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A day-ahead energy market simulation framework for assessing the impact of decentralized generators on step-down transformer power flows

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ABSTRACT

The world wide expected high penetration levels of distributed generation technologies (DG) will modify the operation paradigm of power systems. In this context, this work presents a day-ahead simulation framework to predict, in quarter hour periods, the step-down transform power flow linking the interconnected power system with a distribution network highly penetrated by DG. The capability of integrating in a single platform the simulation of different types of loads, DG technologies and the network at both local and system levels, is recognized as the novel contribution of this work. By using an object oriented approach, different models have been integrated to represent the behavior of the DG. These models include weather changes, load management programs, and contract agreements between customers and suppliers. For the representation of loads, a clustering technique is used. Special attention is devoted to the representation of combined heat and power units and their dependency on weather conditions. Validation of the method and a practical application of the simulation framework to a case study, built with realistic data from German and Chilean distribution systems, are discussed. The results show the potential of the tool in the field of power system operation planning from both, the transmission and the distribution company point of view.

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1. Introduction

Distributed Generation (DG) can be defined as the integrated use of small generation units directly connected to a distribution system or inside the facilities of a customer [1,2]. Trends observed in some power markets suggest that in the future, a substantial share of electricity will be produced by technologies associated with DG in distribution and subtransmission systems [3]. These technologies encompass a wide range of subcategories characterized by fuel type, generation capacity, multiproduct capability, environmental impact and operation flexibility [4]. In the near future it can be expected that ultracapacitors, advanced flywheels, superconducting magnetic energy storage, and hydrogen production units will be integrated into many DG applications [5]. These applications allow intermittent renewable energy storage, bulk power system peak shaving, load leveling, and reserve management.

Increased use of DG will place higher uncertainties in the operation, due to their dependency on meteorological variables (i.e. wind and water inflows) and their operation strategies or modes, which are difficult to forecast. This imposes new challenges for the system operation management.

On the other hand, the structural changes, that have been associated with the arrival of competitive power markets, have placed higher requirements on day-ahead demand estimation. This is due to a more intensive participation of customers in the operation of the system, which is associated with more dynamic retail markets. An increasing problem in this area has been related with the privacy of information, as all players are competitive companies [6,7]. However, market agents share a common need for efficient system operation and prices, seeking profit maximization and risk minimization regarding price spikes [8,9].

To present the problem addressed in this paper, Fig. 1 shows a typical scenario, where different DG units and customers, at distribution level, are supplied by an interconnected system through a step-down transformer.

The curves on top of Fig. 1 correspond to the step-down transformer's power flow. The upper curve shows the situation without DG units. In this case uncertainties are mainly related to load behavior. However, when DG is incorporated in a large scale the resulting transformer power flow can experience a significant reduction. This situation is represented by the lower curve in Fig. 1. In this case, uncertainties increase as DG power injections depend on meteorological variables and independent operation

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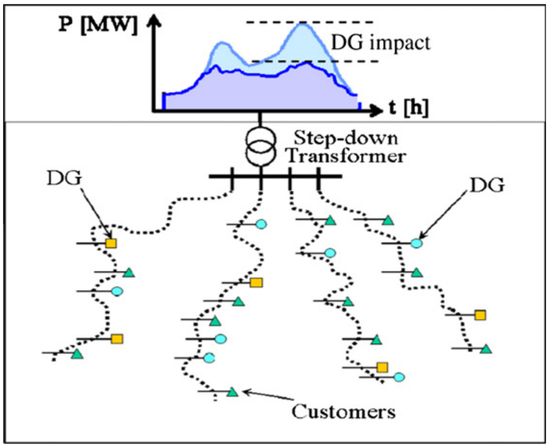

Fig. 1. Supply scenario with DG modeling.

modes of each unit. Therefore, the evaluation of the DG impact on step-down transformer's power flow is nowadays a complex task.

Moreover, DG integration has also promoted implementation of new concepts such as active or passive networks, for the operation of the first ones; Pecas et al. [10] propose a control approach that has two functional blocks: state estimation and control scheduling. The state estimation block uses the network electrical parameters, network topology, load models and real-time measurements to calculate a network state estimate, identifying the importance of load models to improve the network operation and planning. Thus, in order to evaluate the impact of DG connection to distribution networks on existing feeder and/or transformer reinforcements facing the natural load growth in the medium and long-term, Méndez et al. [11] deal with the net demand, which is calculated as the difference between the total load demand and the total energy production from DG connected to the network in each hour. For the previous works, demand modeling is performed for the whole feeder following consumption patterns. Other techniques to forecast demand behavior are based on ANN that can consider weather effects, like the one presented in [12].

Qian et al. [13] focus on the impact of load models on power loss calculation in DG planning. The main contribution is to investigate the impact of detailed load modeling on DG planning. The results presented help to understand the influence of each parameter that might affect power losses with the integration of DG on distribution feeders. Load models are constructed on three types of consumer patterns while DG are basically fuell cells and microturbines avoiding the uncertainty of those based on renewable energy. In [14], optimal capacity of PV and energy storage systems is discussed, the approach considers three types of consumers (industry, commercial building and shopping center), the load modeling consist of making use of historical consumption patterns while the PV generation is estimated based on solar radiation measurements. Complementary, Yamaguchi et al. [15] present a district energy system simulation model which contains a detailed energy demand model. This model adopted the bottom up approach in which the energy flow of a district is modeled as the sum of total energy input and output of each building. In this model, heat and power demands of each building are simultaneously calculated considering climatic conditions, occupant behaviors, use of appliances, adoption of energy saving measures, and etc.

This paper proposes a novel simulation framework for the estimation of the day-ahead step-down transformer power flows, with an explicit incorporation of DG technologies and their operation modes. The proposed framework encompasses several deterministic simulation models, together with a fuzzy clustering tool, which is used to model customer loads. The load flow forecast at the desired voltage level is the result of a bottom-up approach, obtained by the aggregation of different load profiles of customers that are supplied down-streams, and the accounting of the expected power delivered by DG.

The paper is organized in five sections. In Section 2 the proposed model for the network components, customers and DG units is described. Section 3 presents the proposed simulation framework and its integration into an object-oriented based decision support system. Section 4 presents the validation of the proposed model and its application within a realistic case study. Finally, Section 5 summarizes the main conclusions of this study.

2. System modeling

In order to achieve the proposed framework, three aspects are considered:

- System components.
- Customer models.
- DG Operational modes and technology models.

2.1. System components

The object oriented approach represents the state of the art in software analysis and design. It offers a flexible method to model the characteristics and behavior of the network components from a system point of view, including the DG technologies previously presented [6,16].

The system representation is carried out through three object oriented databases [6,17] (see Fig. 2). The equipment and component modeling is based on physical power system objects in the network database (NDB) and on hydro system components in the hydro database (HDB). On the other hand, a market database (MDB) contains market related objects like market actors and contracts.

