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doi:10.15199/48.2017.04.33

Optimal Capacity Planning of Renewable Distributed Generation in Active Distribution Networks to Reduce Greenhouse Gas Emissions

***Abstract**. This work presents an evaluation of the maximum capacity of renewable distributed generation that can be connected to active distribution networks to minimize the greenhouse gas emissions of the electric network. The study aimed at obtaining a methodology applicable to active distribution networks with characteristics of variable generation and demand in order to reduce greenhouse gas emissions from electric power generation activities. The formulation of the methodology is based on an optimal power flow model incorporating special system controls.*

Streszczenie.** W artykule rozważa się maksymalna pojemność odnwialnych źródeł energii rozproszonej która może być dołączona do aktywnej sieci rozdzielczej dla zminimalizowania emisji gazów cieplarnianych. Metoda polega na modelu optymalnego przepływu mocy uwzględniającym sterowanie systemem. **Planowanie optymalnej pojemności odnawialnych źródeł energii w aktywnej sieci rozdzielczej w celu redukcji emisji gazów cieplarnianych

Keywords: greenhouse gas emissions; distributed generation; active distribution networks; wind energy.
Słowa kluczowe: gazy cieplarniane, energia rozproszpona, źródła odnawialne

Introduction

In the last decade, the phenomenon called global warming has been associated with the increase of greenhouse gases emitted during the combustion of fossil fuels like oil, coal and gas. The current conventional generation systems that use fossil fuels emit large amounts of greenhouse gases to the environment. Renewable energy sources are those whose origin lies in natural phenomena, processes or materials that can be converted to usable energy to mankind and is naturally regenerated. Thus, are available continually and periodically.

Distributed generation (DG) is an electric energy generator connected to the electric distribution network or directly to the load consuming electric power. Distributed generation that uses renewable energy sources to generate electricity are called renewable distributed generation (RDG). The inclusion of RDG in distribution networks is a means of effectively reducing greenhouse gas emissions. Besides, DG can improve operational aspects of the network such as voltage profile and energy losses.

In [1], a methodology based on a multi-period optimal power flow (OPF) is proposed to evaluate the maximum variable distributed generation that can be connected to distribution networks using active network management (ANM) schemes. The schemes incorporated to the OPF include coordinated voltage control, adaptive power factor control and energy reduction. In [2], a multi-period OPF is proposed to evaluate the influence of ANM schemes on the maximization of wind energy utilization. In [3], a multi-period steady state analysis is proposed to maximize the connection of intermittent generation, using an OPF technique adapted for active network management. In [4], a technique based on a multi-period OPF is used to determine the maximum capacity of wind energy that can be connected to distribution systems considering control strategies such as dynamic evaluations and coordinated voltage control. To explore how stepwise voltage regulation limits influence the amount of DG that can be connected to distribution networks, the work presented in [5] incorporates voltage constraints in an OPF based method to determine the network capacity to accommodate DG. The work presented in [6] focuses on the innumerous strategies and methods that have been developed in the last years to deal with DG integration and network planning. In [7], a steady state analysis of time series is proposed to evaluate technical issues such as energy exports, losses and short-circuit levels. A multi-objective programming approach based on genetic algorithms is used to find network configurations that maximize wind energy integration, satisfying voltage constraints and line thermal limits. None of the works mentioned ([1]-[7]) consider the reduction of greenhouse gas emissions to the environment.

The objective of the study is the development of a methodology applicable in distribution networks with characteristics of variable generation and load to reduce greenhouse gas emissions derived from the electricity generation. Active distribution networks present variable generation and load characteristics and control devices to optimize network operation. The model includes the behavior of intermittent generation connected to the network, variable demand behavior and the performance of control devices.

The optimization methodology used is based on the formulation of an OPF method that considers all network operational conditions in the planning period (one year) to truly obtain an optimal solution. This fact justifies the formulation of a multi-period OPF with adequate control devices embedded that captures the generation and load variable behavior. The use of an OPF to optimize only one static generation and load condition can lead to sub optimal results. Usually, network planners and scientific papers consider worst case scenarios such as minimum demand and maximum generation. Currently, with the deployment of smart grids, new methodologies need to be developed and applied. To reduce the number of periods (hours) to be analyzed by the methodology, preserving the behavior and inter-relationship between generation and load, data aggregation techniques are employed in accordance with the characteristics of similar periods. The modeling of intermittent generation connected to the distribution system is done using time series of availability of primary energy resources in the region covering the distribution system. This primary energy availability is converted into power output for the RDG. The modeling of the loads is made considering typical demand curves for distribution system users.

