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Data-Driven Load Modeling to Analyze the Frequency of System Including Demand Response: A Colombian Study Case

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ABSTRACT This paper analyzes the potential impact of implementing demand response strategies in a power system. This work aims to present a methodology to evaluate three demand response models to reduce frequency variations in the system. The method starts with the modeling of the system load and the demand response strategies. The power loads are modeled through active power and reactive power measurements in the system's different buses. A data-driven methodology is proposed to obtain three profiles that simulate residential, commercial, and industrial users' behavior. Mathematical modeling is proposed for demand response strategies. Time of Use tariff, Solar PV Distributed Generation, and Load Curtailment are the strategies used for residential, commercial, and industrial users, respectively. A brand-new combination of scenarios is developed in this paper with different penetration levels of the demand response strategy. Besides, a novel analysis of the frequency profile is performed for the proposed scenarios. A modified IEEE-39 power system is proposed, adjusting generation and demand using the Colombian demand profile and the generating units' energy mix. The results indicate that the implementation of demand response strategies improves the system's frequency profile. The frequency drop was reduced by 11.4 %, and power generator units released up to 2.1 GWh through the day with the implementation of the DR strategies.

INDEX TERMS Demand response, load management, frequency analysis, renewable energy, DR strategies.

I. INTRODUCTION

The integration of new technologies into distribution networks, like distributed energy resources (DER) and advanced metering infrastructure (AMI), has allowed to modernized and dynamic network operation. Among the technologies, some devices allow demand to be an active participant in the market. One new source or agent is associated with the demand and can provide some services to the power systems [1]. The AMI devices allow developing demand response (DR) programs to improve the system's performance at a distribution level, significantly contributing to the power system's daily operation as ancillary services or reducing the uncertainty on-demand forecast [2].

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The DR could be a solution to maintain the balance between generation and consumption in a new scheme of operation, like smart grids or microgrids. Some incentives were offered to customers from the system operator (SO) to reduce the uncertainty in demand fluctuations. This uncertainty could reduce disturbances and increase the power grid's reliability and develop a modern power grid called the smart grid [3]. To develop DR in the electricity market was necessary to include information and communication technology (ICT) and advanced metering infrastructure (AMI) to promote the exchange of information and to analyses customer behavior [4].

DR solutions can improve the power system's expected behavior; some electricity markets worldwide show that the penetration level is near 5% of the residential demand [5]–[7]. However, studies about DR integration had found that the power system can include about 30% of annual electricity demand in flexibility options to reduce the generation reserve and deviation. The aforementioned implies that DR penetration can be higher than the expected penetration levels [8], [9].

Uses of DR programs in the distribution operation with a significant amount of Distributed Generation (DG) based on renewable energy are usually combined to reduce the DER forecast uncertainty [10]. Some DR strategies were based on other technologies like DG to complement some schemes and avoid the total disconnection of it [11].

In literature, the demand management techniques are based on the planning and scheduling of energy blocks to enable more inclusive control of the balance between generation and demand [12], [13]. In [14] showed that technological deployment and the interconnection of the electrical and data infrastructure provide many services to the electrical grid. However, it is essential to perform an integration study to take advantage of all the benefits of DR, including some associated with the ancillary services [2]. Uncertainty of electricity demand modifies the frequency response and the reserves. Still, it is necessary to define the optimal demand shedding to improve the demand side participants' economic benefits with optimization models that consider the stochastic nature of demand. DR strategies adapted to the distribution system support adjusting the performance of DER into a smart grid and adapt the electricity market to a new agent and different form to interact with the users, [2], [15], [16].

Among the main technical characteristics that SO can obtain from integrating the demand share or DR in operation, the flexibility enables responding to the imbalances present in the system [17]. On the other hand, DR is considered a distributed resource used in places where voltage issues and overload are placed. In [18] the paper shows some of the optimization models available for the DR and some guidelines to analyze their integration to the electrical power systems. DR can be used to delay investments in distribution networks to integrate the microgrid operation, and in [19] is proposed an optimization model to analyze the pricing and operation strategy including DR in a microgrid. The study shows that it is indispensable to coordinate all the DER in the energy system to obtain profitability to the agents, adjust and improve the reliability index, and optimize all the operations with DR [19], [20].

DR increases agent participation in the offer from a market and economic perspective, considering that they can have incentives [21] for the demand management or through the agreement in bilateral contracts with different structures to analyze the typical Real-time electricity markets to include the DR impact [22]. Other types of incentives are based on the daily price, including some devices [23], and modifying the demand's behavior. Some changes to include another agent, like an aggregator, manage the demand and reduce the generators' market power because of the financial incentives that promote the demand's active participation [24]. In [25], the incentives need to be adjusted or optimized to define the tariff policies to change the demand elasticity through econometric models.

In terms of frequency, demand control is an indispensable resource because of the fast response. The demand needs a robust infrastructure of AMI's to program load–relays to reduce the power load in a few seconds, provide frequency regulation, and help the fluctuation of the distributed generation [26], [27]. Authors in [4], defines that it was necessary to include data analyses to adjust the different behavior and implement a Multi Energy Systems that combine the distributed energy resources. With the DR's integration, the SO can manage the distributed energy resources, and the customer can offer their services to maintain the balance between demand and generation [10]. Different types of loads allow the time of response, which is necessary to categorize and reduce the impact of the distributed generation's fluctuation [28]–[30].

Figure 1 shows the bibliometric analysis of the references and a review that revealed that demand response agglomerate methodologies, proposals, and researches in one theme to develop new strategies to operate the electrical power system. The most robust links are smart grids and energy management through new agents and elements, including power systems and electricity markets.

