Effects of COVID19 pandemic on the Italian power system and possible countermeasures

Pierluigi Gallo[a], Josep Maria Guerrero[b], Rossano Musca[a], Eleonora Riva Sanseverino[a], Juan Carlos Vasquez Quintero[b], Gaetano Zizzo[a]

[a] *Department of Engineering, University of Palermo, Italy*
[b] *Department of energy technology, Aalborg University, Denmark*

Abstract

The paper analyses the dramatic effects of the first wave of the COVID-19 pandemic on the Italian power system, considering the impacts on load and generation, market issues and ancillary services provision. During the period between March and May 2020, the Italian scenario was considered as exemplary due to the large reduction of loads and thermal generation caused by the hard lockdown across the Country. Italy has experienced the most severe effects of pandemic in terms of increase of death rates and of pressure on the health system as well as severity of the countermeasures. As a domino effect, the total lockdown of one of the most industrialized countries in the world has created an emergency situation that has put a big stress on the power system, reducing the possibility for the system to recover under contingencies. The weakness of the system in such an extreme situation is analyzed in depth using open data, while some countermeasures for providing resilience to the power systems in such cases are analyzed in simulation. Two technologies are here considered as exemplary countermeasures for providing resilience to the Italian power system: Fast Frequency Response by Photovoltaic and Wind plants with rated power above 10 MVA and the massive implementation of Demand Response programs through Energy communities and aggregation using Blockchain technology. The simulations show, on one hand, that the frequency recovery under contingency seems compromised in the current situation and that the support from such innovative technologies can provide a significant relief bringing the operational features close to those before the COVID-19 pandemic.

Keywords: Covid-19, Blockchain, Electric load, Pandemic, Demand Response, Aggregation, Flexibility, FFR, FRC.
2020 MSC: 00-01, 99-00

Nomenclature

DA Day Ahead

DR Demand Response

Erh Hydro-power plants power-frequency characteristics

Ers Gain of the Stati converter FFR link

Ert Thermal-power plants power-frequency characteristics

$f19$ Frequency course after a disturbance (loss of connection between Italy and France) in 2019

$f20$ Frequency course in the case of only thermal and hydro plants participating to frequency control after a disturbance (loss of connection between Italy and France) in 2020

$f20.1$ Frequency course with FFR control and FCR equal to 1.5% of the total rated power of the RES plants in 2020 after a disturbance (loss of connection between Italy and France)

$f20.2$ Frequency trend with FFR control and FCR equal to 10% of the total rated power of the RES plants after a disturbance (loss of connection between Italy and France) in this case, RES plants are supposed to be equipped with a battery storage system for the FCR service

FCR Frequency Containment Reserve

FFR Fast Frequency Regulation

HLF Hyperledger Fabric

MSP Membership Service Provider

$NFEE$ Net Foreign Energy Exchange in GWh

$Pst.1$ Power course with FFR control and FCR equal to 1.5% of the total rated power of the RES plants in 2020 after a disturbance (loss of connection between Italy and France)

$Pst.2$ Power course with FFR controla and a step load-shedding action induced by Demand Response in 2020 after a disturbance (loss of connection between Italy and France)

PUN National single Price of electricity

$SCHVHV$ Smart contract HV/HV

$SCHVMV$ Smart contract HV/MV

$SCMVLV$ Smart contract MV/LV

1. Introduction

The Covid-19 epidemic confronts us with a reality that, so far, we have made sure not to see: we live in what Ulrich Beck calls the "global risk society" [1], a society in which, also due to the unwanted consequences of human actions, the risks, with respect to which our knowledge is insufficient, multiply. These are financial and economic risks connected to migratory flows, global terrorism, climate change and threats to health deriving from the increasingly frequent epidemics. The last threat to our industrialized society comes from the COVID-19 pandemic, that has totally changed the scenario in which most industrial realities have grown till now.

The change in paradigm of human transactions, from the physical world to the digital world for limitating the infection, has been accelerated from this pandemic and seems to be a backup solution that has allowed our companies and productive systems to continue to operate (even if at reduced rate) regardless the pandemic. In times of risks, it is thus important to wonder whether the full transition to the digital dimension would provide a Ride-Through solution to some of the global risks we are facing. With respect to climate change effects, most papers indicate as countermeasure the possibility to supply end-users through local generation technologies and microgrids. Recent legislation from the European Parliament has referred to these solutions as 'Renewable energy communities' or 'Citizens Energy communities'[2]. While the latter could be a response to serious climate events compromising the main electrical grid, on the other hand, "local" also means exchanging energy or energy services and tracing them using a trusted certification technology that may not rely on a central authority (i.e.: the grid operator or the market operator).

If we focus on the situation we are living these days and its effects on the power system operation, we can see that these effects are manifold. Many considerations have been already discussed in [3, 4, 5, 6, 7], mostly with reference to the macroscopic effects on the load reduction and on the Gross Domestic Product (GDP) as an extrapolation of electrical consumption data. In this paper, we will try to look forward, trying to analyze how the lockdown during Spring months has affected in Italy the change in consumption in entity and end-use. The steep change in consumption habits is considered and the technical impact on the power system is analyzed. As a matter of fact, such reduction has produced the curtailment of thermal generation and thus serious effects on stability. While the situation we are living these days is extreme, we are also conscious that it will last for some time, since the economic crisis will produce the shutdown of many productive activities and related energy consumption. Furthermore, this analysis helps for being prepared for facing new phenomena and preventing the extra risks that would arise in case of failure of the distribution network. The effects of COVID-19 on power systems can be summarized below:

- total load reduction;
- changes of final use of electrical load in all sectors (residential, industrial, transport, etc.);
- change in the generation system with associated reduction of inertia;
- impact on market and price;

- ancillary services offered from end-users;
- delays in fault recovery due to reduced personnel for operating the distribution network.

The total load reduction has magnified the effect of inertia reduction due to the increasing percentage of renewable energy generation as compared to the thermal production. Moreover, the shift from industrial loads, which are manageable loads, to residential loads, which are less flexible, has indeed an impact on network stability and on grid recovery plans. Interruptible loads are indeed typically related to industries that are expected to be working also in the near future at reduced load. Grid operators will have to rely more strongly on smart grid technologies like Fast Frequency Response (FFR) and on residential end-users involvement for the provision of ancillary services.

While FFR can be provided by suitable technologies for converters control, in end-users involvement for ancillary services provision, ground breaking digital technologies will have to take the lead. In this case, stability and control of the power system are falling on top of a more complex architecture involving aggregators, balance responsible parties and end-users. Providing transparency in ancillary services provision and accelerating the phase of involvement of end-users in the energy market, as recalled by the Electricity Market Directive [8], will be essential for an efficient and effective management of power systems.

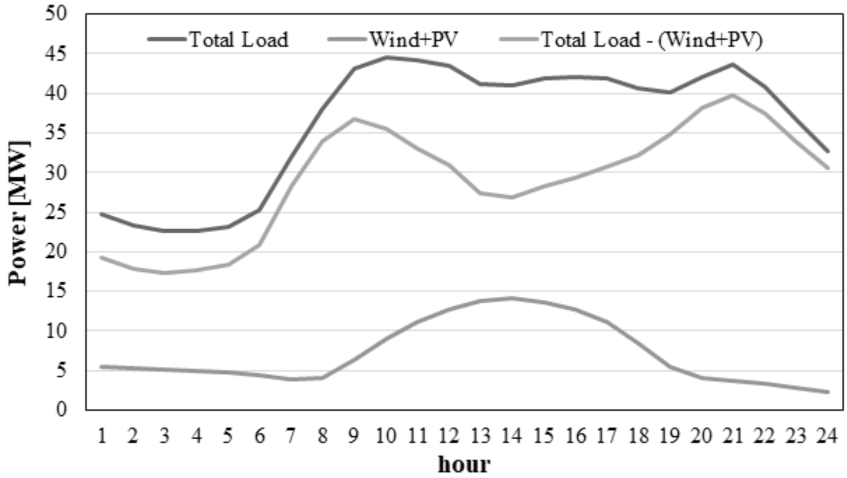
This paper discusses how the adoption of FFR in Photovoltaic and Wind generation above 10 MVA together with a widespread implementation of Demand Response (DR) programs can provide full regulation even in an extreme situation like the one we are experiencing these days. Concerning DR programs implementation, the blockchain technology could be beneficial for creating a validated and unified vision of the energy market reducing the total time for analysis and application of necessary countermeasures with particular reference to the end-users involvement. In previous works [9]-[10], the authors demonstrated the use of the blockchain for several applications in the energy sector, now they prove how blockchain technology could support robustness of the power network under sudden changes deriving from an unexpected event like the recent pandemic. The application section of the paper will show simulations of massive implementation of FFR on Photovoltaics and Wind generation coupled with DR programs to be actuated in times that are compatible with the blockchain technology involving different quotas of the residential customers under given hypotheses.