Methodology

For optimization applications and depending on the network size, number of RDG units, control schemes, etc., time series analysis requires a large computational load. To decrease the number of periods to be analyzed, preserving the behavior and interrelationships between generation and demand, aggregation techniques are used in accordance with the characteristics of similar periods.

Time-Varying Generation

The intermittent generation connected to the distribution network is modeled using time series of availability of primary energy resources in the region covering the distribution system. This work considers wind energy as primary energy resource but other ones can be considered, such as solar. The wind speed data over the year were obtained from the Brazilian National Institute of Meteorology (INMET) of the Ministry of Agriculture, Livestock and Supply. Fig. 1 shows an example of wind speed data throughout the year. Thus, each wind speed data is converted into available electric power at the RDG output using the power curve data of the wind generator chosen.

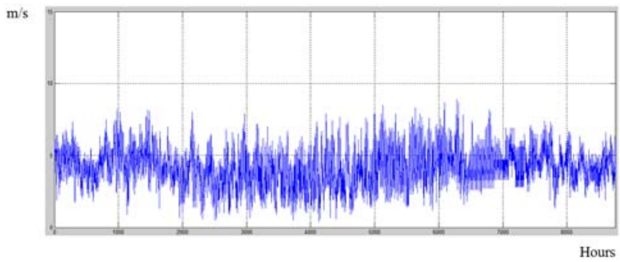

Fig.1 Wind speed over the year.

Time-Varying Demand

The variable demand modeling over the year is done using typical daily seasonal demand curves [11]. For simplicity, and considering similar consumer behaviors, the same seasonal demand curves for all bars of the distribution network were used. Distinct curves that consider consumer behavior to demand response programs, and analysis of their effects on the operation of the network will be considered in future work.

Aggregation techniques of hourly time series according to the characteristics of similar periods were used to reduce the number of data to be analyzed, preserving the behavior and interrelationships between generation and demand. For each hour, the potential generation and demand is allocated to an interval or period. The multi-periodicity is achieved by relating each combination of coincident generation and demand (period) in the year to its duration τ_m where m designates a period. Figure 2 shows an example of the number of periods to be analyzed [1], [4], [8], [10].

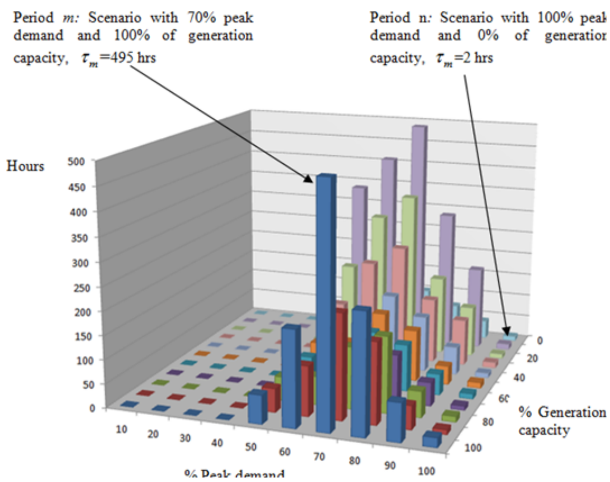

Fig.2. Coincident hours for each scenario of load and generation

The use of real-time control and communications systems forms an Active Network Management (ANM). Active management is based on real-time measurements of the parameters of the distribution network and employs real-time control of generators, tap changing of transformers, reactive power compensators and communication between generators and voltage control devices. ANM schemes used in this work are coordinated voltage control, adaptive power factor control and energy curtailment [1], [4], [13]. These ANM schemes are included in the OPF as operational constraints.