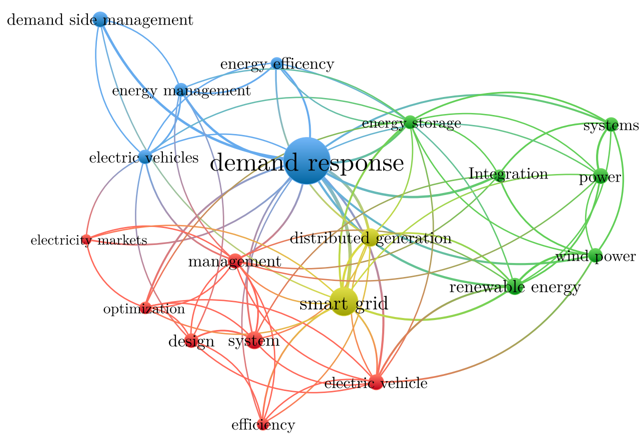


FIGURE 1. Keywords clustering and relationships for analyzed references.

Based on the analysis mentioned above, this paper presents DR's approach based on a modified study case that includes the Colombian demand curve and analyzes the frequency performance. The Colombian demand curve considers the residential, commercial, and industrial behavior to model various DR programs and reduce frequency variations. The proposed models for the different types of users are described as follows. The DR model for residential users is based on the Time of Use strategy program [31]. The DR residential model is characterized by maintaining the total amount of energy throughout the day. The second model implemented is for commercial users. The commercial users model is based on the massive implementation of distributed generation in these consumers. The third model implemented corresponds to industrial users. The industrial user model is based on the emergency DR scheme. The model describes a period and a power curtailment defined and established in a contractual process between the industrial user and the network operator. This paper contributes to developing a model that describes the behavior of the different types of electricity demand to contribute to the system's frequency.

- The model is implemented in the IEEE 39 bus modified with the Colombian demand curve to analyze the frequency behavior when Time of Use strategy in the residential and commercial demand.
- The commercial model includes the integration of DG to complement the real performance of this demand.
- For industrial demand, the model proposed is based on the emergency DR scheme to guarantee supply to that critical demand and minimize their disconnection.

The rest of the paper is organized as follows: In Section II, modeling the DR is presented in detail, including the formulation and description of different demand types. Section III provides international experiences in different DR implementations. In Section V, the main results are presented from the case study described in Section IV. Conclusions and future works are presented in Section VI.

II. MODELING

This section presents implemented models for the analysis of DR in power systems. Demand profile modeling is based on the measurements of the active and reactive of the network operator. In contrast, the demand response model is based on implementations made in other energy markets.

A. DATA-DRIVEN LOAD MODELING

This article proposes a two-stage approach to generating demand profiles in a power system. The proposed approach consists of the generation of demand curves by user types based on the historical measurements of the power system's active and reactive power. The first stage is the characterization of the demand curves from the recorded measurements. The second stage is the demand curves creation by user types. For this, a classification is defined that determines the user's consumption behavior.

The first stage determines the database structure of historical measurements of active and reactive power. Next, dispersion and expected values for a year of study are calculated from the dataset. Then, the expected value profiles of active and reactive power for the year of study are computed. In the second stage, the predicted value profiles of active and reactive power are normalized. This standardization has two objectives: to capture the behavior of the demand (active/reactive) on an hourly basis and the scaling of the installed demand of any test system. Finally, three types of users are defined for calculating the standardized demand curves in terms of active, reactive, and apparent power. Figure 2 and 3 show a schematic of the data-driven modeling approach presented in this section.

This study was conducted based on the historical measurements of the Colombian electrical system. The electrical

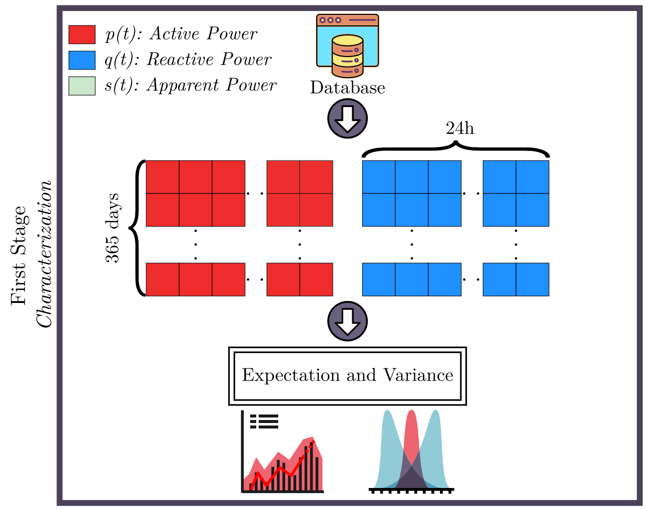


FIGURE 2. Data-driven profiles curve generation flowchart.

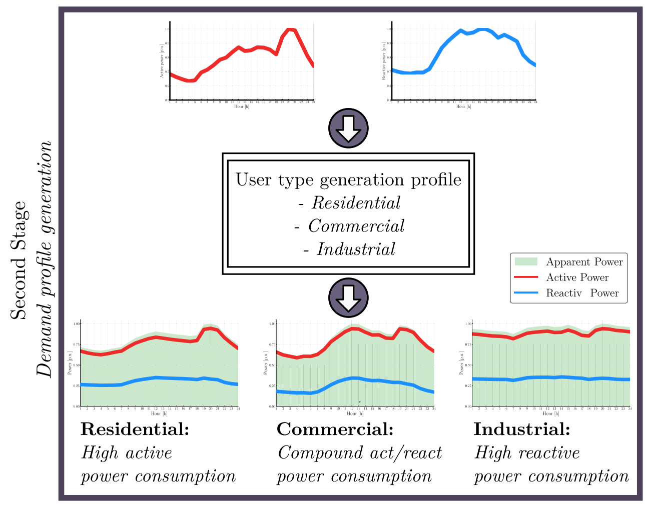
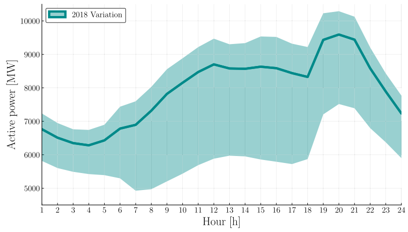