Due to their high hydro generation dependency, an accurate HDB representation of hydro microturbines and their dependencies is an important issue in countries like Chile and Brazil. The individual characteristics of network, hydro and market elements are described by object attributes and the information exchange between objects and the operational behavior is performed by messages following the object-oriented programming paradigm. The object modeling technique in reference [18] has been used for developing the object models presented in this paper. One of the main advantages of the object oriented approach is the easy incorporation and extension of the model for new technologies, market actors and contract types. Furthermore, the methods related to the classes can be easily adjusted to new defined market and operation rules. Fig. 3a shows the hierarchy chart of the NDB. "NDB component" is the most general class and its attributes and methods are available for all subclasses [17]. Since simulation models are typically based on a node/branch-representation, these classes are explicitly included in the object-oriented data model. The class "Branch" is a child-class of the abstract class "2-Pole",

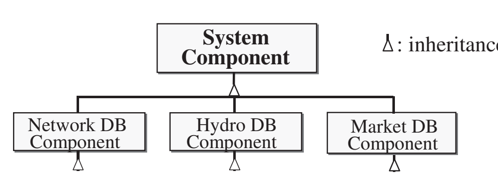

Fig. 2. Object model of the system.

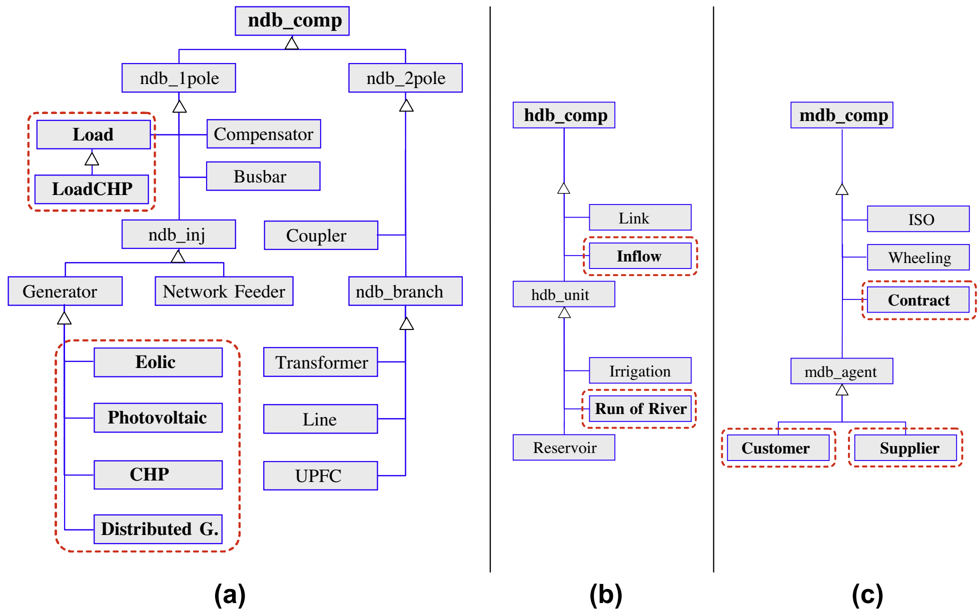

Fig. 3. Hierarchy chart of NDB (a), HDB (b) and MDB (c).

like transmission lines and transformer subclasses, generally characterized by a PI-schematic.

DG units inherit the attributes and methods of a conventional generator represented as 1-pole → injection → generator in NDB. Therefore it is not necessary to redefine reactive and active power output limits, nominal voltage, power factor, specified voltage, etc. In Section 2.3, specific new attributes and methods for each technology and operation mode are presented. In Fig. 3, Load CHP are loads in the system that includes the modeling of heat consumption, needed for a CHP operation representation.

Hydro microturbines are represented as run-of-river hydro units (without reservoir). Their generation depends on water inflows forecasting represented by inflows (see Fig. 3b). Finally, different types of agreements between customer and suppliers can be represented using a generic contract class (Fig. 3c).

2.2. Customer model

In this work, a customer is modeled as an MDB object with the capability to manage one or more electrical loads represented in NDB. As shown in Fig. 4, three different representations of loads can be identified: (i) Load profiles with cluster analysis, (ii) Deterministic load characterization and (iii) Interdependency of electric and heat profiles.

Cluster analysis applies to the majority of loads, where only the daily consumption is known. The basic assumption for load estimation is that there exist certain classes of customers that follow a common pattern. This is achieved by using normalized load profiles, for at least 12 different types of day (4 seasons times 3 days categories). Those patterns can be identified by a clustering process. This type of load modeling is gaining importance worldwide with the definition of flexible retail market design with participation of traders [19]. This representation also captures the representation of load management options within a framework of Demand Side Management programs. To illustrate this idea, Fig. 5 shows the measurement of several clients at different days (expressed in percentage of average load), grouped in two clusters, and represented the corresponding load profiles (bold lines).

Electric and heat loads correspond to consumption types with a strong dependency on heat requirements, which usually are

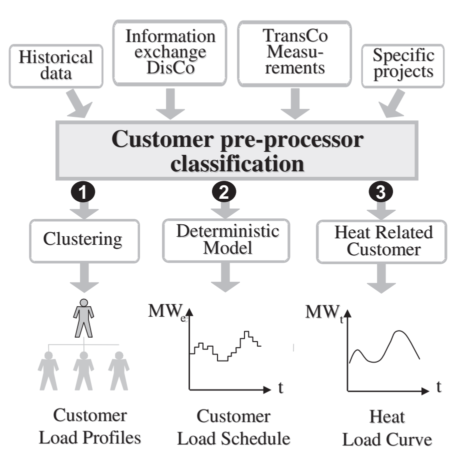

Fig. 4. Load models.

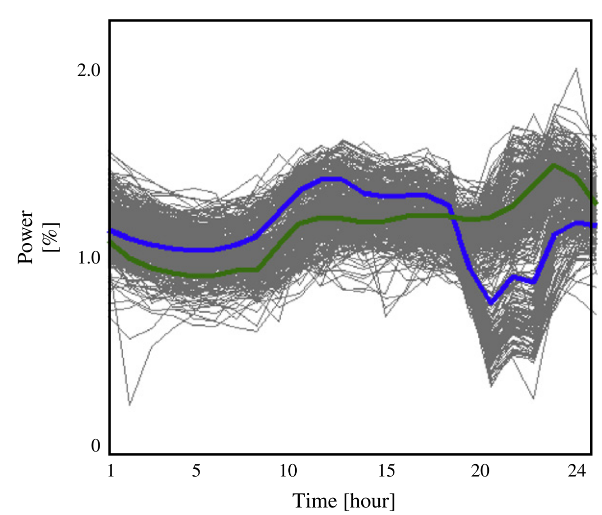

Fig. 5. Load profiles.

influenced by weather conditions. This kind of customers is represented by the power generation of Combined Heat and Power (CHP) [22] related generators.

Deterministic loads are predictable consumptions with known deterministic electrical behavior. Normally, these kinds of loads are associated with industry consumption modeling.