2. Electrical data analysis

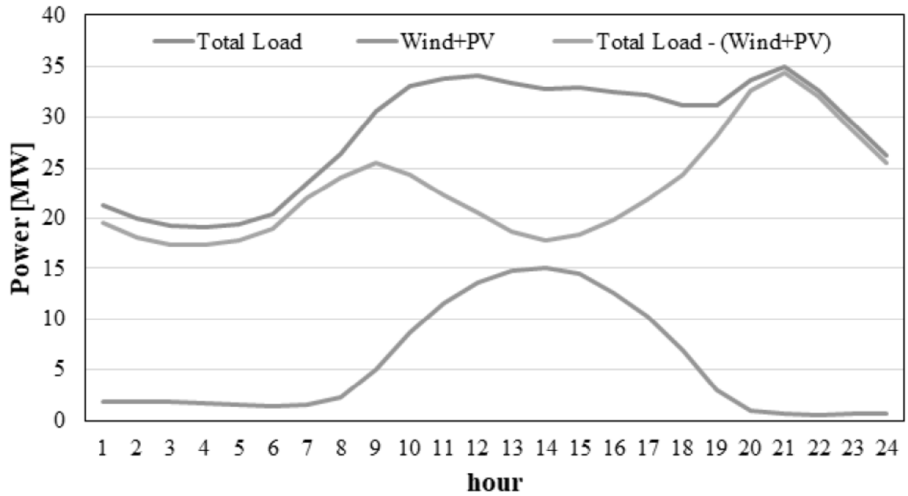
2.1. Current and future scenarios on load and generation

The occurrence of the recent pandemic has changed the electrical energy consumption scenario reducing the net load and increasing the evening ramp, thus creating even greater problems for the regulation in power systems. Figure 1 shows the total load in Italy [11] and the net load obtained by subtracting the contribution from Photovoltaic and Wind generation in Italy in a Monday of April in 2019 and in 2020, showing a reduction of load profiles.

The Italian net electric load decreased mainly in the North of the country, as it can be seen in Fig. 2, where about seventy percent of the national manufacturing industry is located.

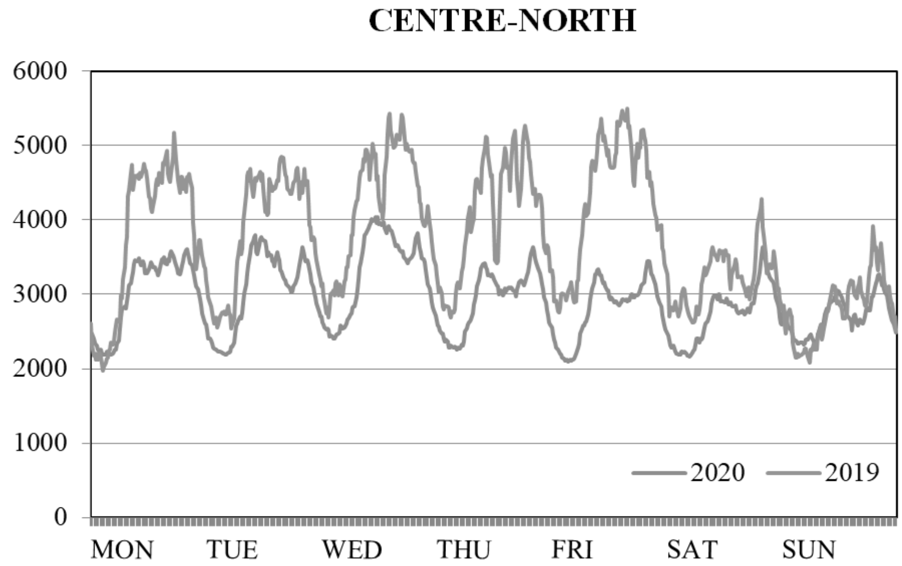


(a)

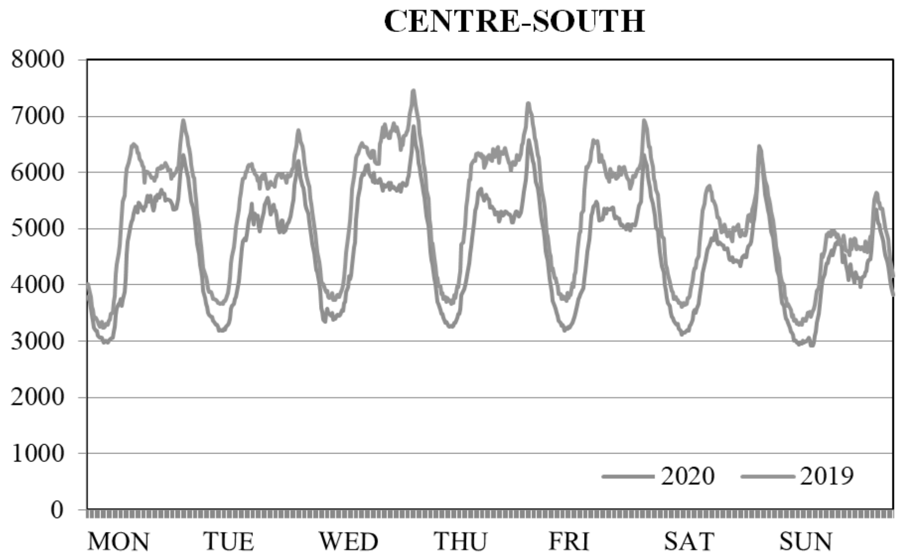


(b)

Figure 1: Total Load [MW], Production from Wind and photovoltaic [MW], NEt Load [MW], April 1st 2019 (a) and April 6th 2020 (b) - Source: Terna



(a)



(b)

Figure 2: Electric load (MW) in the first week of April 2019 and April 2020 in the Centre-North (a) and Centre-South (b) - Source: Terna

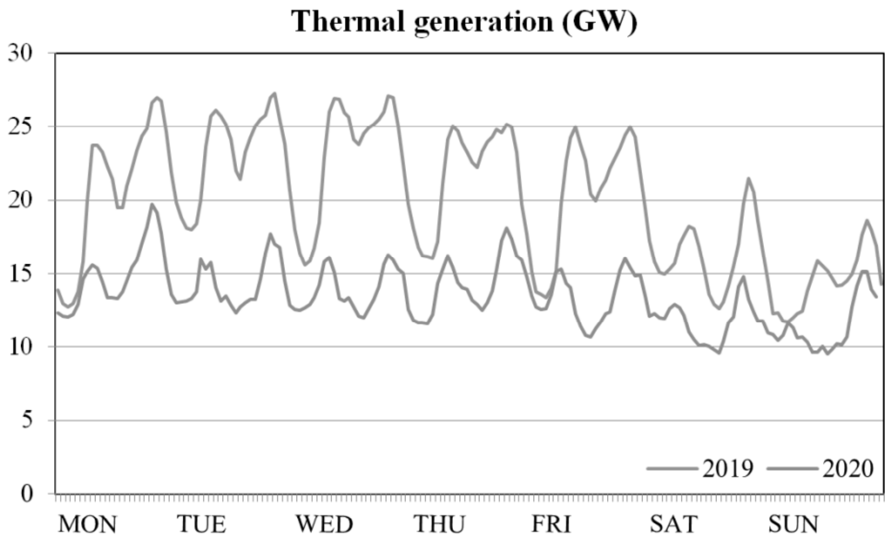


Figure 3: Power generated by thermal power plants in Italy (GW) in the first week of April 2019 and April 2020 - Source: Terna