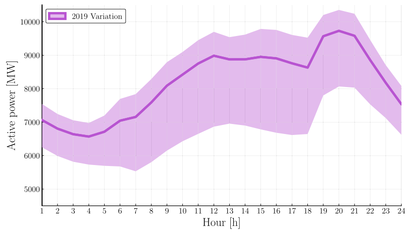
FIGURE 3. Data-driven profiles curve generation flowchart.

system's network operator records historical data-points of the active and reactive power consumption on an hourly basis for each of the system buses. The database is made up of hourly measurements for the time window between January 1, 2018, and December 31, 2019. Figure 4 shows in solid line the expected value of active power consumption and in the area the dispersion of power values for the 2018 and 2019 years. Figure 4 shows that the Colombian demand curve is primarily residential (around 70%) and follows the consumption habits related to homes and family groups' typical activities. Additionally, an energy consumption increment can be seen in the second year in Fig. 4, which is related to the growth in energy demand.

Three demand profiles are represented as three types of users: residential, commercial, and industrial. The main difference between each of the types of users is their active and reactive power consumption depending on the energy consumption activity that they perform. Residential users are characterized by having a power factor close to unity.



(a) 2018.



(b) 2019.

FIGURE 4. Year-demand comparison.

Besides, the residential curve has two significant consumption peaks, one at noon and the other at 19:00 and 20:00 hrs. Commercial users have an active power consumption starting at 10:00 hrs, given the associated business and market activities. The commercial curve has two peaks, one at noon and the other at 20:00 hrs. Finally, the industrial curve has the highest reactive power consumption because of the rotor loads associated with industrial activities. The industrial curve has mostly constant consumption throughout the day due to the corporations' production schedules. The demand curves for the three types of users are presented in Fig. 5. Table 1 shows the standardized active and reactive power data for each user type.

B. DEMAND RESPONSE MODELING

The DR is characterized by the change in the use of electric energy that end-users make of their consumption patterns, in response to changes in electricity prices over time, or to paid incentives designed to induce a decrease in the use of electricity due to price variations or when the reliability of the system is at risk [32]. However, these changes do not imply that users have to change or modify their style and quality of life [33].

Demand management is associated with the distributed generation connection since it allows the reduction of power generation during peak hours, the reduction of losses, relieving congestion in the network, among others, without the user having to reduce consumption [32]. Additionally, in state of the art, demand management without DG has been used to reduce congestion, which tends to flatten the demand curve, through the implementation of dynamic rates, in which users know the demand bands and the different prices per hour, to encourage the use of energy in the hours where electricity is less expensive [34], [35].

To be possible, the implementation of DR in the power systems requires that intelligent meters, integrated into demand,

TABLE 1. Standardized active and reactive power data.

Period	P_{res}	Q_{res}	P_{com}	Q_{com}	P_{ind}	Q_{ind}
1	0.67	0.26	0.66	0.18	0.88	0.33
2	0.65	0.26	0.62	0.18	0.87	0.33
3	0.63	0.26	0.61	0.17	0.86	0.33
4	0.62	0.25	0.59	0.16	0.85	0.33
5	0.64	0.26	0.61	0.16	0.85	0.33
6	0.66	0.26	0.61	0.16	0.84	0.33
7	0.67	0.26	0.63	0.17	0.82	0.31
8	0.72	0.29	0.69	0.21	0.85	0.33
9	0.76	0.31	0.78	0.26	0.88	0.35
10	0.79	0.33	0.84	0.3	0.9	0.35
11	0.82	0.34	0.9	0.33	0.9	0.35
12	0.84	0.35	0.94	0.34	0.91	0.35
13	0.83	0.34	0.94	0.34	0.89	0.35
14	0.81	0.34	0.9	0.32	0.9	0.36
15	0.8	0.34	0.86	0.31	0.92	0.35
16	0.79	0.34	0.87	0.31	0.9	0.34
17	0.78	0.33	0.83	0.3	0.86	0.34
18	0.8	0.32	0.82	0.29	0.85	0.33
19	0.93	0.34	0.94	0.29	0.92	0.34
20	0.94	0.33	0.93	0.27	0.94	0.34
21	0.92	0.32	0.89	0.26	0.93	0.34
22	0.83	0.29	0.8	0.22	0.92	0.33
23	0.76	0.27	0.72	0.19	0.91	0.33
24	0.7	0.27	0.67	0.17	0.9	0.33

Model 1 DR Model for Residential

Power model:

$$P^{\mathrm{DR}}[h] = P[h] + \left(\sum_{i \in h_{\mathrm{pk}}} P[i] \right) I_{\mathrm{DR}}[h] \tag{1}$$

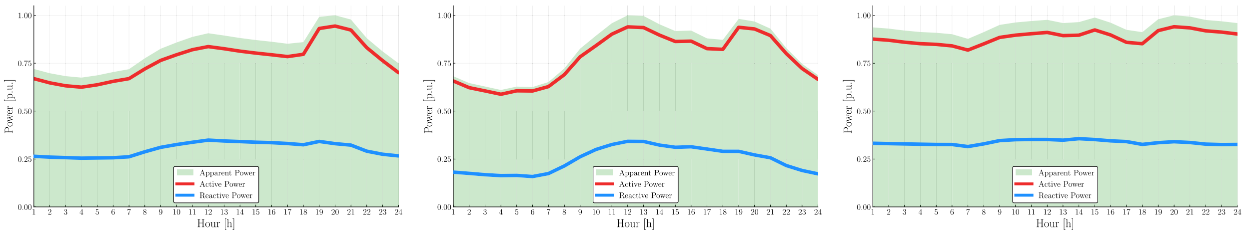
$$I_{\mathrm{DR}}[h] = \begin{cases} \dfrac{-\delta_r}{H_{\mathrm{pk}}}, & h \in h_{\mathrm{pk}} \\ \dfrac{\delta_r}{H_{\mathrm{pk\text{-}off}}}, & h \in h_{\mathrm{pk\text{-}off}} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

Where:

δ_r	Curve flattening index [0,1]	[p.u.]
h	Period index	
h_{pk}	Set of hours in peak	
$h_{\mathrm{pk\text{-}off}}$	Set of hours in peak-off	
H	Number of periods	
H_{pk}	Number of peak periods	
$H_{\mathrm{pk\text{-}off}}$	Number of peak-off periods	
I_{DR}	DR index	
P	Residential active power	[MW]
P^{DR}	Active power with DR penetration	[MW]

have control so that at some critical moments. Additionally, the smart measurement has information on the different electricity rates, classified as bands to encourage user consumption habits to flatten the curve [12], [36].

