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Data center power dynamics within the settings of regional power grid

Gulnara Zhabelova[1], Alireza Yavarian[1], Valeriy Vyatkin[1,2]
[1]Department of Computer Science, Electrical and Space Engineering
Lulea University of Technology, 971 87 Lulea, Sweden
[2]Department of Electrical Engineering and Automation, Aalto University, 02150, Helsinki, Finland
gulnara.zhabelova@ltu.se, alireza.yavarian@ltu.se, vyatkin@ieee.org

***Abstract*— Data centers have grown to become big energy consumers, comparable to traditional industries. At this scale of power consumption, data centers play considerable role in electric networks operation. However, being a relatively new industrial scale consumer, data center requires more careful consideration and research to uncover its specifics and better understand its requirements; and investigate data center's impact on regional grid. Data centers have proven to be not just a collection of computers, but rather complex infrastructure with complex dynamics and subsystem dependencies. This paper reports on the work in progress and at this stage details an effort to understand the impact of dynamic server load of a data center on its power infrastructure and further on the grid; the effects of transient faults in power grid on performance of a data center. This will help regional grid operators to improve power balancing within the network to maintaining network stability avoiding failures and blackouts. The results of this work will be used in developing dynamic power balancing strategy for a smart grid containing large data centers.**

Keywords—data center; power quality; power factor; data center efficiency; data center model; transient fault; power system.

I. Introduction

Within the last decade, data centers have become a part of everyday life for many people. Internet and computing technologies have enabled so –called "online era" bringing new ways of interactions and re-inventing old. Social media has grown, connecting people throughout the world and enabling fast information exchange (e.g. disaster warnings, fund raising etc.). Retailers and customers across the world engage via online shopping. Email, online storage, online video and music streaming, online games, and many other "over the internet" services are continuing to shape modern societies.

Internet connectivity has become a must requirement for businesses of any size and occupation. Companies use servers for emails, storage, communication, databases, intensive computations, custom application hosting and many other internet services depending on business needs. Moreover, business requirements demand highly reliable and available data centers.

This global growth in "over the internet" service drives service providers to search for bigger, more powerful and efficient datacenters.

As a result, a number of servers and data centers throughout the world grows. That results in large data centers, aggregated power consumption of which is becoming an issue [1][2]. Data centers have grown to become big energy consumers, comparable to traditional industries. Facebook total energy use in 2013 made up 822M kWh, and this trend is rising: energy consumption grew from 532M kWh in 2011 to 704M kWh in 2012 [3].

As any other industrial consumers, at this scale of power consumption, data centers play considerable role in electric networks operation. Regional network operators have to account for data center load and its fluctuation in their short and long term network planning. Furthermore, as "high-tech" industrial consumer, data center demands stable, reliable and highly available power with good quality.

However, being a relatively new industrial scale consumer, compared to traditional industry such as steel production and mining, data center requires more careful consideration and research to uncover its specifics and better understand its requirements; and investigate data center's impact on regional grid. This will help regional grid operators (RGO) to improve power balancing within the network to maintaining network stability avoiding failures and blackouts. Understanding the consumer will facilitate RGOs to efficiently utilize available power and resources in the network, and better accommodate customer requirements.

This paper investigates data center dynamics and mutual effect of data center and regional grid. This paper is an effort to understand the dependencies of data center power infrastructure on the utilization of the IT equipment; the effects of power instability on performance of data centers; the impact of data center activity on power networks.

Data centers have proven to be not just a collection of computers, but rather complex infrastructure with complex dynamics and subsystem dependencies.

Data center's IT equipment is sensitive to the variations and spikes in voltage, current and frequency of the supplied power [4]. At the same time power grid has known issues of power quality, voltage and frequency variations which might lead to system instability. Poor power quality supplied to the critical load can affect performance of the equipment and even damage it.

Moreover, data center is a relatively volatile load. The power consumption not only depends on a number of servers used in the facility, but also on workload of an individual server. The power consumed by a server on a light to heavy load can vary up to 100% [5]. IBM BladeCenter HS20 Full Chasis 14 blades server consumes 2.16 kW of power on low server utilization and up to 4.05 kW on high utilization [5]. The higher is the workload on the servers, the more heat is generated. This heat needs to be removed and servers need to be cooled down and kept at the operational temperatures. This requires an entire cooling infrastructure which in turn consumes power to operate. Therefore, the variation in workload on the servers translates into the power consumed by the data center and the fluctuations of power in the regional grid.

At the same time the workload on the servers is relatively hard to control. The workload depends on the behavior of the end users, for example, users of the social media. The behavior of the business users is relatively predictable, as they often are active during the office hours. However, with the trend of flexible hours and home offices, that is changing as well.