2.3. DG operation modes and DG technology models

In the context of this work, DG can be operated according to one of the following modes:

- C.1. Electricity-only.
- C.2. Heat following or CHP.
- C.3. Peak shaving.
- C.4. Virtual generator, Combined modes.

2.3.1. Electricity-only mode

In this group, the generation of electricity is mainly associated with primary energy resources that depend on weather conditions. Thus, the sale of energy and power depends on the availability of the primary energy, and they have very low or zero opportunity cost. Typically DG technologies that belong to this group are Photovoltaic Systems, Wind Generators and Hydro Microturbines.

2.3.1.1. Photovoltaic systems (PV systems). For PV systems units the output power $P(t)$ has the typical form shown in Fig. 6.

For a time period t it can be calculated by using the following expressions [20]:

$$P(t) = K_z \times K_c \times S \times \eta \times R_{\text{suf}}(t) \tag{1}$$

$$R_{\text{suf}}(t) = S_c \times T_k(t) \times \sin(\psi(t)) \tag{2}$$

$$\begin{aligned} T_k(t) = {} & (0.6 + 0.2\sin(\psi(t)))(1 - 0.4 \times \text{cch}(t)) \\ & (1 - 0.7 \times \text{ccm}(t))(1 - 0.4 \times \text{ccl}(t)) \end{aligned} \tag{3}$$

$$\begin{aligned} \sin(\psi(t)) = {} & \sin(\phi)\sin(\delta_s) - \cos(\phi) \\ & \times \cos(\delta_s(t))\left(\frac{\pi \times t_{\text{UTC}}(t)}{12} - \lambda_e\right) \end{aligned} \tag{4}$$

$$\delta_s = \phi_r \times \cos\left(\frac{2\pi(d - d_r)}{d_y}\right) \tag{5}$$

$$t_{\text{UTC}}(t) = t_{\text{local}} + \lambda_e \frac{12}{\pi} \tag{6}$$

where K_z is the zonal efficiency factor [0–1], K_c is electrical connection efficiency factor [0–1], S is equivalent PV systems panels surface in [m^2], η is PV panel efficiency [0–1], R_{suf} is surface radiation of the sun [W/m^2], S_c is solar constant, 1370 W/m^2 at the atmosphere surface, T_k is atmosphere transmitivity, ψ is sun elevation degree [°], cch is cloud cover high [0–1], ccm is cloud cover middle [0–1], ccl is cloud cover low [0–1], ϕ is location latitude [Radians] (north positive), t_{UTC} is universal coordinated time.[hh:mm:ss], t_{local} is universal coordinated time, λ_e is location longitude [Radians] (west positive), δ_s is sun declination degree [Radians], ϕ_r is tropic of Cancer latitude [23.45° = 0.409 radians], d is day number inside the year, d_r is day number of summer solstice (northern hemisphere), d_y is the average number of days in a year (365.25).

2.3.1.2. Wind generator (WG). The output power $P(t)$ of a wind generator is shown in Fig. 7. For a period t it can be represented by the following expressions:

$$P(t) = K_z \times K_c \times P_c(v(t)) \tag{7}$$

$$v(t) = \frac{\ln(z/z_0)}{\ln(z_r/z_0)} v_{z_r}(t) \tag{8}$$

where P_c is the power curve of the wind generator defined by the manufacturer usually as piece wise linear function, z is height of the generator rotor axis [m], z_0 is roughness length [m], z_r is height associate with the wind velocity data from the weather service [m], v, v_{z_r} is the wind velocity at height z and z_r respectively in [m].

2.3.1.3. Hydro microturbines (HM). In a day-ahead context, inflows in a river can be estimated on hourly steps for the next day. The coefficient ρ of following power output representation summarizes the performance of the unit considering height, type of turbine, network connection and electrical losses [21].

$$P(t) = \rho \times q(t) \tag{9}$$

where ρ is the hydro to electric power rate, q is the water inflow [m^3/s].

2.3.2. Heat following (CHP)

Heat following mode is mainly associated with units where the electricity generation is a byproduct of heat generation. In this mode, the electrical generation is strongly influenced by weather, usually measured by temperature. It is obtained directly from the expected heat generation by a CHP coefficient that depends on the DG technology that is being used. These coefficients are typically indicated by the manufacturer as a piecewise linear function. To determine the heat requirements, it must be considered the location of the building where the unit is installed, the year of construction, the daily temperature forecast and the equivalent number of units. Fig. 8 summarizes the calculation procedure. Typical DG technologies that belong to this group are Fuel Cells and gas microturbines [22].

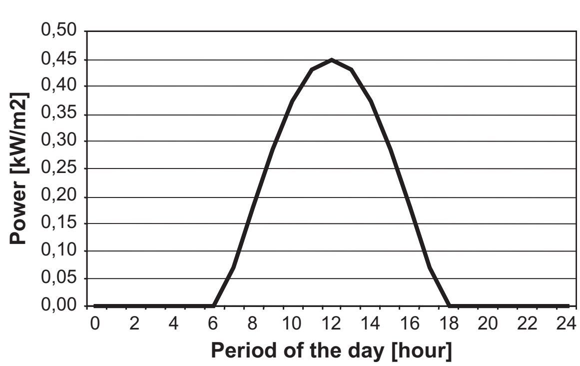

Fig. 6. PV systems typical power injection profile.

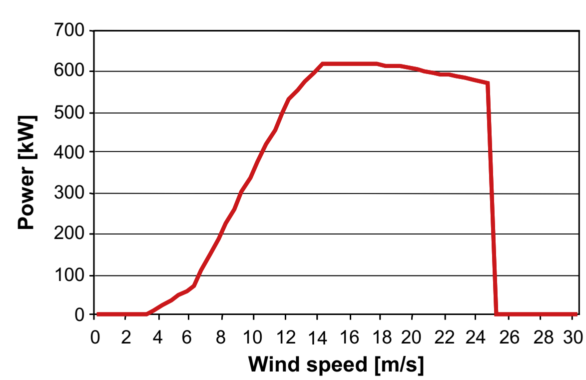

Fig. 7. Wind typical power curve. Source: NORDEX N3/600 kW.

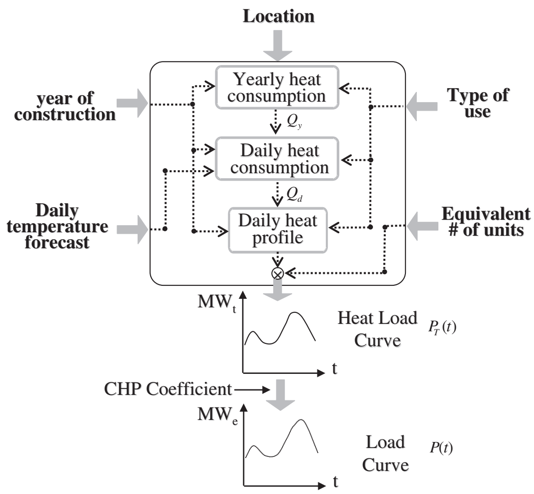

Fig. 8. CHP load profiles calculation procedure.