In this article, a DR model is presented for each type of user evaluated. The DR model for residential users is based



(a) Residential. (b) Commercial. (c) Industrial.

FIGURE 5. **Active and reactive demand profile per user type.**

Model 2 DR Model for Commercial Loads

Power model:

$$P^{\text{DR}}[h] = P[h] - \delta_c \sup\{P[h] : h \in H\} P^{\text{DG}}[h] \quad (3)$$

$$P^{\text{DG}}[h] = \begin{cases} \cos[\gamma(h - h_n)], & h \in \{h_{sr}, h_{st}\} \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

Where:

δ_c	DG penetration index [0,1]	[p.u.]
γ	Peak sun-hours index	
h	Period index	
h_n	Midday	(12:00)
h_{sr}	Sunrise	(06:00)
h_{st}	Sunset	(18:00)
H	Number of periods	
P	Commercial active power	[MW]
P^{DG}	Normalized DG power generation	[p.u.]
P^{DR}	Active power with DR penetration	[MW]

Model 3 DR Model for Industrial Loads

Power model:

$$P^{\text{DR}}[h] = \begin{cases} P_{\text{CL}}, & h \in H_{\text{CL}} \\ P[h], & \text{otherwise} \end{cases} \quad (5)$$

Where:

h	Period index	
H_{CL}	Set of periods in curtailment.	
P	Industrial active power	[MW]
P_{CL}	Power curtailment	[MW]
P^{DR}	Active power with DR	[MW]

on the implementation of the Time of Use strategy [31]. In the DR residential model, define a penetration index (δ_r) directly related to the curve's flattening. The penetration index is defined in the interval of [0, 1]. The maximum flattening is when the index equals 1 and no DR implementation when it equals 0. Two-hour blocks are defined (peak and peak-off) where changes in electricity prices are addressed to modify energy consumption. The flattening of the curve affects both the behavior of consumption of active power and reactive power. The DR residential model is characterized by maintaining the total amount of energy throughout the day. Fig. 6 shows an example of flattening a residential user's typical power curve.

The second model implemented is for commercial users. The commercial users model is based on the massive implementation of distributed generation in these consumers. The penetration of DG is modeled as active power between the hourly periods of sunrise and sunset (simulation of generation based on photovoltaic technology [37]). The model defines a penetration index δ_c that measures the amount of DG supposedly being installed. The variable index between [0, 1] and 1 is the total supply of the active power peak in the middle of the day. In Fig. 7 the model only presents active power injections and does not conserve the amount of energy consumed.

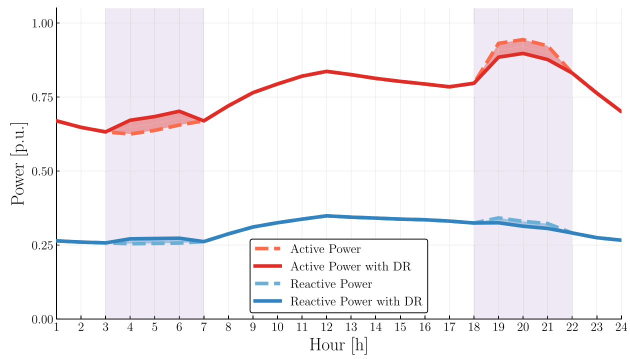


FIGURE 6. **DR residential model implementation.**

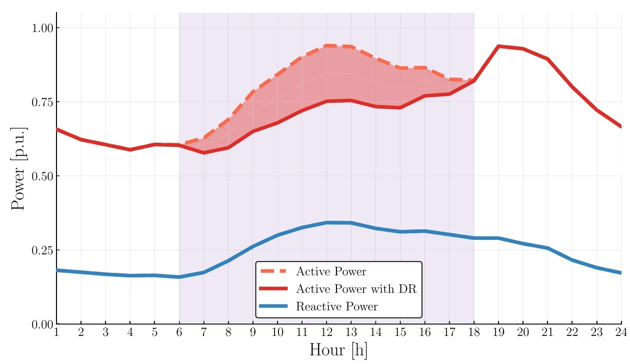


FIGURE 7. **DR commercial model implementation.**

The third model implemented corresponds to industrial users. The industrial user model is based on the emergency DR scheme. The model describes a period and a power curtailment defined and established in a contractual process between the industrial user and the network operator. The model is characterized by an active and reactive power reduction in the specified period simulating a load output. Fig. 8 shows an example of implementing the industrial users model. Typically, this model is used to curtail activated power blocks in periods of high consumption, such as peaks in demand between 19:00 - 20:00 in the Colombian electricity market. The three implemented models of demand response are fully parameterizable and applicable to any demand curve. The indexes and periods are described according to the different types of users' characteristics and consumption habits.

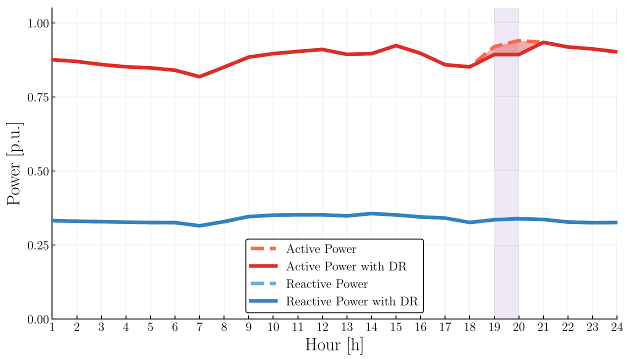


FIGURE 8. DR industrial model implementation.