Table 1: Kinetic energy of the Italian Power System

Kinetic Energy [MWh]	**2019**	**2020**
min	20.9 (30/03/2019)	24.0 (01/04/2020)
max	67.7 (05/04/2019)	55.5 (07/04/2020)

While load was dramatically reduced as described, due to the dispatching priority of renewables, the power generated by thermal plants was reduced as well, as shown in Fig. 3. As a result, the rotating reserve of the Italian generation system has been and is still severely compromised.

In such a condition, an estimation of the kinetic energy of the rotating masses of the Italian generation system has been carried out, for the first week of April 2019 and April 2020, assuming average values for the inertia constant of thermal and hydro generators (see Table 1). As shown in Table 1, in April 2020, the maximum kinetic energy decreased by about 19% with respect to the same week of 2019, resulting in a consequent reduced capacity of contrasting disturbances in the active power balance. The same table shows that the minimum kinetic inertia of the system slightly increased in 2020 with respect to 2019. This can be related to the fact that the condition of minimum kinetic energy occurs, in the analyzed weeks, in two week-end days: Saturday, March 30th, 2019 and Sunday, April 5th, 2020. Week-end electricity consumption, as clearly shown in the previous figures, has been less affected by the COVID-19 pandemic and lock-down and, as a consequence, the schedule of the Italian power plants is almost the same in 2019 and 2020. On the other hand, the maximum kinetic energy has been calculated for two week-days: Monday, April 1st, 2020 and Tuesday, April 7th, 2020, that have been more affected by the change in the generation mix.

Table 2: Net Foreign Energy Exchange

	2019	**2020**	**DE%**
Total	31.3 TWh	24.6 TWh	-21%
Jan	2.8 TWh	3.3 TWh	18%
Feb	3.8 TWh	4.1 TWh	6%
Mar	3.8 TWh	3.9 TWh	4%
Apr	2.3 TWh	0.7 TWh	-71%
May	3.1 TWh	1.3 TWh	-58%
Jun	3.3 TWh	0.5 TWh	-85%
Jul	3.5 TWh	3.1 TWh	-11%
Aug	2.2 TWh	1.5 TWh	-32%
Sep	2.8 TWh	2.1 TWh	-25%
Oct	3.7 TWh	4.1 TWh	11%

2.2. Market effects

Together with the reduction of the electricity generation from thermal power plants, the energy imported from neighboring countries decreased too. In Table 2, the net foreign energy exchange (NFEE) in GWh is reported for the first four months of both 2019 and 2020. These values show that, while the NFEE was slightly higher in January-March 2020 with respect to the same months in 2019, it suddenly dropped from April 2020. Fig. 4 shows a comparison of the net power exchange with the neighboring countries in the first week of April 2019 and 2020. On the market side, all across Europe, electricity prices have fallen dramatically following the collapse of oil prices and the increased amounts of unsold electricity (Fig. 5). The dramatic reduction of energy price maintains the typical daily shape with two peaks.

In June 2020, the National Single Price (PUN) in Italy was at historic lows with a reduction of about 57% with respect to the value in June 2019 [12] due to a progressive reduction in the electricity purchase in the Day-Ahead (DA) market and in the oil barrel price in the international market (Fig. 6). The higher coverage of the load from RES is also witnessed at market level. A larger recourse to the balancing market and the increased volumes exchanged on infra-day markets (Fig. 7) are a prove for this.

3. Blockchain for supporting power system behaviour

As power systems are regulated, operated and finally used by a plethora of public entities and private actors, the blockchain and its unified vision on the data collected from multiple sources is extremely beneficial and may guarantee transparency in a system where decisions are taken unilaterally and centrally [9]. On the other hand, while transparency is a cornerstone feature that the blockchain is able to provide, in many cases, only part of the data can be given publicly while other data have to be shared among small groups and kept undisclosed for preserving customers' privacy and the security of the national power system. In the power systems area, data about electrical energy consumption are personal data under GDPR [13]. In the class of permissioned blockchains, where the identity of participating actors is known, there are few platforms

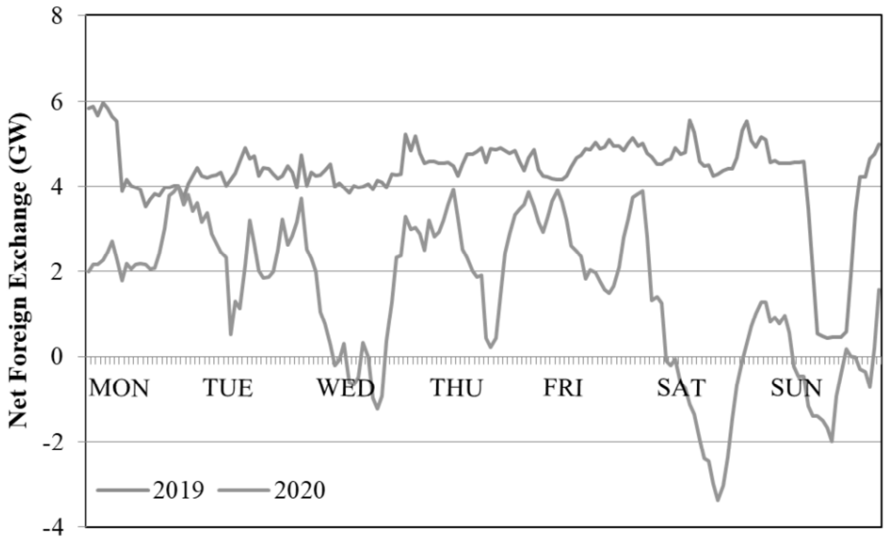


Figure 4: Net Power Exchange with neighboring Countries in the first week of April 2019 and 2020 - Source: Terna