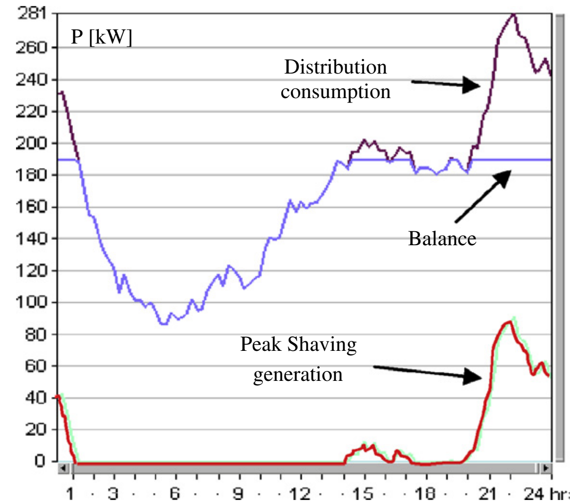

Fig. 10. Typical peak shaving mode operation.

Output of electric power $P(t)$ for period t is estimated using the following expressions [23]:

$$P(t) = K_c \times \mathrm{CHP}(P_T(t), t) \quad (10)$$

$$P_T(t) = \mathrm{DHC}(\mathrm{type}, \mathrm{year}, \overline{T}, t) \times Q_d \times N_{\mathrm{units}} \quad (11)$$

$$Q_d = \frac{h_p(\overline{T})}{h_{\mathrm{descaling}}}\overline{Q}_y; \quad h_p(\overline{T}) = \frac{A_S}{1 + \left(\frac{B_S}{\overline{T}-40}\right)^{C_S}} + D_S \quad (12)$$

$$\overline{Q}_y = \frac{Q_y(\mathrm{type}, \mathrm{location}, \mathrm{year})}{365}; \quad Q_y = f_v \times b_u \times Q_n \quad (13)$$

where CHP(.) is the heat to electric power rate defined by the manufacturer usually as piece wise linear function, $P_T()$ is heat consumption for period t, DHC(.) is heat consumption for period t extracted from a predefined database indexed by type of end use, year of construction, and $\overline{T}$ [kWT], $\overline{T}$ is average daily temperature [°C], Q_d is daily heat consumption [kWh/day], N_{units} is number of equivalent units considered, h_p is standardized heat usage value, $h_{\mathrm{descaling}}$ is h_p descaling factor, $A_s - D_s$ is coefficients of the Sigmoid adjusting function, Q_y is yearly heat consumption that depends on the type of end use, year of construction, and average temperature $\overline{T}$ with through following parameters [kWh$_T$], Q_n is specific heat demand [W/m^2], f_v is b_u descaling factor, b_u is the full usage hours.

Fig. 9 represents different types of contract agreements between customers and supplier objects, including the case of CHP modeling.

2.3.3. Peak shaving

Peak shaving mode is associated with units that operate mostly at peak load hours of the day. Due to price signals in the market they need to reduce the system power purchase during these hours. This mode can be modeled as an agreement between a customer and a supplier (Fig. 9). Fig. 10 shows a generator that is operated as a peak shaving unit.

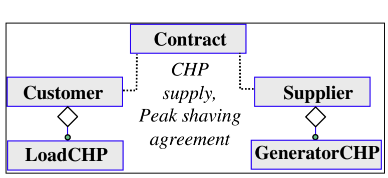

Fig. 9. CHP or peak shaving agreement.

The curves in Fig. 10 shows that the actual load (Balance curve in Fig. 10) is less than the distribution consumption (curve above), due to the presence of some peak shaving units (curve below). Thus, by neglecting the distribution losses, the consumption faced by the system equals the total consumption minus the peak shaving units' generation.

2.3.4. Other operation modes

The operation in a virtual generator mode allows the coordination of a group of DG in order to maximize profit selling power, energy, and ancillary services. The simulation of this type of behavior includes unit commitment techniques and market price simulations [4,24]. Finally, it is possible operate combining aspects of the previous presented operation modes.

3. Simulation framework

Fig. 11 summarizes the general structure of the proposed Daily Load Forecasting simulation framework for Distributed Generation (DLFDG). This simulation framework consist of two main elements: (i) A Database that integrates the previous described system

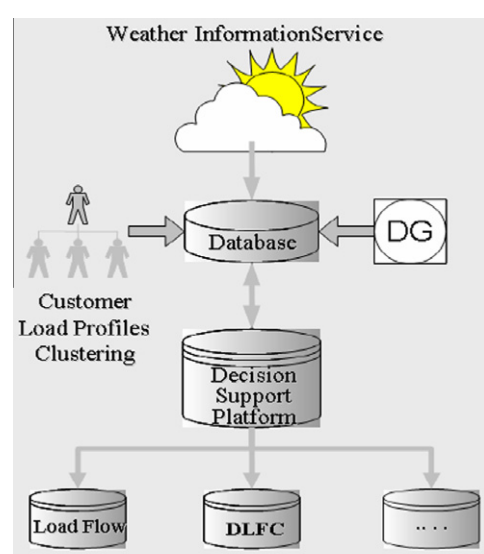

Fig. 11. Simulation framework.

modeling and simulation approach, encompassing the different DG technologies, customer representations, and *weather forecasts information*. (ii) The Decision Support Framework which is linked with the database and is able to execute the Daily Load forecast (DLFDG), Load Flow studies, and further analysis tools like shortcicuit estimation represented by the third box at the bottom of Fig. 11.

3.1. Weather information service

The influence of weather conditions in the electrical load behavior is already well known [22]. Load Forecasting methods make use of basic weather information like temperature, wind speed, humidity and cloud conditions. In comparison to the traditional methods, the DLFDG proposed approach uses additional weather information with a higher resolution. Table 1 shows the necessary data and resolution level for the implemented system components.

The daily average temperature for CHP technology is used to retrieve a heat demand curve from a historical database, which has an hourly resolution [23]. The database is constructed for specific building types and locations.

The estimation of weather data for the next day can be obtained by different methods. An effective way corresponds to the use of Internet weather services. These services offer basic and also specific data for a great number of locations, for the next three or more days, based on wide area measurement system and simulation models. Specialized services offer weather data forecasts for the next 48 h in hourly steps. Local databases can be updated using an automatic download of weather information services.

3.2. Database management

In order to enable simple expandability and maintenance of the proposed DLFDG system, all relevant data are separated from the application and stored in different databases as shown in Fig. 12. Due to this separation, changing and enhancements of existing models and data variation can be done without recompiling the whole system. Only changes of database structure and the introduction of new models require changes in the program source code.