III. INTERNATIONAL SUCCESS STORIES

A. GERMANY

Germany is one of the pioneer countries in adding clean energy policies, including a high percentage of non-conventional renewable energy. In 1991, the first law was created that gave the system the possibility of having a decentralized supply of renewable energy. Specifically, these type of unconventional sources supplies more than 30% of the energy demand. For this reason, significant challenges were sat for the energy sector. In many cases, the generation is entirely dependent on climate changes, there being certain seasons or hours of the day in which there is no continuous flow of energy generation. In general, energy demand management has to be divided into categories that allow the same objective to be achieved. These categories are energy efficiency, on-site generation support, and demand response.

Concerning this, Germany has currently developed adequate measures that have allowed us to increase the first two categories significantly. The insertion of new energy storage systems to the power system has been inserted as incentives that promote self-consumption laws, created in 2013 (KfWprogramm 275) [38].

Similarly, [39] identifies that Germany currently has an electrical potential of 6.4 GW/h in demand response, and with a good chance in the market regulatory framework, demand response may replace about 10 GW of generation plants. One of the fundamental requirements to carry out on-demand management is the addition of meters and electricity consumption data collection, which must be carried out utilizing ISO 50001 and EMAS certification. Until 2016, Germany had more than 90,000 companies that had this certification. Specific industrial processes can produce 2,660 MW in this country, which can be offered to the system. Therefore, three markets have been developed that allow use in the German electrical system. These are the spot market, the primary, secondary, and tertiary reserve market, and the market created by the interruptible cargo ordinance. However, most of these industries use the tertiary reserve market [38]. Furthermore, in this country, different incentive policies have been implemented that are related to customer demand. Today, energy providers offer a variable rate with an incentive for energy savings, where it varies over time about the load on the system [40].

B. CHILE

In recent years, Chile has had a prominent growth in energy production from renewable energy sources since they have great natural resources to be used. In 2008, law 20257 was defined as 10% of the demand due to being supplied by non-conventional renewable sources. Likewise, the generation incentives of this country continued to grow even more in 2013. Law 20,698 was defined, which states that non-conventional renewable resources should supply 2025, 20% of the demand.

For this reason, the energy ministry has developed policies based on three fundamental pillars. a) energy at competitive prices. b) energy security. c) Environmentally friendly sources [41]. With this, a substantial investment has been made in network energy measurement equipment, allowing the interaction between demand and generation to be observed, from which pertinent decisions can be made [42]. Additionally, the Chilean Ministry of Energy defined that by 2050 the sector, such as the public, commercial and residential sectors, should take advantage of the potential of distributed generation and electricity demand management [38].

In the same way, in 2016, Law 20936 is defined, establishing a New Electric Transmission System and creating an Independent Coordinating Body of the National Electric System. In this, definitions such as energy storage and technological equipment are added for the first time. These storage systems are of great importance for demand response, as they provide flexibility to the system. Subsequently, in 2018, Law 21,118 is defined, which is intended to generate incentives in residential generators' development. Specifically, it is established that users will be able to inject energy into the network, where it is specified that the concessionaires must request the user the necessary measurement equipment and therefore define a tariff option [38]. Moreover, many of the actions taken to carry out incentives in this sector are carried out based on Germany's experience in this area.

C. SPAIN

In Spain, public entities and the national government have developed different initiatives, intending to control the country's demand more adequately [43]. Spain implemented different DR strategies in the past decade. For example, the *Energy Saving and Efficiency Strategy in Spain (E4)* was developed, relating to the *Madrid Saves with Energy* philosophy. Subsequently, Spain defined a *Renewal plan for household appliances in the community of Madrid*, where an incentive of €80 is given to household purchaser appliances that are part of the 2006 campaign [43].

Similarly, a night rate is defined in this country, where energy prices reach approximately half the day rate. It is established that daytime prices are somewhat penalized. Based on these tariffs, users tend to use their consumption more consciously [24], [44]. On the other hand, the Spanish Electricity Network (REE by stand-for in Spanish) defines an interruption contract with large industrial clients. This contract defines rate discounts for one year for users who are willing to reduce their consumption. REE currently has 3,700 MW defined for users with interruption contracts [43].

D. CAISO

The demand response has some requirements for its implementation and market participation. Market participation requires a programming coordinator and entry quality meters with ISO certification. Besides, the tender for ancillary services requires specialized certification and direct telemetry installation [45]. For the participating generators and the participating load to offer ancillary services, auxiliary services certification is required. The requirements are found in the ISO Rate Business Practices Manual for market operations, such as Participating Generator (GP) requirements and Participating Load requirements (PL). Generators and loads must establish and maintain telemetry with the ISO Energy Management System (EMS)

Proxy Demand Resources: End-use customers can offer demand response services directly to the wholesale market per day and in real-time through a demand response provider as proxy demand resources. The market uses a baseline energy calculation to determine the amount of energy-reduced [45].

The first is the Proxy Demand Resource (PDR), where the services are composed of energy, spinning reserve, and residual commitment unit (RUC). The market dispatch is economic daily and in real-time, and the description is made with offers in markets as supply [46].

PDR can offer financially in the following markets: energy day-ahead market, non-spinning reserve market of the previous day and real-time, and spinning reserve, the energy market in real-time of 5 minutes. On the other hand, the PDR must have a minimum load reduction: 0.1 MW (100 kW) for daily and real-time energy, 0.5 MW (500 kW) for advance, and real-time standby power with no turn and turn reserve. Finally, for smaller loads, they can be added collectively to achieve a minimum [47].