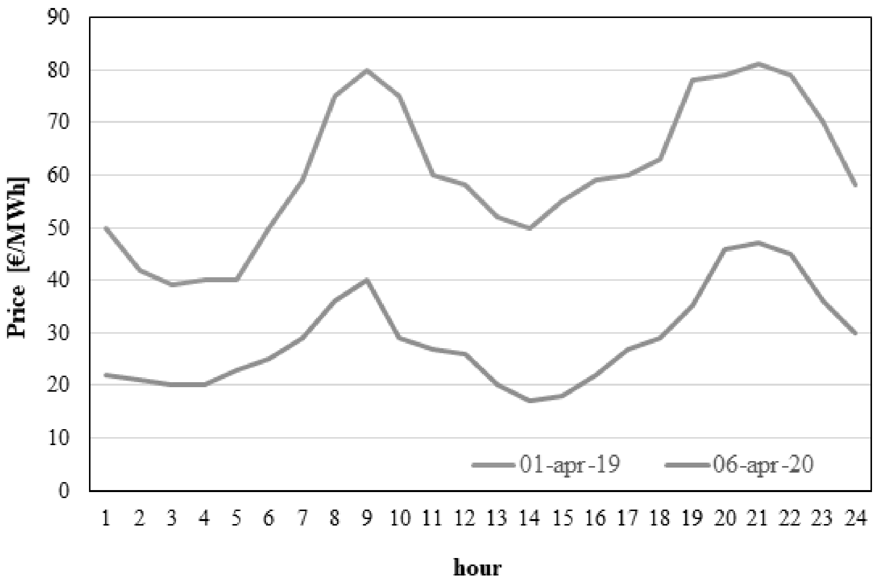


Figure 5: Market price [€m/MWh], April 1st 2019 - April 6th 2020 - Source: GSE

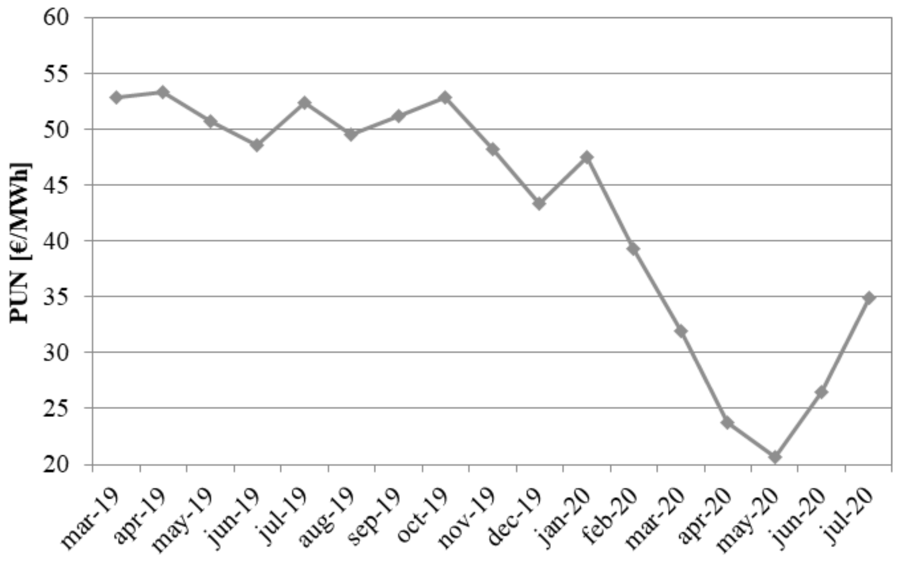


Figure 6: Italian National Single Price from March 2019 to March 2020 - Source: GME

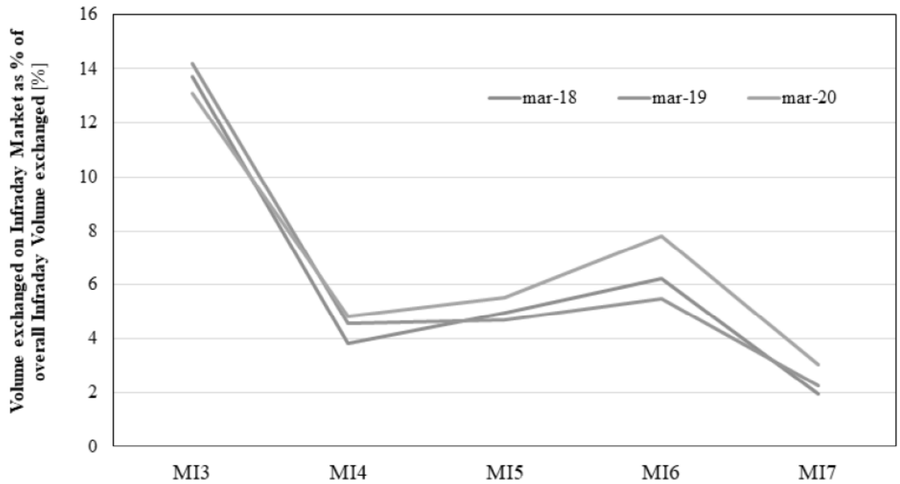


Figure 7: Infra-day market volume as a percentage of overall volume in the infra-day market in percentage - Source: GSE

that address privacy issues by limiting data visibility to specific groups of nodes. Data are grouped depending on sets of stakeholders with homogeneous visibility; from the user it will appear as a unique blockchain but there will actually be several blockchains, one for each set. The consistent replication of data and the resulting unified view of the system status would be only partially effective without a prior validation process, which aims at verifying that the data included in the blockchain are trusted. Furthermore, the blockchain can manage, under a unified protocol, users, physical assets (electric vehicles, charging stations, solar panels, etc.), energy transactions, rewarding mechanisms. This approach facilitates the integration with existing and dedicated data sources and IoT infrastructures disseminated along with the city (e.g., public charging stations, sensors, solar cells on roofs, totems, poles, traffic lights, smartphones). In the following, the potential role of blockchain technology for solving few issues in power systems, especially those exacerbated by the COVID-19 pandemic, is highlighted. We distinguish two kinds of data related to power systems: those which are of exclusive interest to the transmission and distribution system operators and those that are also relevant to prosumers. To this latter group belong, for example, photovoltaic production, load consumption and network parameters by Service Level Agreements (SLAs). In the latter case, even if the Distribution System Operator (DSO) has a degree of trust provided by the law, several disputes may occur between the DSO and prosumers regarding metering data, most resolved by leveraging the data provided by the DSO, which are typically, the only ones available. Metering data may be eventually affected indeed by inaccuracies due to faults of the smart meter, the communication line, leakage currents and many other causes, including periodic calibration and frauds. For tackling these issues, a distributed data validation mechanism is helpful and may, at the same time, support the widespread adoption of Demand Response (DR). This data validation uses redundant metering, managed by independent organizations and even by the customer, all included as members of the blockchain network. In these cases, independent observers could reach a consensus on the measure provided by the DSO and in case of not consistent values, they will rise early warnings. Generally, end-users double check their consumption comparing them with their own typical ones, which brings to the definition of Customer Baseline (CBL) [14]. Moreover CBL is used to remunerate end users for regulation services offered to system operators under DR programs.

The pandemic outbreak is accelerating several societal and technological processes demonstrating, in all its urgency, the need of a deeper digitalization, the reduction of people physical involvement and a stronger virtual participation. As shown in the previous sections, the modification in the end-users' electricity consumption, mainly due to the reduced energy request from industry and services sectors jeopardizes the security of the power systems. For compensating the reduction in the primary reserve, the novel model of digital democracy must include a stronger involvement of end-users in supporting frequency regulation and provisioning of ancillary services [10]. In table 3, the typical timings between request and provision, required for the different services, according to ENTSO-E regulation, are given. The table also outlines in the third column what is the possible support provided by the blockchain technology. In the column, 'tracing and certification' refers to the possibility of the blockchain to simply keep track (write) of the measurements collected by the measuring units, to prove that a given service has been provided. The terms 'balancing transactions', as well as 'transactions in Day-Ahead Market' refer to the possibility to trade on the blokchain, namely to publish an offer and run a matching algorithm through a smart contract. The sequence of operations supported by blockchain can be detailed in two different cases:

- primary regulation services provision;
- secondary and tertiary regulation services provision.

In the first case, based on a smart contract between the grid operator and the end-user, part of the load can be directly switched off/on when needed. In Italy, this service is implemented by "interruptible loads" at HV level, typically industrial facilities. If these are not in service when their action is needed, then the grid operator must look at lower voltage levels. In other parts of the world, such as in the US, currently, this capacity is available to the grid operator at MV and LV level. The "PJM Interconnection" experience with grid-interactive water-heaters [15] is cited as an example of primary regulation provided with electric resistance water heaters in about 4 second [16]. In this case, each day at 00:00, a dedicated smart contract will assess the CBL. Then, the operation to be registered on the blockchain is the measurement of the power absorbed by the end-users during the DR event. Therefore, the blockchain puts no delay since it is used only for certification of what happened during the DR event. In the second case, a smart contract connects the end-users to the grid operator (or aggregator) for ancillary services provision under the ancillary services market. Fig.8 shows the sequence of the operations described below for this case. In the figure, BL is the Baseline of the aggregate, while CBL is the Customer Baseline. Also in this case, each day at 00:00, the CBL - phases 2 and 3 - is calculated by a dedicated smart contract. All the subsequent operations need to be carried out within the minimum timeframe acceptable for ancillary service market in Italy (15 minutes).