Multi-Period AC Optimal Power Flow

The optimal power flow is a constrained optimization problem in which the solution of this problem determines the best operating point of the system by optimizing an objective function subject to a set of constraints. The OPF can be represented mathematically by a general optimization problem with equality constraints, inequality constraints and variables limits. The proposed approach, based on the formulation of a multi-period nonlinear OPF, was elaborated in order to maximize the exploitation of wind energy, including active management systems and the time varying characteristics of load and wind generation [1]-[4], [6], [8], [14].

Objective Function

The basic formulation of multi-period OPF minimizes emissions of greenhouse gases to the environment by minimizing the non-green active power flowing into the distribution network through external connections [15] in the whole set of periods (planning horizon), according to the following objective function:

$$(1) \qquad Min(CO_{2emissions}),\ \forall m \in M$$

where:

$$CO_{2emissions} = (p_{x,m})(\tau_m)(K_{CO_2-grid}), \forall x \in X, \forall m \in M$$

$$p_{x,m} = p_{d,m} - \sum_{g \in G} P_g$$

where $CO_{2emissions}$ are the carbon dioxide (CO_2) emissions due to non-renewable energy purchased from the grid in tons (t). M is the number of periods and m is the identification of each period. X is the set of external connections to the network and x is the identification of each external source. $p_{x,m}$ is the active power purchased from the transmission network and τ_m is the number of hours of each period. $K_{CO2\text{-}grid}$ is the factor of carbon dioxide emissions of the energy purchased from the transmission network in ton CO_2/MWh. $p_{d,m}$ is the total demand in period m and p_g is the active power generated by each RDG (capacity) in each period. G is the set of generators and g is the identification of each RDG.

Coordinated Voltage Control Variable Limits

The power transformer is a key element in electrical networks. It is used to adjust both the magnitude and the phase angle of the voltage. The transformers have taps in the windings to adjust the conversion ratio and tap changes can be made while the transformers are energized. These transformers are called transformers with on load tap changers (OLTC). In each period, the secondary voltage of the OLTC will be treated as a variable rather than a fixed parameter. Therefore, dynamically controlling the OLTC in the substation and the corresponding secondary voltage, more RDG capacity can be connected to the distribution network. The voltage on the secondary of the OLTC should maintain its value within the regulatory range [1]-[4], [9], [13]-[15].

(2) $$V_{bOLTC}^{-} \le V_{bOLTC,m} \le V_{bOLTC}^{+},\ \forall m \in M$$

where $V_{bOLTC,m}$ is the secondary voltage of the OLTC during the period m. V_{bOLTC}^{-} and V_{bOLTC}^{+} are the lower and upper voltage limits of the OLTC, respectively.

Adaptive Power Factor Control Variable Limits
The generation of reactive power of synchronous machines can, for a fixed amount of active power, be adjusted within the limits of the capacity curve through the excitation system. Wind turbines (WT), with electronic power controllers are able to provide necessary reactive power support to the network. The power factors of WT can be controlled so that the penetration of wind energy in the network is maximized. In each period, operating with unitary, leading or lagging power factors is feasible. The power factor angle of each generator is considered as a variable that must operate within a certain range of power factors[1], [2], [4], [9], [13]. This service can be considered within a market environment as an ancillary service.

(3) $$\phi_g^{-} \le \phi_{g,m} \le \phi_g^{+},\ \forall g \in G, \forall m \in M$$

where ϕ_g^{-} and ϕ_g^{+} are the lower and upper power factor angle limits of the wind turbine.

Energy Curtailment Variable Limits
In order to alleviate the problem of overvoltage, it may be necessary to reduce a certain amount of wind power injected into the network. To limit the power generated from WT, specific controls are needed. Thus, power output lower than the rated power is produced. The energy reduction is formulated by adding a negative generation variable at the same location of each RDG unit, solely affecting the constraints related to active and reactive nodal power balance[1]-[4], [9], [13]-[14].

(4) $$0 \le p_{g,m}^{curt} \le \omega_m p_g^N,\ \forall g \in G, \forall m \in M$$

Bus Voltage Level Constraints
Bus voltages are limited by maximum and minimum levels[1], [2], [4], [5].