The proxy demand resource is a market participation model that allows the agent to offer demand response to the CAISO market independently to reduce the wholesale markets' load for energy and ancillary services. The load change facility is a newly developed market share model; enables a two-way dispatch product that rewards PDRs for increasing consumption during negative prices (i.e., oversupply events). Exclusive rules apply to the participating load model, which includes pumped hydroelectric storage. These resources act as a load while energy is used to pump water to higher elevation reservoirs; they then act as generators creating energy by releasing water back to the lower reservoirs [46], [47].

IV. CASE STUDY

This section describes the case study in which the implementation of the models of DR is evaluated. Initially, the characterization of the demand curves for electricity in Colombia is carried out. Subsequently, the 39 Bus New England System is used as a test power system for the case study [48]. The test system is adapted and scaled to simulate an equivalent of the Colombian electrical system where the demand response models scheme can be evaluated. The evaluation criteria will be a dynamic state analysis focused on the frequency of the system.

A. MODIFIED 39 BUS NEW ENGLAND SYSTEM

The 39 bar system is known as the *New-England* 10 machine system. In the system, each generator represents an equivalent of numerous generators connected to the bar. For the case study, this system is modified in voltage levels and is scaled in the load values to simulate the system's typical demand curves. Fig. 9 shows the single-line diagram of the modified system. Table 2 and Table 3 show the consolidation of the generator parameters and the modified system loads, respectively. For the generators, the connection node, the active power, the voltage level in p.u. and the apparent nominal power. For the loads, the nominal values of active and reactive power are detailed, and the bars to which they are connected.

TABLE 2. Data from generators connected to the system. Taken from [49].

Gen	Bus	Type	P [MW]	V [p.u.]	S_{nom} [MVA]
1	39	PV	1000	1.03	10000
2	31	SL		0.982	700
3	32	PV	650	0.9831	800
4	33	PV	632	0.9972	800
5	34	PV	508	1.0123	300
6	35	PV	650	1.0493	800
7	36	PV	560	1.0635	700
8	37	PV	540	1.0278	700
9	38	PV	830	1.0265	1000
10	30	PV	250	1.0475	1000

On the other hand, the software used to perform the simulations was PowerFactory DIgSILENT. Table 4 shows the parameters of the generators of the implemented model.

TABLE 3. Load data connected to the system. Modified from [49].

Load	Bus	P [MW]	Q [MVAr]	Load	Bus	P [MW]	Q [MVAr]
1	3	322	118.79	11	23	247.5	91.31
2	4	500	184.46	12	24	308.6	110.00
3	7	233.8	69.83	13	25	224	66.90
4	8	522	192.57	14	26	139	41.51
5	12	7.5	2.24	15	27	281	100.16
6	15	320	118.05	16	28	206	76.00
7	16	329	121.37	17	29	283.5	101.06
8	18	158	47.19	18	31	9.2	2.75
9	20	628	231.68	19	39	1104	407.28
10	21	274	97.67				

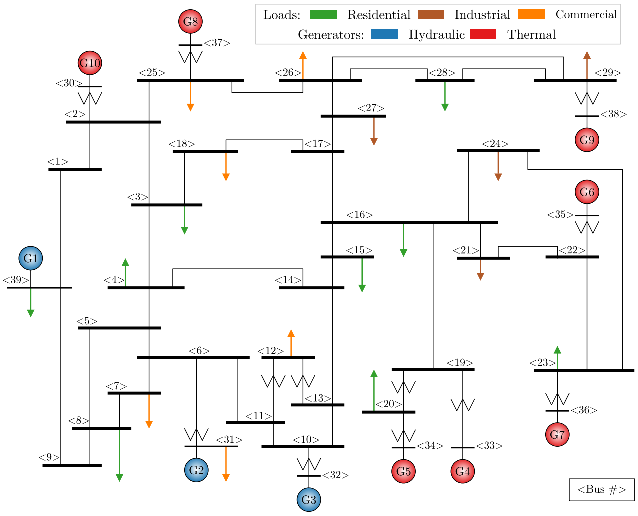


FIGURE 9. Oneline for modified 39 Bus New England System.

B. LOAD PROFILES WITH DEMAND RESPONSE PENETRATION

In the case study, the evaluation of different demand curves will be carried out, calculated from the proposed DR models. Initially, three scenarios were studied for residential users, where the flattening rate of the curve took the values of δ_r = 1/30, 2/30, and 1/10. On the other hand, for commercial users, the DG penetration rate evaluated was $\delta_c = 0.3$. Finally, it was established for industrial users that they would have a 10% reduction in their consumption in three periods of the day. The previously proposed scenarios were chosen to decrease the system's consumption peaks and relax the slopes in the demand curve. All to evaluate the impact these will have on the frequency and operation of the system. Fig. 10 shows the base case's demand profile with the implementation of all demand management strategies in the system. From this figure, it can be seen that the implementation of all these strategies helps to reduce consumption peaks and flatten the demand curve.

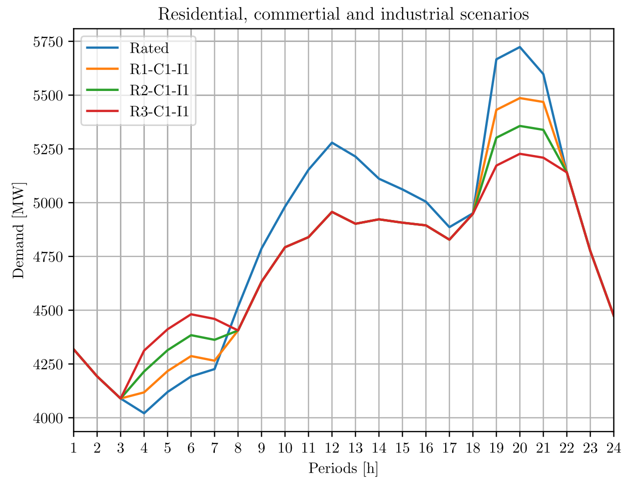


FIGURE 10. Result simulation residential users.