The main contribution of the paper is detailed below:

- We show the effect of transient fault in regional power network on data center dynamics. During transient period, servers are shield by the uninterruptable power supply (UPS). In an effort to understand boundaries of safe operation, we show that capacity and state of charge of UPS play crucial role in protecting data center from transient faults (section IV).
- We show data center dynamics, e.g. the effect of power factor (PF) of IT equipment on power loss and hence the efficiency (section IV). This contributes towards understanding data center dynamics and further consideration of data center as an industrial consumer.
- We demonstrate that by building the data center model described in section III and simulating developed use cases (section II) imitating various conditions within the power network and data center (section IV).

II. USE CASES

A. Data center and regional grid: transient fault condition

This scenario studies effect of transient faults such as one- and three-phase earth faults. Transient fault is the fault which is no longer present in the power network.

Consider sample distribution feeder as shown in Figure 1. The model is based on the IEEE 13 node test feeder model [9]. The fault is simulated near the data center location. Protection scheme of the distribution network clears the fault typically within 2-3 cycles [10]. This period of 40 ms – 60 ms is enough to create voltage and current sag. These short transient conditions will not damage equipment, however, may cause malfunctioning of server components, such as hard drive and memory, which can result in corrupted data. In order to compensate for the voltage sag, IT equipment will draw more current to maintain required power levels. However, when both current and voltage levels drop, then equipment cannot obtain required power levels.

Acknowledging this, IEEE 1668-2014 standard defines recommended practice for voltage sag for electronic equipment [11]. The voltage should be more than 50% of nominal voltage in a 200 millisecond time period [11]. UPS is used to dampen these voltage and current variations within the allowed range.

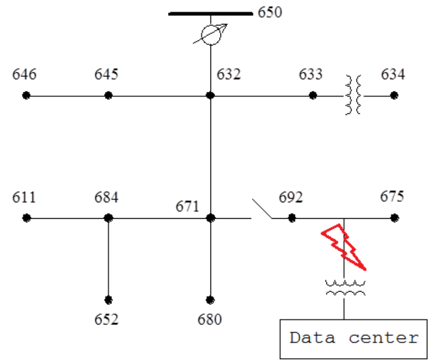

Figure 1. Sample regional distribution network based on IEEE 13 node test feeder [9].

There are several UPS configuration used in data centers. Most data centers have configuration of N+2, 2N, 2N+1 [12]. “N” denotes the power capacity required to feed the protected equipment. This implies that UPS configurations carry extra capacity to provide highest reliability up to 99.995% [12].

UPS batteries with full charge provide safe operation for critical loads even under the short power interruptions. However, we want to investigate the boundaries of safe operation considering limits of protecting equipment: what is the safe minimum charge of UPS batteries?

Additionally, knowing safe limits of UPS batteries is useful for demand response applications in a smart grid environment. Data center can participate in the power balancing mechanisms of the grid operators and provide ancillary services. The capacity of UPS configuration is designed to take on critical load at its peak. Hence, data center can get disconnected from the grid and move to UPS supply for a short period of time, sufficient to help network operators to meet reliability standards. To perform these types of demand response actions, data centers should be aware of boundaries of safe operation e.g. minimum UPS capacity and limitations of protection devices.

This scenario investigates the effect of transient fault in the distribution feeder on to the data center IT equipment under various levels of UPS state of charge.

B. Data center dynamics: power factor of critical load

IT equipment has dynamic PF. During the data center life span, IT equipment gets changed, updated and often new more powerful devices are installed. This may impact the total PF of the server room. Also, PF of the server power supply changes with the load [6]. The Figure 2 shows the relation between power factor and load in the server HP DL360 [13]. The lower the load is, the lower the PF. At 10% load on the server, its PF drops to 0.8. Servers often operate at medium to low load and occasionally reach their peak load [7]. This constantly evolving IT load affects PF.

Low PF affects power quality in the electrical distribution network of data center. PF is a ratio of true power to apparent power, i.e. ratios between consumed power (useful power) and absorbed power (total power).

$$PF = \frac{True\ power}{Apparent\ power}$$

The circuit containing reactive components (inductive and capacitive) has PF<1. This means that the circuit wiring (cables) have to carry more current to deliver the same amount of true power than in the circuits with no reactance. The reactive power dissipates in the circuit. Higher current in the wiring means more lines losses and require equipment with higher capacity. Poor PF results in an inefficient power delivery system [14].