- Notification of the need of a DR event (writing on the blockchain by the grid operator client application) - phase 4;
- Calculation by means of a smart contract invoked by the grid operator or TSO of coefficients for the distribution of the regulation services to the end users is carried out [17] - phase 5.

At the time of the DR service delivery, actuation on loads is carried out directly from the grid operator or from end-user. A smart contract writes the measures during the DR event (writing on the blockchain) under request of the grid operator client application - phase 6. Finally, the remuneration service is calculated by a smart contract under request of the end user client application - phase 7.

Table 3: Typical timing requirements for ancillary services

Regulation Service	Timing	Blockchain feasibility
Primary	30 s	tracing certification
Secondary	15 minutes	tracing certification balancing transactions
Tertiary	120 minutes	tracing certification transactions in Day-Ahead Market

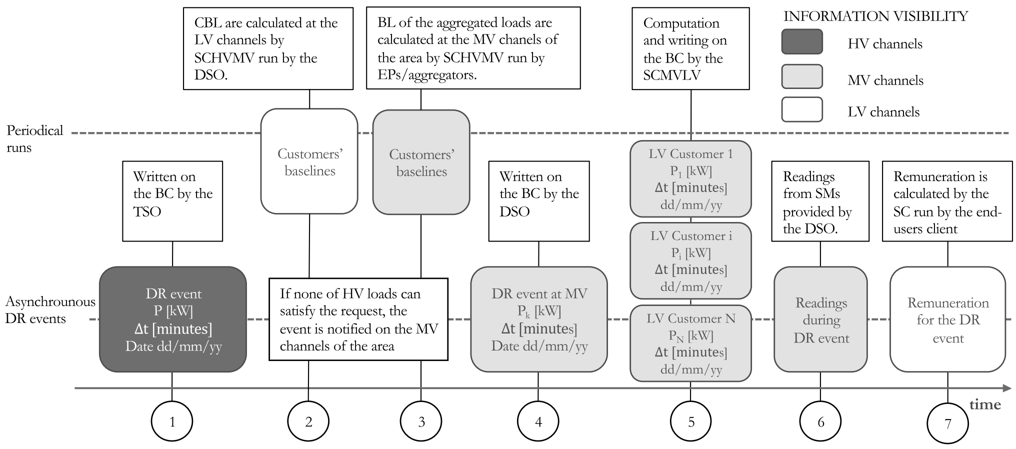


Figure 8: Sequence of events using the BC architecture for DR; DR in 7 steps.

4. Countermeasures for facing reduced inertia and reduced industrial loads control

In this section, two possible countermeasures to face the above described issues are considered and their efficacy is analyzed by simulation in Matlab/Simulink environment. One countermeasure is on the side of distributed renewable generation, the other, employing the blockchain technology, is on the side of residential end-users, by an effective implementation of Demand Response.

The simulations carried out in this section show the effectiveness of both measures considering correct operation timing and the effect of their widespread applicability as post-pandemic recovery measures. The simulations consider the effect of both countermeasures separately and applied together.

4.1. Fast Frequency Response for recovery of frequency dynamics

During the transient period due to a disturbance, any amount of energy injected (or drawn in the case of loss of load) prior to reaching the frequency nadir will limit the

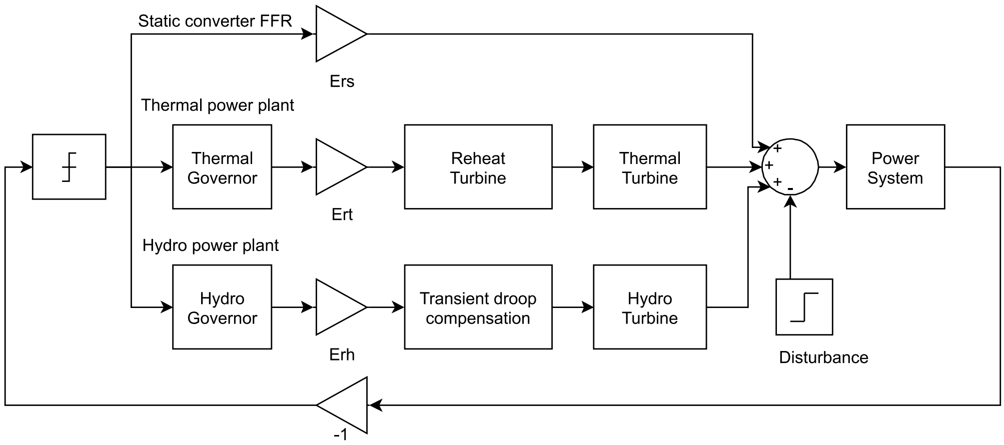


Figure 9: Matlab/Simulink model for studying the frequency evolution in the Italian power system

amplitude of the frequency deviation. The need for power injection is thus driven by this basic concept. In this way it is, indeed, possible to stop the frequency decline. According to the definition from North America Electric Corporation (NERC), Fast Frequency Response (FFR) can be defined as 'fast power injected to or absorbed from the grid as a response to changes in measured or observed frequency during the arresting phase of a frequency excursion event to improve the frequency nadir or initial rate-of-change of frequency'[18]. FFR can be provided in many ways by suitable control systems for different kind of generators. The inertial response of synchronous machines, a part of the turbine-governor response, controls to extract more power from the rotational energy of the turbine in wind turbine generator, as well as controls for batteries and solar PVs can provide power during the arresting phase: these can all be classified as FFR. In this paper it was hypothesized that all Photovoltaic and Wind generators with rated power above 10 MVA in Italy are able to provide the FFR service. Some simulations have thus been carried out, for assessing the promptness of the Italian generation system, in this scenario, to respond to contingencies in the new operating conditions with a reduced contribution from thermal power plants. Using the model in Fig. 9, the dynamic behavior of the Italian power system is simulated in the case of loss of connection between Italy and France at 8:00 p.m. of April 7th, 2020 (System split hyphotesis considered also by ENTSO-E). The system response is simulated on April 7th 2020 and compared to the response on April 1st 2019. For the sake of simplicity, the contribution to frequency regulation due to the rest of the control area is neglected. This simplifying hyphotesis can be assumed as realistic since the neighboring countries have been affected by the pandemic with a different timing of Italy and, as a consequence, it can be assumed that their contribution to frequency stability was the same in April 2019 and 2020. Under this assumption, the observed frequency deviations is higher than the real one but this does not affect the validity of the general conclusions of the calculation. For modeling the power plants in Fig. 9, typical parameters are assumed for their time constants [19]. The data for the calculations are reported in Table 4.