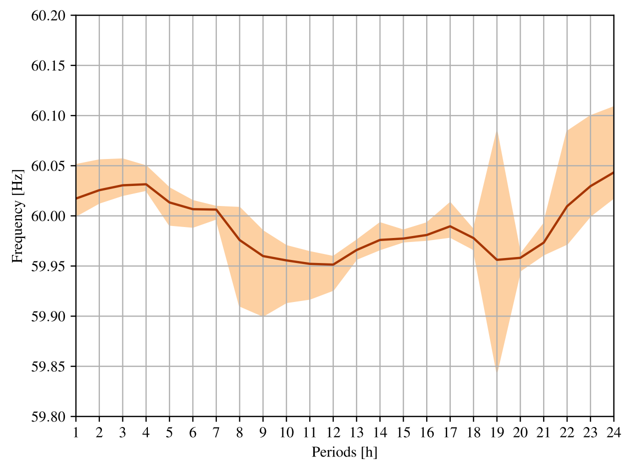
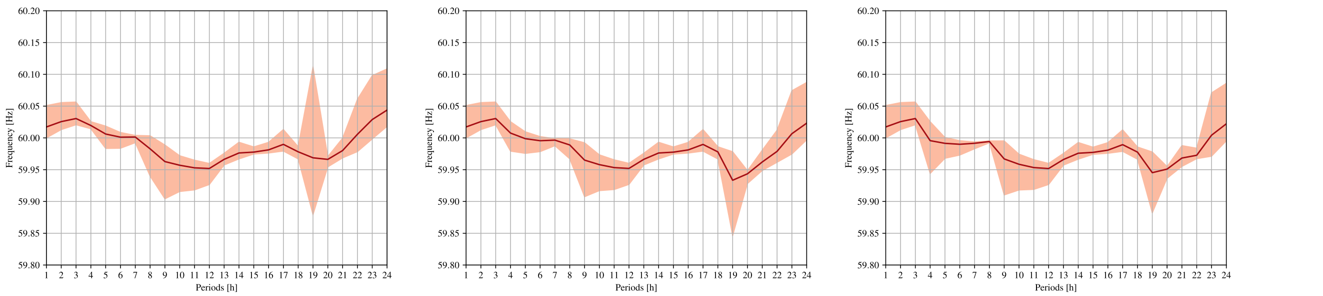


FIGURE 11. Result simulation base case.

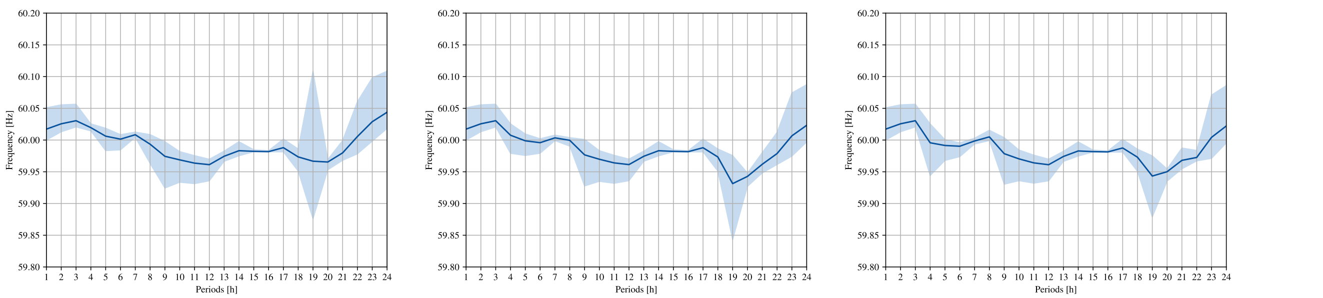
TABLE 4. Data of generators in the PowerFactory model (x"=x"d=x"q).

H [s]	Ra	x'd [p.u.]	x'q [p.u.]	xd [p.u.]	xq [p.u.]	T'd0 [s]	T'q0 [s]	xl [p.u.]	x" [p.u.]	T"d0 [s]	T"q0 [s]
5,000	0	0,6000	0,8000	2,0000	1,9000	7,0000	0,7000	0,3000	0,4000	0,0500	0,0350
4,329	0	0,4879	1,1900	2,0650	1,9740	6,5600	1,5000	0,0245	0,3500	0,0500	0,0350
4,475	0	0,4248	0,7008	1,9960	1,8960	5,7000	1,5000	0,2432	0,3600	0,0500	0,0350
3,575	0	0,3488	1,3280	2,0960	2,0640	5,6900	1,5000	0,2360	0,2800	0,0500	0,0350
8,667	0	0,3960	0,4980	2,0100	1,8600	5,4000	0,4400	0,1620	0,2670	0,0500	0,0350
4,350	0	0,4000	0,6512	2,0320	1,9280	7,3000	0,4000	0,1792	0,3200	0,0500	0,0350
3,771	0	0,3430	1,3020	2,0650	2,0440	5,6600	1,5000	0,2254	0,3080	0,0500	0,0350
3,471	0	0,3990	0,6377	2,0300	1,9600	6,7000	0,4100	0,1960	0,3150	0,0500	0,0350
3,450	0	0,5700	0,5870	2,1060	2,0500	4,7900	1,9600	0,2980	0,4500	0,0500	0,0350
4,200	0	0,3100	0,5000	1,0000	0,6900	10,2000	0,0000	0,1250	0,2500	0,0500	0,0350