Additionally to the object oriented databases presented in Fig. 3 (NDB, MDB, and HDB), which are associated to the simulation platform and depicted at the top of Fig. 12, the proposed DLFDG decision support system requires of several databases, depicted at the bottom of Fig. 12. Each kind of load (customer) and generation type is linked to a specific database. CHP database contains all data for heat controlled loads, like location, type, and year of construction. The records of the various wind generator models are held in DG database. The load profiles for the different customer's clusters are stored in Cluster database and all necessary weather records, as described in section 4.1, are integrated in weather database. Using en ODBC-JDBC-bridge and SQL-statements, the stored information is available for the simulation model.

3.3. Graphical user interface (GUI)

DLFDG is implemented in JAVA as a menu option in a larger decision support framework for power systems analysis called DeepEdit

Table 1
Weather model.

Technology	Weather information	Resolution
CHP	Average temperature	24 h
PV	Cloud cover level (high, medium, low)	(1/4 h) – 1 h
WG	Wind speed	(1/4 h) – 1 h
HM	Water inflows	(1/4 h) – 1 h

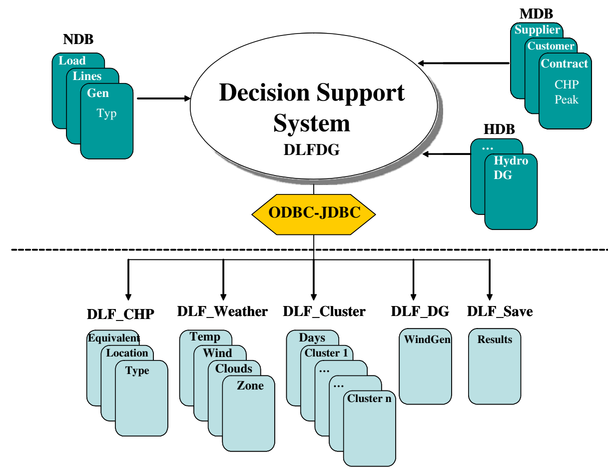

Fig. 12. Database model.

[6,25], which is available for research purposes in [10]. The authors decided to leave a free available simulation platform and test cases for validation purposes at http://centroenergia.cl/software/dlfdg/index.html. Fig. 13 shows the GUI of the developed system, which was defined based on the following goals: visualization of network topology, location and type of DG units; free selection of step-down transformers for DLFDG studies, easy overview of DG and loads behavior in quarter of hour steps (curves and reports).

4. Validation and case study

Several tests were developed, in order to validate the proposed model and to analyze the performance of the system in realistic operation conditions. A case study is presented in order to illustrate the scope of the developed framework from both System Operator (ISO) and distribution company point of view.

4.1. Validation studies

Validation was performed, by analyzing each module that integrates to the overall system. In order to do this, results were compared with real measurements (costumer load profiles) and previous studies (PV systems, WG, and H, and CHP). The most important aspects of this validation procedure are:

- *Customer load profiles:* Based on load measurements over a period of 2 years of 1.000 residential customers, provided by the distribution company that supplies the Santiago area, real and cluster load profiles were compared (Fig. 5). Results show a consistent behavior and acceptable mismatches [19].
- *PV systems, WG, and HM:* Several simulations were carried out for each one of these models, documenting coherence between the obtained results and reference information available. In the case of PV systems (Fig. 6), the results were compared with test cases [20]. For WG units (Fig. 7), the results were compared with the manufacturer curves associated with each model, manufacturers considered in the library of wind generators (DLF_DG database) are Vestas, NORDEX, REPower and Enercon. Especifically, NORDEX N29/250 kW, Enercon E-66 1500 kW were considered in the simulation studies. Finally, in the case of HM plants, a check of implementation was pursued, as the used models are considered as widely accepted and proven, as it is described in [21].
- *CHP*: Exact modeling of the heat demand of small buildings is a task which is still gaining importance in relation to the penetration level of dispersed CHP facilities. As no field measurements

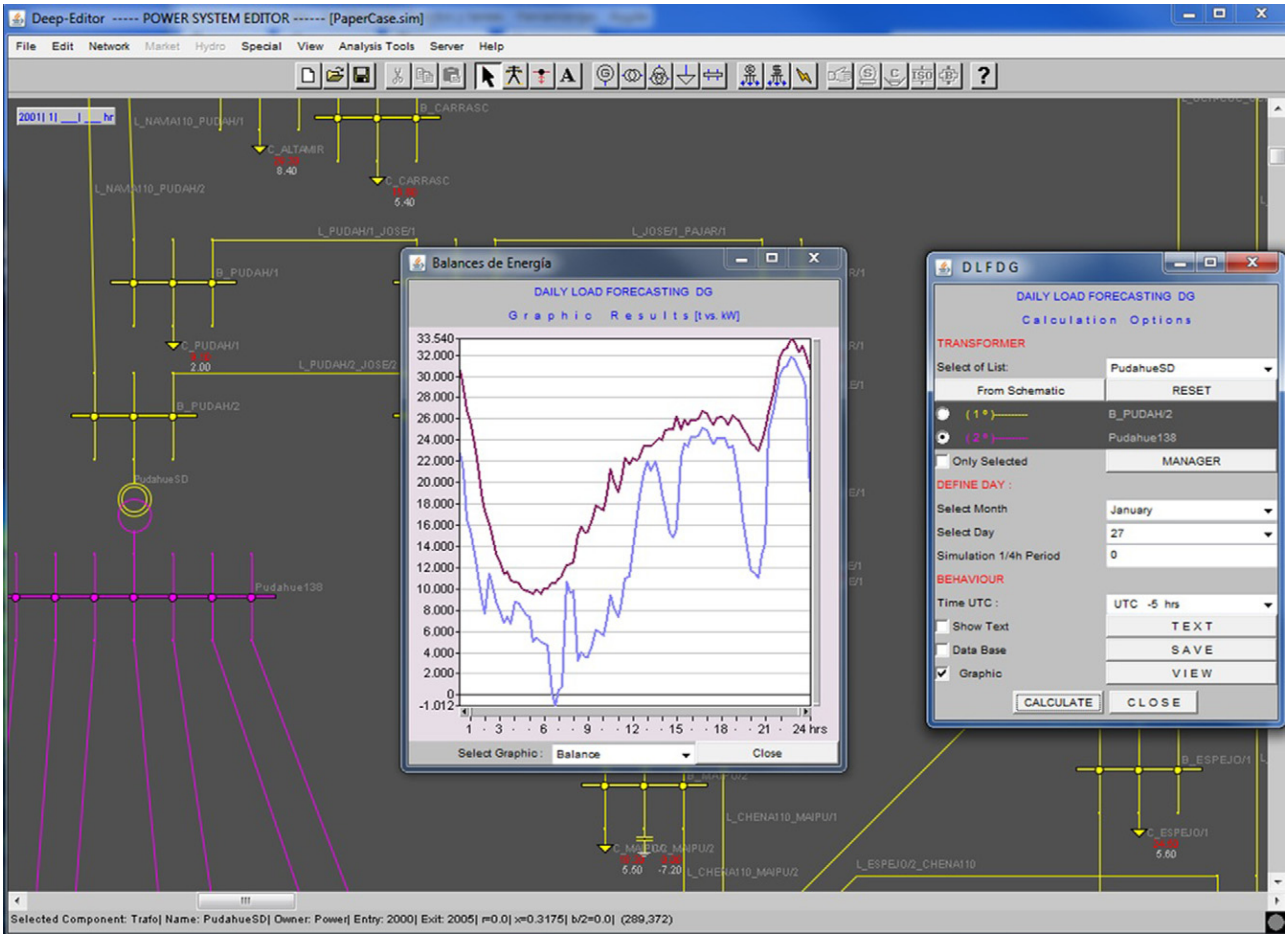

Fig. 13. Graphic user interface.

for this technology were available yet, theoretical models from the literature and public data were used. For validation purpose, an analysis using Ref. [26] proved the consistency of the model.