The considered working conditions in the two days of the two years, correspond to

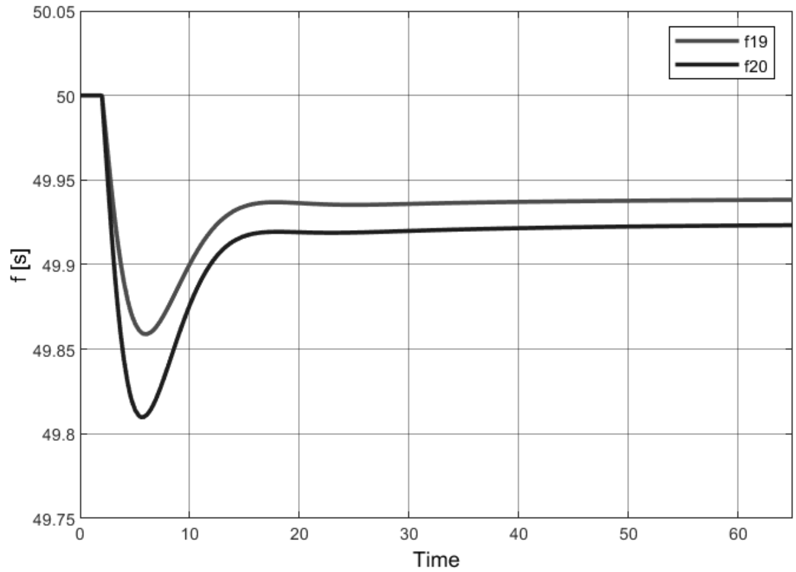


Figure 10: Comparison of frequency trends for a loss of production: 2019 vs 2020

Table 4: Parameters for the simulation of the Italian power system

	April 7^{th} 2020	April 1^{st} 2019
Total load [GW]	34.48	41.74
Thermal power [GW]	18.45	27.61
Hydro power [GW]	10.27	8.07
Wind power [GW]	1.04	0.26
PV power [GW]	0	0
Imported power from France [GW]	0.95	1.82
PV and Wind capacity (Rated power above 10 MW) [GW]	19.47	10.21
Thermal plants droop [MW/Hz]	0.05	0.05
Hydro plants droop [MW/Hz]	0.04	0.04
Kinetic energy [MWh]	55.5	67.7
System intertia [s]	4.85	5.46
Standard frequency range	± 20mHz (Thermal) ± 10mHz (Hydro)	

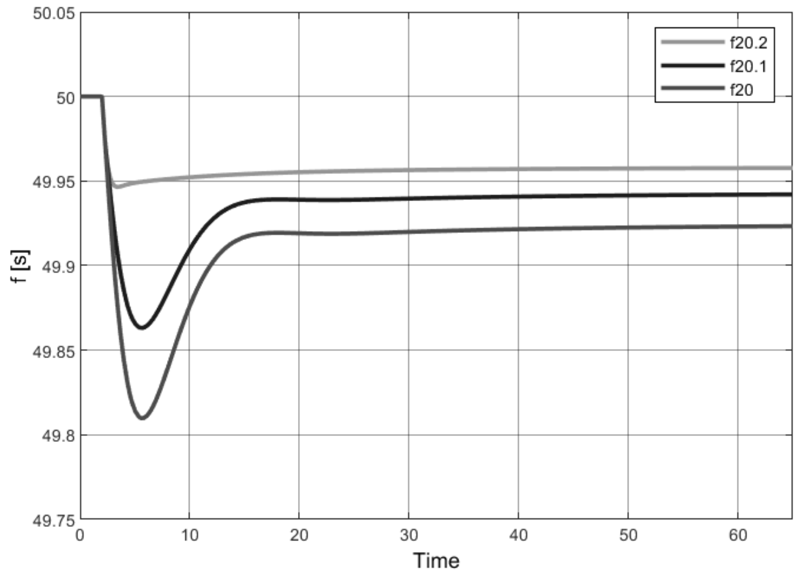


Figure 11: Comparison of frequency trends for a loss of production with and without Fast Frequency Regulation (2020)

the maximum kinetic energy of the rotating masses in the period under observation. In this way, the operational situation under contingency of 8:00 p.m. of April 1st 2019 was compared to that of 09:00 p.m. of April 7th, 2020, as detailed in Table 4.

Fig. 10 shows the mean frequency trend after the contingency (at t=2s) in the 2019 (in the legend in red f19) and in the 2020 scenarios (in the legend in blue f20). In the simulations, the frequency confinement reserve has been assumed sufficient for contrasting the disturbance. The 2020 operating condition shows higher frequency nadir and steady-state frequency deviation with respect to the 2019 situation. In this context, FFR can provide an important contribution to the enhancement of the system stability by suitable controls implementation in inverter-interfaced RES-based generators. Indeed, assuming all Photovoltaic and Wind plants with rated power above 10 MVA provided with FFR controls, the frequency trend in 2020 for the same disturbance changes as depicted in Fig. 11, where:

- f20 is the frequency course in the case of only thermal and hydro plants participating to frequency control;
- f20.1 is the frequency course with FFR control and Frequency Containment Reserves (FCR) equal to 1.5% of the total rated power of the RES plants;
- f20.2 is the frequency trend with FFR control and FCR equal to 10% of the total rated power of the RES plants (in this case, RES plants are supposed to be provided of a battery storage systems for the FCR service).

Table 5 reports the results of the simulations and shows how the adoption of FFR control with FCR equal to 1.5% of the total rated power of the RES plants can restore the

Table 5: Frequency variations due to the disturbance

Scenario	Frequency Nadir [Hz]	Steady-state Frequency [Hz]
2019	49.86	49.94
2020	49.81	49.92
2020 RES (FCR 1.5%Pn)	49.86	49.94
2020 RES (FCR 10%Pn)	49.95	49.96

same working conditions of 2019, reducing the risk of instability caused by the reduced overall system's kinetic energy.

4.2. Demand Response and Ancillary Services

The second contermeasure examined is the involvment of final end-user through DR actions for detaching rapidly a part of the load and supporting the dynamic response of the power system. The issue if of great interest since in many European countries, DSO an Aggregator implement DR programs involving final end-user for such an application [20]. It is worth nothing that, although the total national load decreased during the pandemic, this reduction has affected the industrial and commercial load, not the residential one, as shown in Section 2. Therefore, residential load appears as a secure reserve for DR during a lockdown. The analysis is performed below considering a blockchain-based structure for DR programs management. Blockchain technology can create a direct interaction between the grid operator or the balancing responsible party and the end users, thus eliminating middlemen and reducing costs. In what follows, a numerical assessment about the timing in which a Hyperledger Fabric (HLF) blockchain can support DR operation for the Italian scenario is reported in the case depicted in Fig.8.

The 2019 Italian yearly report from ARERA indicates 29.5 million of domestic end-users and 7.3 million of other end-users, with a total number of 36.8 million of end-users [21]. A near real-time management of data coming from a such large number of smart meters is not feasible with an unique blockchain, therefore a hierarchical architecture for data management, which partially maps the physical architecture of the power system should be adopted, for the blockchain and smart contracts, as indicated in Fig. 12. The segmentation of the power system provides efficiency to the process because the computation and the amount of data is limited to the observed segment. To implement this segmentation, we suggest to use the channels of Hyperledger Fabric, which help both providing data privacy and are implemented through independent sub-blockchains. In order to improve performance almost linearly with the number of channels, we suppose that any company has a dedicated orderer for each of the channels it participates and has dedicated bandwidth resources for each of such channels. In fact, the logical split in multiple channels provides performance benefits only if it is supported by additional computational and communication resources given, respectively, by extra orderers and bandwidth.

Thus, the network is partitioned in its HV, MV, and LV grids, and dedicated smart contracts will run on the machines of the actors involved, related to local acquired data (SCHVHV: Smart Contract HV/HV; SCHVMV: Smart Contract HV/MV; SCMVLV:

Table 6: Hypotheses for assessing the potential of HLF blockchain for ancillary service provision

Parameter	**Value**
Mean number of end-users per HV/MV station	25.000
Mean number of end-users per MV/LV station	500
Fraction of interested users in DR	10%
Fraction of participating users to a DR event	5%
Fraction of flexible load	40%

Smart Contract MV/LV). These smart contracts, named 'chain codes' in HLF nomenclature, are indicated close to the station whose data are considered for validation and computation. So, data are collected at the HV/HV station from the downstream primary stations (HV/MV) and are validated at the HV/HV station.

Validation is carried out either by state estimation routines or other measurement units.

Locally, computations can be carried out.