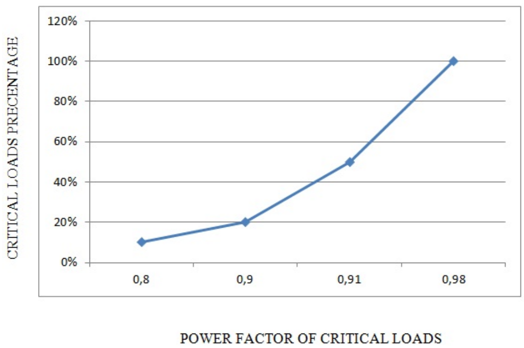

Figure 2. IT load to power factor curve of HP DL360 server [13].

Data centres, as industrial facilities, will be charged penalty by the network operators, if their PF is much different from 1.

The correction of PF of thousands of servers can be done individually or aggregated in power distribution units (PDUs). Power factor depends on reactive power (inductive or capacitive). The reactive power in data centre power infrastructure can be compensated using special equipment such as compensators.

Additionally, power quality is affected by non-linear loads, which draw a distorted waveform that contains harmonics. Harmonic is a higher order frequency (e.g. 100Hz, 150Hz, 200 Hz) current and voltage distortion of fundamental waveform (50 Hz) [15]. Added together they produce distorted waveform. Electronics equipment can behave as a non-linear load, due to their switching power supplies [14][15], which exhibit lower PF. The main issue of harmonic distortion, besides the energy waste, is overheating of equipment or conductors [14]. To limit the harmonic injection into AC mains, many computer vendors developed PF corrected (PFC) power supplies. Main goal of PFC is to bring PF as close as possible to 1.

In this scenario the effect of various PF of IT load on data center power dynamics (power quality) is investigated.

It is important to understand the mutual effects of various subsystems, designed as an independent arrangements, however, working together within one facility.

III. Simulation Model

For the simulation of the above scenarios, data center model was developed.

The power infrastructure of a data center consists of several main building blocks, which is common for all data center such as utility transformer, automatic transfer switch (ATS), switchgear, UPS, backup generator, power distribution units (PDU), cooling system and servers. Figure 3 shows developed model.

The *critical load* consists of IT equipment such as servers, network and storage devices, and modeled as RLC load of 105 kW. This power capacity was estimated using HP Power advisor calculator [8], by modeling 6 racks of BL460c Gen8 blade servers (384 servers) and 4 racks of network and storage devices. Critical load changes during the day, as the server utilization and load on other IT equipment follows the end-users behavior pattern. IT load needs to be protected from the fluctuations in the utility power and power failure and therefore power is supplied via UPS.

UPS model contains battery with charge and discharge curves of Li-Ion battery. It is important to correctly select capacity of the UPS battery, since it has to be able to supply peak critical load when utility power fails. UPS contains AC/DC and DC/AC converters, thus filtering out voltage and frequency fluctuations present in incoming utility power. The developed model has tier III 2N+1 UPS configuration.

The power from UPS is distributed and delivered to the servers and other equipment by the PDUs. PDUs also step down the voltage to the right level for the equipment. In our model, each PDU unit consists of a transformer with capacity of 500 kW and rating 480/208 V, fuses as protection devices and miniature circuit breakers.

The lighting loads have fixed power; they constitute *non-essential loads* and connected to the substation via PDU. The size of lighting loads is 0.645 kW, calculated according to the method described in [4], taking into account size of the server room (3m×10m×5m). The motor of fans and pumps of cooling