4.2. Case study

4.2.1. System description

The developed models and methods are applied to an electrical system that integrates transmission, subtransmission and distribution levels. The system corresponds to a future scenario with high penetration of DG (DG penetration equals 92.5% of the distribution system peak load). For transmission and subtransmission networks, a simplified model of the Central Interconnected System of Chile (SIC), based on real data, was used. The transmission level represents power lines energized at 220 and 500 kV while subtransmission network operates at 110 kV. Subtransmission represents nearly 40% of the SIC's total consumption and it is fed by five substations from the transmission system. On the other hand, for the distribution level, a fictitious network is built to meet the real conditions at the step-down transformer under consideration. Its topology is obtained from a typical German distribution system. The electrical parameters are taken from typical overhead distribution lines. The step-down transformer constitutes the system interface between the distribution and subtransmission levels. Fig. 14 shows the topology of the simulated network detailing the location of DG units. Table 2 summarizes the main features of the system [16].

The transmission and subtransmission network are modeled with equivalent loads of 2495.6 MW and 796 MVAr. The Slack bus is located in generation center in the south of the system.

Load composition includes 12 deterministic and 134 cluster modeled loads with a peak load of 28.1 MW. In addition 12 heat related loads are included in the simulation. As shown in Table 3, the simulated distribution network encompasses different types of customers and DG units. The composition of the technologies considers a major proportion of WG units, which is followed by conventional DG generators. This mix is in line with current deployment trends [3].

Once the necessary information is loaded into databases a single full day simulation with 96 (15 min each) steps is carried out requiring 1 seg in a 1.3 Ghz Intel U7300 processor with 3 GB RAM. Additionally each detail AC load flow study requires 2 seg for a full Newton Raphson algorithm.

4.2.2. System operator point of view

A DLFDG simulation is carried out for a typical working day in summer season using 96 quarter hour periods. Fig. 15 shows the resulting power injection for each DG type, the total consumption at distribution level, and the load faced by the Step-Down transformer (Balance curve).

Fig. 16 corresponds to a zoomed portion of Fig. 15 showing in detail the PV systems and CHP power injections, which are comparably low within this realistic case study.

The difference between the *consumption* and the *balance* curves corresponds to the total power injected by DG units, shown as *all DG units* curve in Fig. 15. The *balance* curve, compared with the original *consumption* curve, shows a highly irregular behavior during the day as shown in Fig. 15 between periods 60 and 80. This behavior can be explained by the variability of wind speed during the day. For the interval of maximum daily load (28.1 MW in period

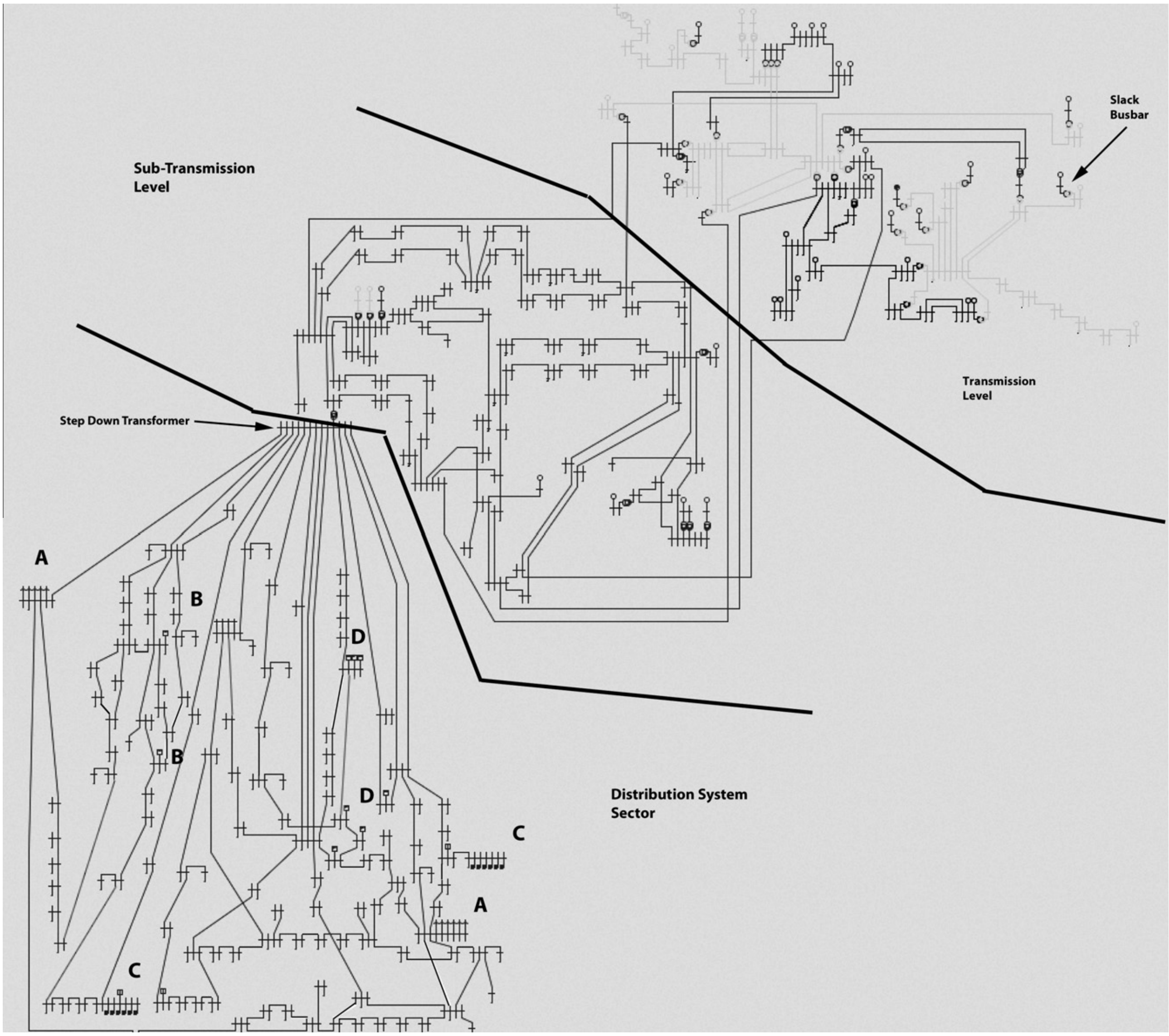

Fig. 14. Network used for the real case study.