(5) $$V_b^{-} \le V_{b,m} \le V_b^{+}, \forall b \in B, \forall m \in M$$

Where $V_{b,m}$ is the voltage level at bus *b*. V_b^{-} and V_b^{+} are the lower and upper voltage limits at bus *b*.

Bus Voltage Level Constraints
Each wind generator has limits of generating capacity [2], [5].

(6) $$0 \le p_{g,m} \le p_g^N, \forall g \in G, \forall m \in M$$

Grid Supply Point Constraint
The distribution network has external connections at the grid supply point (GSP) substation. The GSP is taken as the reference (slack) bus with the voltage angle set at zero. The constraints for the GSP are [1], [2], [4]:

(7) $$p_x^{-} \le p_{x,m} \le p_x^{+}, \forall x \in X, \forall m \in M$$

(8) $$q_x^{-} \le q_{x,m} \le q_x^{+}, \forall x \in X, \forall m \in M$$

Where p_x^{+} and p_x^{-} are the upper and lower limits of active power from the external source, respectively. q_x^{+} and q_x^{-} are the upper and lower limits of reactive power from the external source, respectively. In the Brazilian power market, the export of power from the RDG to the transmission grid leads to additional payments for the generators due to the use of the bulk transmission system. This was avoided by setting p_x^{-} equal to zero.

Active And Reactive Nodal Power Balance Constraints
The sum of the network supply and generation at a bus is equal to the total injected power into lines and transformers plus the nodal demand at the same bus. Kirchhoff's current law describes the active and reactive nodal power balance[1], [4], [5].

$$\sum_{l \in L / b_l^{1,2}=b} p_{b,m}^{L,T} + d_b^p \eta_m = \sum_{g \in G_b / b_g = b} p_g + \dots$$
$$\dots + \sum_{x \in X / b_x = b} p_{x,m}, \forall b \in B, \forall m \in M$$
$$\sum_{l \in L / b_l^{1,2}=b} q_{b,m}^{L,T} + d_b^q \eta_m = \sum_{g \in G_b / b_g = b} p_g\, tan(\phi_{g,m}) + \dots$$
$$\dots + \sum_{x \in X / b_x = b} q_{x,m}, \forall b \in B, \forall m \in M$$

where

$$\sum_{g \in G_b / b_g = b} p_g = \sum_{g \in G_b / b_g = b} p_g^N \omega_m - \sum_{g \in G_b} p_{g,m}^{curt}$$

$$\sum_{g \in G_b / b_g = b} p_g\, tan(\phi_{g,m}) = \sum_{g \in G_b / b_g = b} p_g^N \omega_m\, tan(\phi_{g,m}) - \dots$$
$$\dots - \sum_{g \in G_b} p_{g,m}^{curt}\, tan(\phi_{g,m})$$

where *B* is the set of buses and *b* is the identification of the bus. *L* is the set of lines and *l* is the identification of the line. The terms $p_{b,m}^{LT}$ and $q_{b,m}^{LT}$ are the sum of all injections of active and reactive power onto lines and transformers at b. d_b^p and d_b^q are the peak active or reactive demands at some bus *b*. η_m is the demand level relative to peak in period m. $q_{x,m}$ is the reactive power purchased from the transmission network and $\phi_{g,m}$ is the power factor angle of the wind turbine in each period m. p_g^N is the rated capacity of each RDG. ω_m is the generation level relative to nominal capacity as dictated by the variable primary resource in that period. $p_{g,m}^{curt}$ is the negative generation variable at the same location of each RDG unit. b_g is the index of the bus that has generators and G_b is the set of generators at bus *b.*

Implementation and Case Study
The set of FPO equations integrating the ANM schemes were coded in the AIMMS optimization modeling environment and solved using the CONOPT 3.14V solver.
The following analyses are based on a 24-bus 13.8 kV radial distribution network whose data is given in [17]. The distribution network is fed from the transmission system

through an OLTC power transformer. The maximum demand of this network is 3.63MW. The distribution network is shown in Fig. 3.

