the integration of the renewable energy source models. This case is considered as the base case. Subsequently, two study cases are carried out in which the renewable energy source models are integrated in a) the energy supply nodes and b) in the nodes where the greatest amount of load is installed, in order to observe the effect that clean energies have in the different SEP operating areas.

In both cases, a wind power plant with a generation capacity of 35,725 MW and a photovoltaic power plant with an active power of 48,094 MW are integrated simultaneously. It is important to mention that in the OPF analyses carried out, the cost function and the emissions function are combined in the global function with the same weight factor, in order to analyse the operation of the power system, giving equal importance to the economic and environmental aspects.

In the first case study, a wind power plant is integrated at node 7 and a photovoltaic power plant at node 9, both of which are nodes at which energy is supplied to the power system. A brief comparison of results with and without the integration of renewable energy sources is presented in Table 2, while Figure 1 shows the voltage profile obtained when renewable energy sources are integrated.

Parameters	Without P_W y P_S	With P_W y P_S
P_G (MW)	318.001	235.36
Q_G (MVAR)	5.818	2.44
P_{losses} (MW)	3.001	4.177
Q_{losses} (MVAR)	-109.182	-112.551
Cost ($/hr)	1134.055	885.492
Emissions (lb/hr)	845.603	702.8172
Global objective function	1129.8	910.526

Tabla 2 Summary of results with and without simultaneously connected renewable energy sources at the energy supply nodes

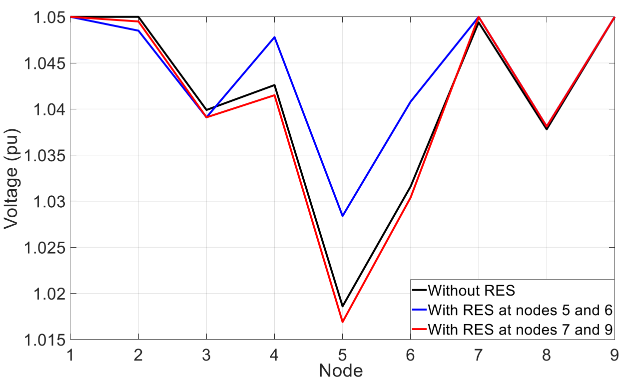
In the second case, wind and PV power plants are integrated at load nodes 5 and 6, respectively. A summary of the results for this case study is shown in Table 3, which compares these results with those obtained in the base case.

Parameters	Without P_W y P_S	With P_W y P_S
P_G (MW)	318.001	232.49
Q_G (MVAR)	5.818	-12.64
P_{losses} (MW)	3.001	1.307
Q_{losses} (MVAR)	-109.182	-127.646
Cost ($/hr)	1134.055	878.183
Emissions (lb/hr)	845.603	699.995
Global objective function	1129.8	904.992

Tabla 3 Summary of results with and without simultaneously connected renewable energy sources at load nodes

As expected, the results presented in the tables above show that integrating renewable energy sources decreases active power generation because less power is demanded from the generators to meet the load and losses in the transmission elements. It is clear that reducing active power generation reduces both the cost of generation and carbon dioxide emissions. It is important to emphasise that, according to the results shown, generation costs and CO_2 emissions decrease when renewable generation plants are installed close to consumption centres, due to the decrease in transmission element losses.

However, it is sometimes not possible to install clean power plants close to loads, as they are limited to the availability of wind and sun. Fortunately, in Mexico there is photovoltaic potential over the entire surface of the country, which can favour a location of renewable energy plants as close as possible to load centres, in order to improve the economic and environmental operation of power systems. On the other hand, with the integration of renewable energy sources, generation and reactive power losses are reduced, which translates into an improvement in the nodal voltage profile of the power system, as shown in Graphic 1. Node 5 has a lower voltage, as it is the node where the largest load is connected to the power system. The integration of wind and photovoltaic power plants at the energy supply nodes of the power system does not cause significant changes, unlike the case in which they are installed at the load nodes.



* RES: Renewable Energy Sources.

Graphic 1 Nodal voltage profile considering the effect of renewable energy sources

Finally, it should be noted that active power losses are higher when adding renewable energy sources to the power system, which is due to the redistribution of power flows that occur in the system.

Conclusions

An analysis of the economic and environmental dispatch, where CO2 emissions and the cost of active power generation are minimised by integrating the wind and solar energy source models, has been presented. According to the results obtained, it can be concluded that by integrating the renewable energy source models there is a reduction in carbon dioxide emissions and generation cost, thus improving the economic and environmental operation of the power system, despite the increase in active power losses.

Similarly, it is concluded that the integration of renewable energy sources improves the nodal voltage profile of the system due to a decrease in generation and reactive power losses. Finally, it should be mentioned that the cost of generation and carbon dioxide emissions decrease considerably when generation plants with renewable energy sources are installed close to power consumption centres.

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