Table 2
System data.

	Number of elements at each Level		
	Transmission	Subtransmission	Distribution
Busbars	69	85	134
Lines	65	94	138
Transformers	29	8	1
Loads	71	65	146
Generators	33	8	23

Table 3
Distribution network description.

Component		Installed capacity (MW)	Number
A	WG	22	11
B	PV	0.5	2
C	CHP Generators	0.5	3
D	Other DG	3	7

93), the difference between *consumption* and *balance* curves is minimal. Thus, for this specific case Wind Power is minimal at the peak hour (It has to be stressed that this cannot be generalized. for any location). As a consequence, the distribution company must satisfy its peak demand almost entirely from the interconnected system.

For the interval of minimum daily demand (8.8 MW in period 27), the difference between both curves is enormous. In fact as shown in Fig. 15, between periods 26 and 29 and periods 33 and 41, the *balance* becomes negative. Consequently, for these periods in the day ahead operation, the expected power flow through the step-down transformer is reversed.

It is important to note that for the estimation of power flows through the step-down transformer, no detailed information of the Distribution system network structure and parameters is needed. Indeed, for a basic study using the proposed platform, the power flow estimation at the step down transformer is constructed by the subtraction of the aggregated load and the aggregated DG generation at each 15 min step. Therefore, non additional information is strictly required. Nevertheless, the platform allows a more detailed study using AC or DC load flow tools. This aspect is of key importance for load estimation models applied at high voltage level (subtransmission, transmission), where with limited information the load at the step-down transformer is

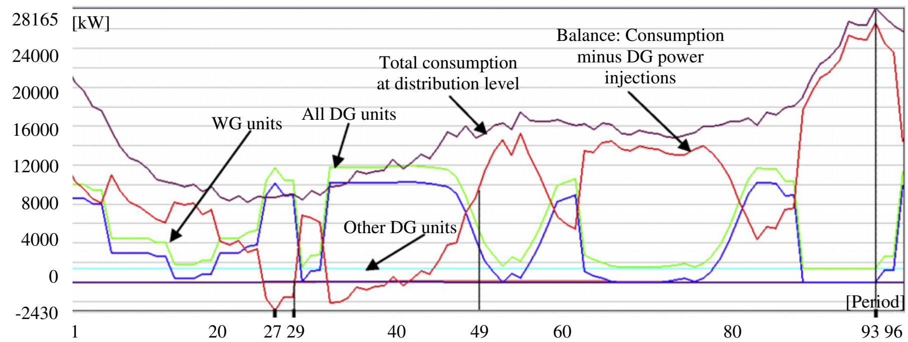

Fig. 15. Results obtained in the case study.

estimated for the next day. Consequently, from the ISO point of view this tool helps to define a more accurate dispatch of energy and reserve markets for the day ahead. In addition, these results can be used by traders to dimension the purchase commitments for the next day and to evaluate different business strategies.

4.2.3. Distribution company point of view

From the distribution company point view, a detailed analysis of each curve presented in the previous section, offers valuable information for the operation management of its own network.

In this Section the same case study is considered with the focus on operation management inside the distribution control area. By taking into account the minimum, mean and maximum demand faced by the step down transformer, periods 27, 49, and 93, respectively (Fig. 15); several power flow simulations carried out with the same simulation framework (DLFDG) are presented. Table 4 summarizes the results for the scenarios with and without DG injections and for three tap positions of the step-down transformer. All DG are modeled as PV busbars while satisfying reactive power constraints of each unit.

In Table 4, the following variables are included:

P, *Q*: active and reactive power injected in the distribution network through the step-down transformer;
cos(φ): power factor resulting from *P* and *Q*;
V_c: voltage at low voltage side of the step-down transformer;
V_d: average voltage in the distribution level busbars.

Finally, ohmic losses are shown for the whole system in MW (Syst. L), and at the distribution level in kW (Dist. L).

From Table 4, voltage profile, ohmic losses and reactive power of the system may be analyzed as follows:

(i) **Voltage profile:** In Fig. 17 the V_d is plotted against demand levels.

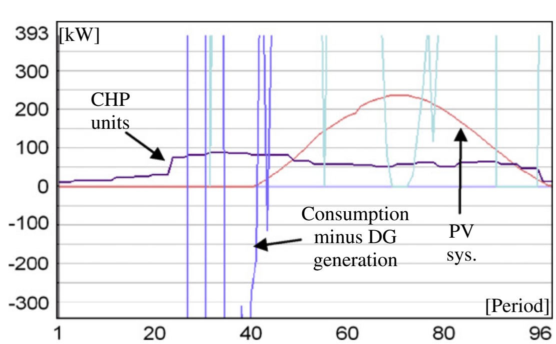

Fig. 16. Detail of figure 15.

As expected, for the case without DG, the voltage profile decreases as the demand is increased. This effect is attenuated when DG is incorporated. In fact, for the case of 2% tap position in Table 4, V_d is 0.89 without DG and becomes 0.98 when DG is activated.

(ii) **Ohmic losses:** Fig. 18 shows average *Syst. L* and *Dist. L* for 3 different load conditions. As expected, system losses are increased with the demand, and they are decreased by 1–2 MW when DG is injected. A similar behavior is observed for the distribution losses without DG.

However an interesting effect is observed in distribution ohmic losses when DG is injected. *Dist. L* are higher for minimum demand as compared to medium demand. According to the topology shown in Fig. 14, Loads and DG are distant from the step down transformer. Consequently, a major proportion of the ohmic losses are concentrated in the distribution lines between the step-down transformer and units A–D (Fig. 14). Wind power contribution is higher than the minimum load condition as shown in Fig. 15, therefore the losses in the lines connecting WG with local distribution loads are higher for this condition.

(iii) **Reactive power:** Fig. 19 shows the average Q value for the three different load conditions.

As expected, for the situation without DG, Q requirements increase proportionally with the distribution system demand. However, in the case with DG the opposite behavior is observed. For mean and maximum load conditions, DG units operate under the chosen preconditions mostly as synchronous compensator as the active power generated by DG units is minimal. From the modeling point of view, in this specific case, these units are PV busbars, and adjust their reactive power injection to maintain the voltage set point.

In the case of minimum load, this capability is also used, nevertheless DG units absorb reactive power. As a consequence, Q at step-down transformer is slightly higher than the case without DG.

A negative effect of this voltage support capability is the damage in the power factor of the distribution company. From Table 4 the cos(φ) for minimum and mean demand may be as low as 0.78 (mean, tap −2%), 0.41 (min, tap 0%) or even 0.25 (min, tap −2%). In fact, in Chile, bilateral contracts between distribution and generating companies and grid-code regulations usually include fines when the power factor is lower than a predefined limit. Therefore, this effect should be studied carefully to define appropriate contract schemes.