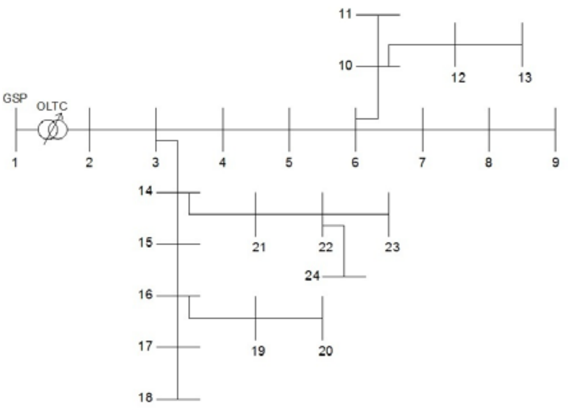

Fig.3. 24-bus distribution network[17].

The wind speed data are real hourly measurements (8760) from the city of Natal, Rio Grande do Norte, Brazil. Wind turbines (500 kW) are connected in buses 9, 13 and 20 of the distribution network. The installed power is 3.5 MW. The 500 kW wind generator output [18] is obtained using the frequency distribution curve of the wind speed. The power generated for each value of wind speed over the year is obtained using data from wind speed throughout the year and the power curve of the wind generator selected.

Table 1. Values of coincident hours of load and generation in each interval

% Generation capacity	10	20	30	40	50	60	70	80	90	100
0	0	0	58	474	199	227	411	288	42	17
10	0	0	268	1071	814	915	897	466	393	100
20	0	0	32	92	192	356	335	126	232	77
30	0	0	2	6	57	117	147	34	115	59
40	0	0	0	0	6	21	40	4	35	21
50	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	3	1	0	8	2
70	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0

% Peak demand

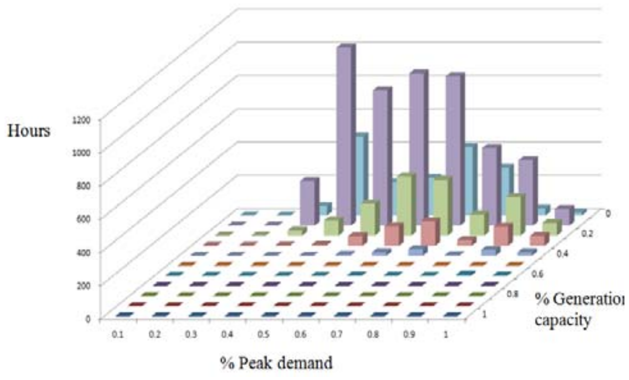

Fig.4. Coincident hours of load and generation in each interval.

The demand behavior modeling of the distribution network throughout the year is done considering seasonal daily load curves from the literature [11]. The demand at each node of the network is assumed to follow the load curve that represents possible behaviors of typical residential customers. The power generated by the wind turbines and the demand curve of the distribution network throughout the year are aggregated to reduce the number of data to be analyzed. The interrelationship between generation and demand is achieved by relating each hourly combination of generation and demand to its duration τ_m.Thus, for each hour, demand and potential generation are assigned to an interval. Demand has 10 intervals ([10%, 20%], [20%, 30%] ... [90%, 100%]) and generation has 11 intervals ([0%, 10%], [10%, 20%] ... [90%, 100%]). Table 1 and Figure 4 show the 44 non-zero sets and the number of coincident hours.

Results

Network Without DG

Table 2 shows the number of hours of operation, load values, power injected into the distribution network, emissions and power losses for each demand level. The total CO_2 emission from the distribution network without DG throughout the year is 2589.832 tons. The power loss of the network without DG is 104.75MWh.

Table 2. Values of coincident hours of load and generation in each interval

	Demand (%)									
	10	20	30	40	50	60	70	80	90	100
Hours (h)	0	0	360	1643	1268	1639	1831	918	825	276
Demand (MW)	0	0	1.08	1.440	1.800	2.160	2.520	2.880	3.240	3.600
Power Network (MW)	0	0	1.091	1.456	1.822	2.188	2.555	2.922	3.290	3.659
Emissions (ton)	0	0	51.47	313.5	302.6	469.86	612.89	351.46	355.63	132.3
Losses (MWh)	0	0	0.923	7.515	9.088	16.964	25.867	16.987	19.377	8.026

Network With Firm DG

Table 3 shows the number of hours of operation, load, firm DG, power injected into the distribution network, emissions and power losses for each demand level. The total CO_2 emissions from the distribution network with firm DG throughout the year is 2348.0 ton. The power loss of the network with firm DG is 146.0 MWh.