Chain codes are executed on selected peers, depending on the policy [22], which in our case, involves different nodes. At all voltage levels, the controlling authorities take part to the relevant blockchain (in Italy, the Italian authority ARERA and the Italian market managing entity GME). In the LV network, chain codes run on peers operated by end-users (through energy communities, customer associations or even directly in case they are interested in operating a blockchain node), DSOs, energy providers, aggregators. In the MV network the interested actors are MV clients, DSOs and aggregators. In the HV network, the actors are the TSO and the HV loads. In all cases, controlling entities and insurance companies are interested both in the data and execution logic. The DSO periodically runs the SCMVLV at the MV/LV stations, where also customers associations and control entities take part. These measurements are written on a dedicated channel that makes data available only to those actors who are interested in the data visibility at the MV/LV station.

To define at which level of this hierarchical structure it is required to manage aggregation and what are the requirements, we can compute the minimum number of end-users that sums up to the minimum regulating power admitted by national regulatory framework. In Italy, the minimum aggregated unit must provide 1 MW of flexible load [23], considered as a quota of the contractual installed power. For this computation, the typical parameters of the Italian power system are considered, as reported in 6. Additionally, for this assessment, we assume that only a fraction of the users wants to participate to the DR program (10%), and only half of them would actually participate to a specific DR event. From table 6 it can be seen that for DR operation to be effective, under given hypotheses, under Italian regulations, 3 HV/MV stations must be involved, 150 MV/LV stations, and 75000 domestic (or, in general, small) end-users; the measurements and signals of all these elements could be handled by a dedicated blockchain. As a result, this blockchain has to manage 75000 execution of a smart contract for assessing the contribution of a given aggregated set (75000 end-users, 150 MV/LV stations and 3 HV/MV stations). This hierarchical segmentation also matches the needs of the involved actors, whose interest is related to the area served by the same MV/LV, the aggrega-

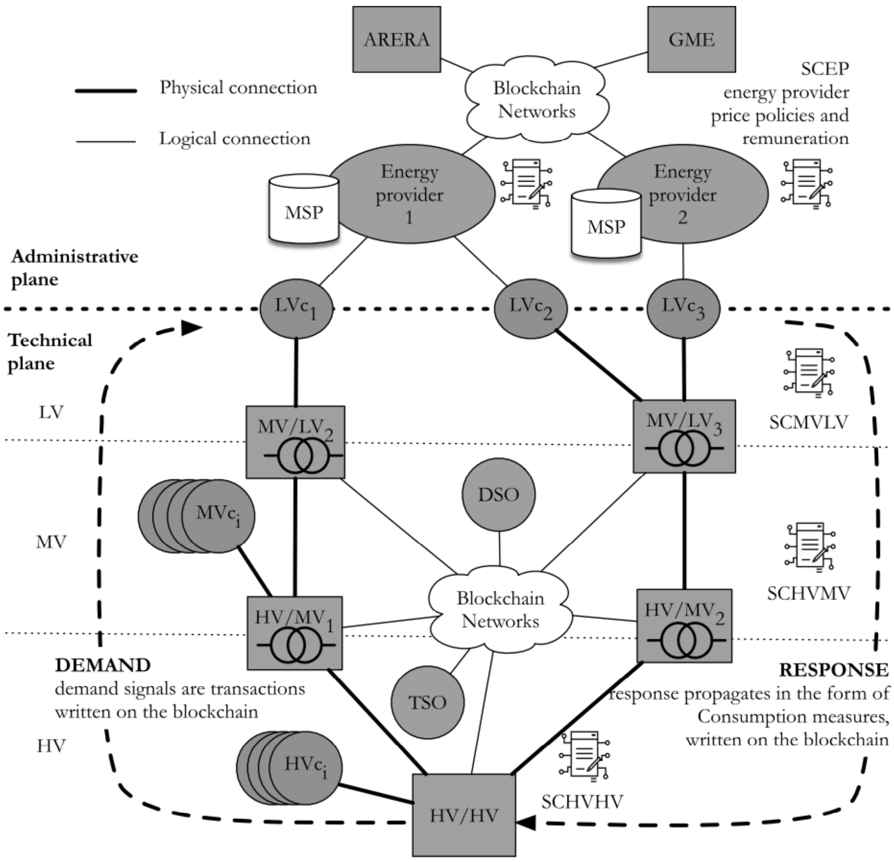
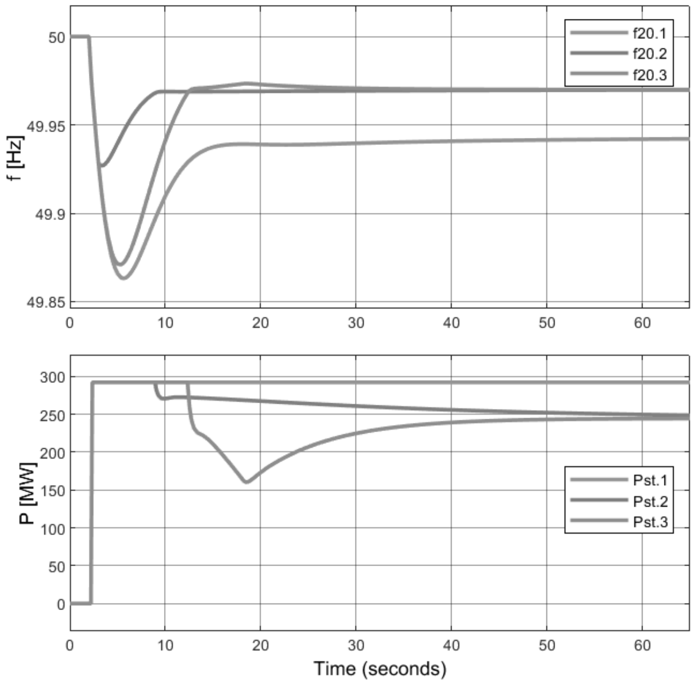


Figure 12: Power System and Hierarchical Smart Contracts for HV/HV, HV/MV, MV/LV stations.

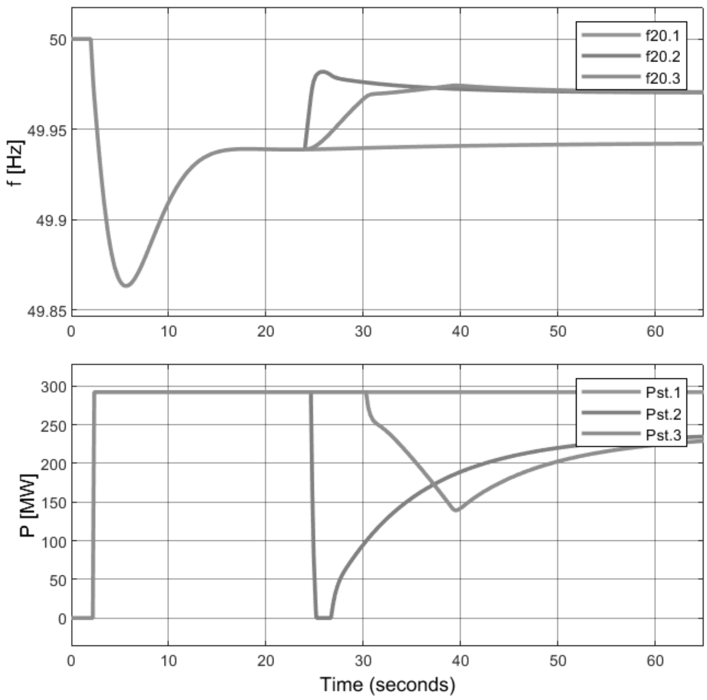
tor is interested to the branches of the tree that include the HV/MV stations indicated above (upstream) and their descendants in the tree (downstream). The typical partitioning of the power system applies also to the blockchain-based DR system; so that small logical (non-geographical) zones guarantee the compatibility of the blockchain reaction time with the requirements of ancillary services. Such partitioning of data, which also reflects the power network hierarchical organization, is also quite feasible to efficiently support balancing services. Hyperledger Fabric supports about 3500 transactions per second [22], therefore the measures can be handled in about 21 s. This timing is not fast enough for guaranteeing primary regulation, if notification to end-users and identification of the amount of load to be turned on/off must be carried out in advance within the time indicated in table 3. However, additional segmentation is even possible, to further reduce the latency introduced by the blockchain and process data in near real time. If, instead, blockchain is needed only for registering the users contribution to the event (tracing and certification), then times appear to be compatible. In the following, a simulation that proves the effectiveness of the extensive DR application is proposed in the two cases. Namely considering running the smart contract for identifying the users that need to take part to the regulation (delay for running the smart contract), check Fig. 8. The simulation is carried out using the Matlab/Simulink model above described. In this case, the base scenario is that of April 7, 2020 with FFR control and FCR equal to 1.5% of the total rated power of the RES plants. The same disturbances as in Section II is considered (loss of connection between Italy and France with a reduction in the imported power equal to 0.95 MW). The 5% of the Italian load is considered to be able to participate in the primary regulation reducing by 1570 GW. Nevertheless, in the following simulations, it is assumed a load reduction of 50% of the missed imported power. Fig. 13a shows the variation in the average grid frequency and in the power injected by the RES plants in three cases:

1. in the base scenario with FFR and no DR (f20.1 and Pst.1);
2. in the case of FFR and a step load-shedding action (f20.2 and Pst.2) in times compatible with blockchain operation;
3. in the case of FFR and load-shedding action with a progressive (linear) reduction of the load (f20.3 and Pst.3) in times compatible with blockchain operation.

The load-shedding action, in both cases, allows to obtain better values of steady-state frequency and to reduce the power injection by RES. In addition, the frequency nadir is reduced both in the second and in the third scenarios thanks to the effects of the load detachment. When blockchain is introduced in timing compatible with realistic operation, the load shedding action is performed with a delay of about 22 seconds, resulting in the graphs reported in Fig. 13b for the same three cases. As shown in the graphs, the delay introduced by the blockchain operation permits to reduce only the recourse to the primary reserve of the generators after some tens of seconds from the disturbance, but this would not allow to maintain system stability only with load shedding. Indeed, in the absence of other regulating actions provided by traditional and RES-based plants, the under-frequency transient would results in the collapse of the system. Finally, it can be concluded that the delay introduced by the blockchain does not allow to reduce the maximum frequency deviation.



(a)



(b)

Figure 13: Variations in frequency and power from RES for the three considered cases without the blockchain (a) and with the blockchain (b).

4.3. Discussion

Italian regulation is currently on the way for creating the conditions for making feasible the proposed solution. Indeed, with the document [24], in 2019, the Fast Reserve Unit pilot project has been started, with the aim of making available at least 230 MW of battery capacity for FFR. The last public audition has collected 1330 MW [25] demonstrating the great interest of stakeholders for being involved in this service. With the Deliberation ARERA 2017 300/2017/r/eel [23] of the Italian Authority on energy, grids and environment, the conditions for end-users aggregation and participation in the balancing market have been established and in 2020 almost 1200 MW of capacity were assigned [26]. A new edition of the technical standard CEI 0-21 [27], a mandatory standard regulating the conditions for connecting end-users to the LV utility grid, was issued in 2020, containing a better specification of the ancillary services that must be provided by low-power (below 100 kW) generators and storage systems, including primary frequency regulation. Finally, in 2018, the Italian Ministry of the Economic Development nominated a group of experts for the definition of a national strategy for developing projects on blockchain and Artificial Intelligence and in June 2020, the same Ministry, started a public consultation on the position paper on the Italian National strategy on blockchain and distributed ledger [28]. The law 11 february 2019 introduces in the Italian legislation the notion of 'smart contract' as 'the translation into a code of a contract so that the contractual clauses can be automatically executed, when given conditions, estabilished ex-ante, take place. The same conditions are inserted in the same code'. the same law recognizes in the Distributed Ledger Technologies, tools for implementing transactions among peers and for tracing. This technology by the law is defined as a "technology using a distributed ledger, that is shared and can be accessed from many parties and based on cryptography, so that it is possible to register, validate, update the storage of data .... and these data can be verified from each participant to the ledger and cannot be altered nor modified". The above-cited documents demonstrate that Italian regulation presents all the preconditions for making feasible the proposed approach and the results of the experimentation on UVAM is showing that the timing of the control of the distributed devices is compatible with the approach proposed in this paper. Nevertheless, many efforts still must be done in different dimensions for spreading the blockchain technology at the end-users level. Firstly, the energy blockchain concept must become popular, entering the small prosumers' culture like, in the early 2000s, it was made with domestic photovoltaics. This process could be, somehow, slow but it could benefit of the recent Italian initiative "Digital Republic" aiming at promoting cultural events for the diffusion of the digital culture at any level [29]. A second barrier concerns the regulatory framework and the notion of smart contract as outlined before. This barrier is however common to all applications using blockchain for digital contracts implementations. Immutability, the correct definition of all possible scenarios in a digital environment as immutability prevents from possible changes along time. Another important issue concerns the need to identify a responsible party for correct data used as inputs on the smart contracts. In this respect, it is important to identify a third party which is able to guarantee for the consistency of such data. In the power systems world, it is not easy to easily identify this party. A third barrier that must be faced is the creation of a blockchain infrastructure comprising the utility and the end-users. Nevertheless, in the last years, the commercial solutions currently available for building automation, renewable energy communities and distributed generation are introducing cloud-located data storage, energy management systems and blockchain in their layout. The issue that will be faced in the future is the data interchange between the available blockchain solutions. In this case, another issue to be solved is related to the energy consumption, due to the potentially high number of edge devices that could be connected and involved in sending and elaborating data. Cloud-based architectures, in which blockchain nodes are physically resident on concentrated machines and for which edge devices only are entitled to send data and host a client application to register or retrieve data from the blockchain are to be carefully analized. Finally, the last barrier to be overcome and which is related to the widespread adoption of DR and unrelated to blockchain, is related to the definition of an economic incentive for end users to take part to this service. For involving prosumers in the provision of ancillary services, an adequate remuneration must indeed be paid. In this sense, the absence of an aggregator and the direct communication between smart prosumers and the DSO/TSO is able to increase the amount due to the final end-user for the provided service. In conclusion, some important steps must be taken before the blockchain-based DR proposed solution of this work becomes real, but the state of the art of Italian regulation and technology is a notably good starting point.

5. Conclusions

As the globe is still involved in the pandemic disease and its effects on the economy of the most industrialized countries, there are a few scenarios that are more probable to happen. This paper aimed to analyze what have been till now the effects on power system operation in Italy, where the effects of the pandemic have been harder, especially in the first phase of the pandemic. Nevertheless, the emerging considerations in the paper are general enough to be applied also to other national power systems. The paper also explored possible countermeasures and the effects they would have had in terms of system stability. Also the feasibility of applying some groundbreaking technologies both on the supply and on the demand side has been explored as well as their effect on the power system operation. A particular contribution of this paper is the proposition of a hierarchical architecture for blockchain platforms mapping the physical structure of the power system and providing even more efficient service to the grid operators for power balancing. The proposed arrangement allows to overcome the problem of managing large numbers of readings/writings on the blockchain as the number of end-users taking part to the regulation becomes realistic. A further work will consider other applications of the proposed measures as well as their laboratory implementation to assess practical application scenarios. Finally, a further work will also consider possible scenarios of extensive EV mobility widespread, V2G services in place and possible modification to such services due to global risks and associated modifications on peoples mobility habits. In facts, modern sustainable mobility systems in the short term are based on the use of Electric Vehicles. Charging stations have a significant impact on the distribution network because of their rated current for fast charging. Using the blockchain technology it is possible to have a user-centric approach that takes into account citizens' mobility needs as primary input, secondarily, the needs of vehicles and charging infrastructures [30].