4.2.4. Comments

It is possible to define a wide variety of applications to the proposed framework. First of all, the model maybe applied to long term studies, such as expansion planning. In this area, the tool

Table 4
Power flow results with and without DG units.

Dem. level	Variable	Scenario with DG				Scenario without DG			
		Tap −2%	Tap 0%	Tap 2%	Aver.	Tap −2%	Tap 7%	Tap 2%	Aver.
Min.	P (MW)	−2.38	−2.43	−2.45	−2.42	8.86	8.86	8.86	8.86
	Q (MVAr)	9.30	5.38	1.86	5.51	4.34	4.34	4.34	4.34
	cos(φ)	0.25	0.41	0.80	0.49	0.90	0.90	0.90	0.90
	Vc (pu)	1.00	1.00	0.99	1.00	1.02	1.00	0.98	1.00
	Vd (pu)	1.00	0.99	0.99	0.99	1.01	0.99	0.97	0.99
	Syst. L (MW)	81.06	80.87	80.73	80.89	82.64	82.65	82.65	82.65
	Dist. L (kW)	531.84	481.84	461.84	491.84	55.77	55.77	55.77	55.77
Mean	P (MW)	8.97	8.94	8.97	8.96	15.10	15.11	15.13	15.11
	Q (MVAr)	7.10	3.25	−0.27	3.36	7.45	7.46	7.46	7.46
	cos(φ)	0.78	0.94	1.00	0.91	0.90	0.90	0.90	0.90
	Vc (pu)	1.01	1.00	0.99	1.00	1.00	0.98	0.96	0.98
	Vd (pu)	1.00	0.99	0.99	0.99	0.99	0.97	0.94	0.97
	Syst. L (MW)	82.86	82.71	82.62	82.73	84.18	84.19	84.21	84.19
	Dist. L (kW)	172.48	142.48	172.48	162.48	181.30	191.30	211.30	194.63
Max.	P (MW)	27.27	27.35	27.46	27.36	28.87	28.90	28.95	28.91
	Q (MVAr)	4.43	0.74	−2.78	0.80	14.51	14.56	14.61	14.56
	cos(φ)	0.99	1.00	0.99	0.99	0.89	0.89	0.89	0.89
	Vc (pu)	1.01	1.00	0.99	1.00	0.97	0.95	0.92	0.95
	Vd (pu)	0.99	0.98	0.98	0.98	0.94	0.91	0.89	0.91
	Syst. L (MW)	87.21	87.16	87.18	87.18	88.15	88.21	88.27	88.21
	Dist. L (kW)	643.99	723.99	833.99	733.99	754.13	784.13	834.13	790.80

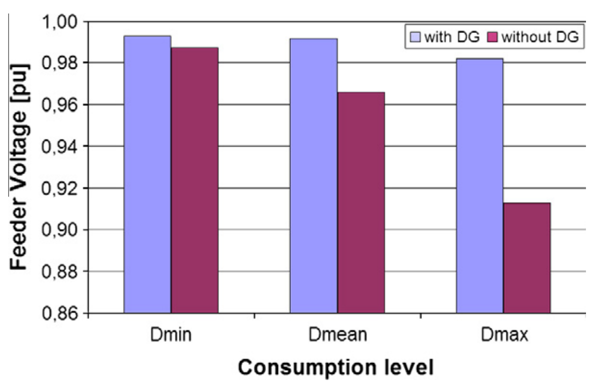

Fig. 17. Average voltage in distribution nodes.

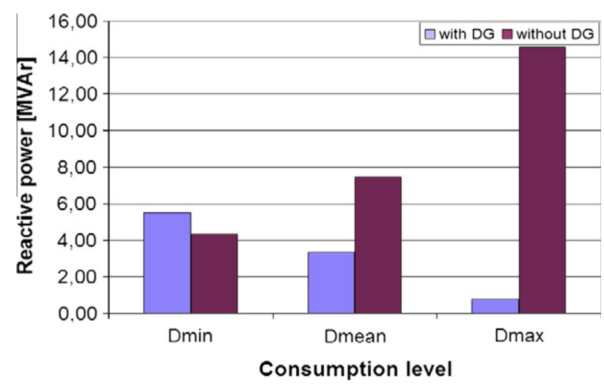

Fig. 19. Reactive power requirements.

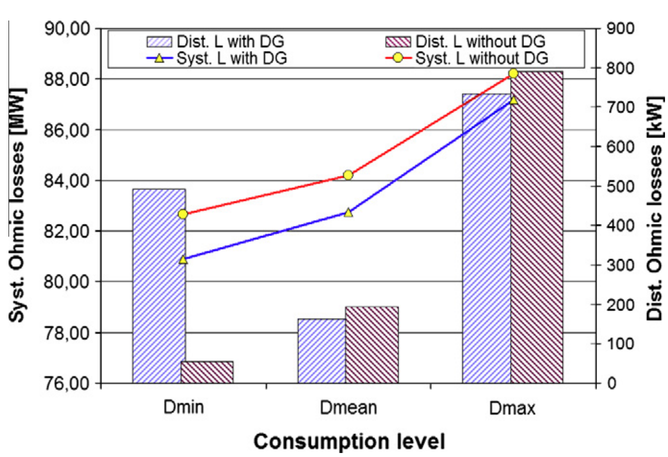

Fig. 18. System and distribution ohmic losses.

offers the possibility to ascertaining an appropriate reinforcement of networks, so distributed generation can be incorporated complying with required standards. In short term studies, the system can be used for analyzing the state of networks, as well as an operation planning tool, for generation scheduling or network configuration.

5. Conclusion

The novel contribution of the presented work is to integrate in a single platform the simulation of different types of loads, DG technologies and the network at both local and system levels. A day-ahead simulation framework to evaluate the impact on load estimation by large scale installations of DG (DLFDG) was developed. Different models of DG technologies have been analyzed and implemented into a computational tool together with a day ahead load estimation based on a clustering technique. The tool for the estimation of power flows at a step down transformer encompasses models of customer categories and system components, together with different operation modes for the DG. Special emphasis is set on CHP generators, whose models have explicitly incorporated heat demand as a function of weather conditions. The simulation framework, includes weather forecasts, an appropriate database management and a user friendly GUI.

The simulation model was validated by using a test network based on real parameters taken from German and Chilean power networks. Results show that DLFDG offers a wide scope of applications, and allows studying effects such as voltage profile, ohmic losses and reactive power of the system.

The proposed system architecture, based on an object oriented approach, enables simple expandability and maintenance of the proposed step-down transformer power flow estimation framework.

The developed framework is freely available for research purposes at [16].

Finally, this framework will serve as a decision support system for network operators, which is particularly important for the development of new markets.

Future work includes an extension to simulate the behavior of storage devices, stochastic loads (load forecasting model), and uncertainties related with weather predictions.

Acknowledgments

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