Table 3. Data and results of the network with firm DG.

	Demand (%)									
	10	20	30	40	50	60	70	80	90	100
Hours (h)	0	0	360	1643	1268	1639	1831	918	825	276
Demand (MW)	0	0	1.08	1.440	1.800	2.160	2.520	2.880	3.240	3.600
Firm DG (MW)	0	0	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Power Network (MW)	0	0	0.889	1.252	1.615	1.978	2.342	2.705	3.069	3.432
Emissions (ton)	0	0	41.9	270	268	425	562	325	332	124
Losses (MWh)	0	0	1.15	9.64	12.07	23.19	36.2	24.22	28.04	1176

Table 4. Maximum power generation in each period (MW).

% Generation capacity	10	20	30	40	50	60	70	80	90	100
0	0	0	0	0	0	0	0	0	0	0
10	0	0	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
20	0	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
30	0	0	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35
40	0	0	0	0	1.8	1.8	1.8	1.8	1.8	1.8
50	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	2.5	2.7	0	2.7	2.7
70	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0

% Peak demand

Network With RDG And ANM

The maximum capacity of RDG active power that can be connected to the distribution network in each period is obtained using the methodology presented in this work. Table 4 shows the maximum active power connected to the distribution network using ANM in each period. The maximum power obtained is 2.7 MW.

The CO_2 emissions to the atmosphere, resulting from electricity generation activities were also obtained. Table 4 shows the values of CO_2 emissions in ton for each period with RDG. The total CO_2 emissions from the distribution network using RDG with ANM and throughout the year is 2025.0 tons.

The total power loss of the network with RDG is 761.1 MWh.The total reduction in CO_2 emissions over the year is of 241.83 ton for the network with firm DG. This represents a 9% reduction of CO_2 emissions during the year in comparison to the distribution network without DG. Also the total reduction in CO_2 emissions over the year is of 571.16 ton for the network with RDG using ANM. This represents a 22% reduction of CO_2 emissions during the year in comparison to the distribution network without DG. Figure 6 shows the total reduction in CO_2 emissions over the year of the distribution network.

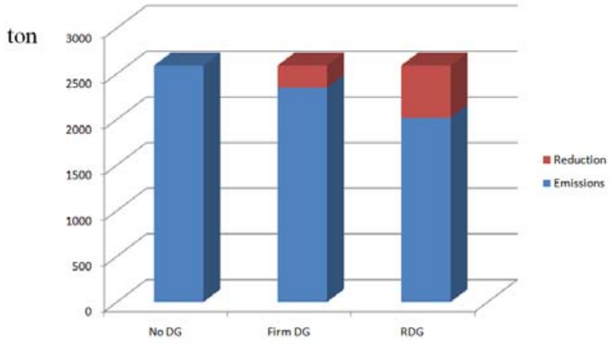

Fig.5. Total reduction of CO_2 emissions during the year.

The increase in total energy losses during the year is of 656.35 MWh for the network with RDG using ANM in comparison to the network without DG. This is due to the location of the RDG at the extremities of the feeder. If buses 3,6 and 16 are used for DG connection, the total increase in energy losses during the year is reduced to 45.35 MWh.

Conclusions

This article presents the development of a methodology for assessing the maximum active power generation of RDG that can be connected to modern distribution networks, using new control strategies, to reduce emissions of greenhouse gases to the environment, resulting from the generation of electric energy.

The methodology developed considers modern networks with features of active networks, which include variable demand and generation in time, actuation of control devices in real time and bi-directional power flow in the lines.

The results of this research show that the use of the optimization methodology developed in this project, based on the formulation of a OPF containing the strategy of ANM with schemes such as the coordinated voltage control, adaptive power factor control and energy reduction, allows higher GDR connection capacity in distribution networks to minimize greenhouse gases emissions to the environment resulting from the electric energy generation.

Future research should evaluate the technical benefits provided by the ANM strategy taking into account their characteristics to the good performance and cost-effectiveness of each scheme.

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