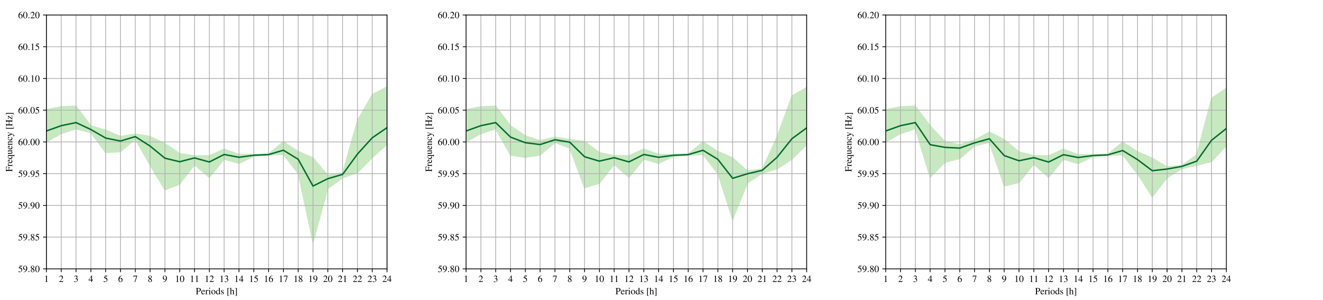
(a) Residential case 1. (b) Residential case 2. (c) Residential case 3.

FIGURE 12. Result simulation residential users.



(a) Residential case 1. (b) Residential case 2. (c) Residential case 3.

FIGURE 13. Result simulation residential and commercial users.



(a) Residential case 1. (b) Residential case 2. (c) Residential case 3.

FIGURE 14. Result simulation residential, commercial and industrial users.

V. RESULTS

This section describes the results obtained from the simulations developed. It is important to note that in the base case to maintain frequency levels between $60.2 - 59.8$ Hz, it was necessary to add an active power generation event to maintain the frequency in that range. Figure 11 shows the base case frequency, where the area plot shows the frequency variation and the line the average in each period.

The results are organized as follows: first, only the demand management scheme with the residential scheme's penetration was simulated with the previous section's penetration scenarios. Fig. 12 shows the results obtained from the simulations under different penetration levels of the DR implemented in residential users. The results show that the DR strategy's higher penetration leads to decreased frequency variations in the system. Additionally, the frequency profile is flattened by the deployment of the residential DR strategy.

TABLE 5. Statistical parameters of the frequency profile.

	Rated	Low Penetration	Medium Penetration	High Penetration
Mean	59.9902	59.9873	59.9872	59.9869
SD	0.0301	0.0269	0.0239	0.0218
Min	59.8446	59.8413	59.8774	59.9133
Max	60.1085	60.0868	60.0861	60.0846
Range	0.2640	0.2455	0.2087	0.1714

The first DR strategy implemented is the residential model. Then, commercial users with distributed generation were

TABLE 6. Comparative results for DR strategies.

	Residential	Commercial	Industrial
DR strategy	Time of Use strategy	Includes the integration of DG to complement the real performance of this demand	The emergency DR scheme
Impact in frequency	High frequency impact Device-free deployment Market share of users	Medium frequency impact Active power injections More flexibility for strategies	Reduced impact on frequency Impact on the specific time Control system in site
Variation in frequency	Slow flattening of variations Reduced impact even with large deployment	Same decreases as in residential Large solar plants can increase variations	Implementation in focused loads Poor impact on the reduction of variations

included. The impact of the injection of distributed generation in the different residential insertion levels was measured previously defined. Fig. 13 summarizes the case studies for the insertion of DG units. The results show that a high DG penetration exclusively affects the average frequency profile and has little impact on the variations. Finally, industrial users were the last to be analyzed as a flexibility strategy in the system. Fig. 14 shows how the industrial DR contributes to decreasing the consumption slope and allows an on-peak adjustment of the power demand.

Also, it was obtained that the power that was not delivered by the power system due to the distributed generation and voluntary disconnection of commercial and industrial users was 2.188 GWh. Likewise, it was evident that the frequency drop was reduced by 11.4%, considering that the initial generation event was not necessary to include it.

Table 5 shows an analysis of the proposed scenarios' statistical variables. The analysis variables are the mean as a measure of central tendency. The most significant impact occurs in the highest penetration of DR in residential users from the mean indicator. The second indicator presented is the standard deviation (SD) to measure the data's dispersion throughout the day. As a result, the smallest variation in frequency occurs again due to the higher penetration of the demand response. A progressive increase in the DR strategy's penetration improves the proposed indicators from central tendency and dispersion indicators. Finally, significant impacts on system performance occur due to the massive implementation of the DR strategy in residential users. For commercial and industrial users, the implementation of DR can improve specific peaks in the demand curve behavior. Table 6 shows a comparison between the different strategies implemented and the main impacts on the average frequency and frequency variation.

VI. CONCLUSION

In this paper, a demand response model that describes the behavior of the different types of electricity demand to contribute to the system's frequency has been proposed. Three models were integrated to reflect residential, commercial, and industrial clients' behavior in a normalized profile to analyze the system's frequency. The article described the workflow to perform an analysis of the frequency under different scenarios of demand response.

A model for residential users based on times of use tariff is proposed, where the periods and penetration percentages of the demand response strategy are defined. A model for commercial users is proposed based on the insertion of distributed generation of solar PV. In the commercial model, penetration levels are defined exclusively for active power, given the generation source. A model for industrial users is proposed based on load curtailment. The cut-off time and the maximum cut-off percentage were defined in the industrial user model.

The results show how reducing the demand profile produces a flattening of the frequency profile due to the demand response strategy. Furthermore, it shows a statistical variable analysis as indicators to measure the central tendency and the dispersion of the frequency profile. The simulation results displayed a reduction of frequency variations and peak values. These simulations explained that the DR programs need to be adjusted according to the power system and the different resources that were available throughout the day.

In future research, demand's stochasticity can be considered in the residential model to adjust the behavior. In these circumstances, the residential demand can have more participation in the market and consider the variability and the residential demand culture. Additionally, the integration of DG in all the demand models can be included in all the models to analyze a flexible operation and transmission support from the distribution system. The proposed research is focused on analyzing demand as an actor in the energy transition through active participation in the market and operation.

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