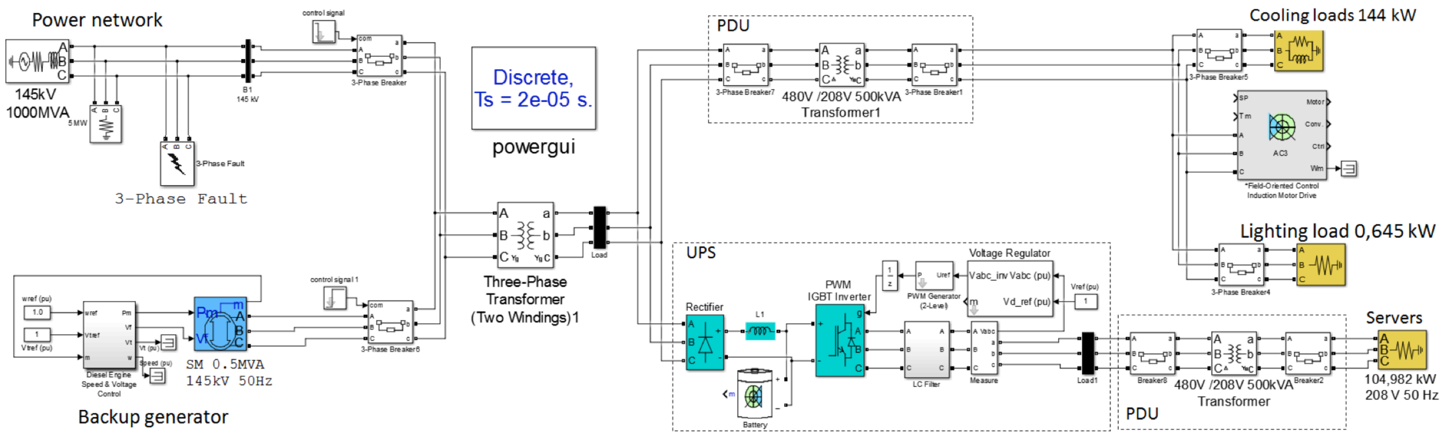

Figure 3. Model of a typical data center, developed in Matlab Simulink.

system are the *essential loads*; a 72 kW induction motor is considered as the aggregated cooling fan load and another 72 kW is modeled as equivalent RLC load.

The distribution network shown in Figure 1 for the purpose of this exercise is modeled as “Three phase source” block with large capacity. The power is stepped down by the power transformer, modeled as 2-winding transformer with configuration parameters of capacity 2MVA and rating 145 kV/0.48 kV. The data center model has 500 kVA standby generators set. The generators provide backup power in case of utility failure. ATS has an interlock; when the utility is not available ATS disconnects the utility and connects the generators set to data center power infrastructure. UPS batteries allow time for standby generators to start up, and pick up the critical load in order to keep the power uninterrupted.

The Table 1summarizes the parameters of the data center model.

TABLE 1. DATA CENTER PARAMETERS.

Item	Size (kW)
Critical load	105
Lighting	0.645
Cooling load (induction motor)	72
Cooling load (RLC load)	72
Standby generator set	500 kVA
UPS	262

IV. SIMULATION AND RESULTS

A. Simulation of a transient fault

The simulation was carried out in Matlab Simulink. Simulation model is shown in Figure 3. Three cases are considered with UPS at 20%, 50% and 100% of its statement of charge.

One- and Three-phase earth faults are simulated close to the data center, using “Three phase fault” block. The fault is injected at 0.15 sec. The protection scheme clears the fault within 50 ms, and transient conditions end at 0.2 sec.

The transient behavior of current and voltage of data center is then studied. Figure 4 and Figure 5 show current and voltage of critical loads under one-phase fault respectively. At 0.15 sec current and voltage drop in all three cases. However, UPS at full capacity prevents dramatic power dip and controls the power level at 9% of initial value.

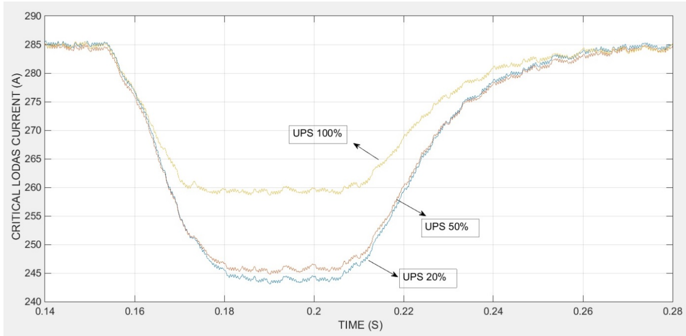

Figure 4. Transient of critical loads: current curve under 1-phase earth fault.

UPS with 50% and 20 % of charge allow the voltage to keep falling till 0.18 sec where is stabilizes at around 180 V (Figure 5). The power dip in first case is 13% and in the second case is 15%. Thanks to the extra capacity of the UPS (2.5N, where N is 105 kW), the conditions of the transient fault do not threaten the stability of the data center and do not reach dangerous level to damage equipment. The voltage and current levels are well above IEEE 1668-2014 standard.

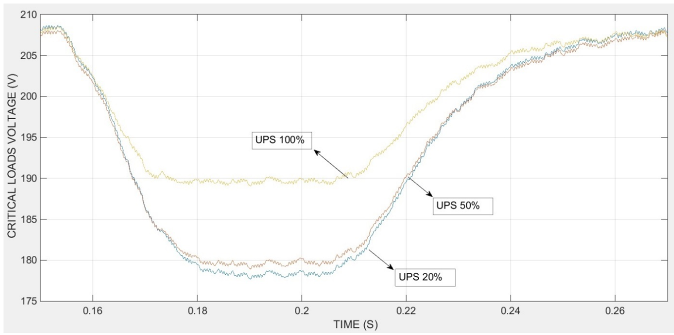

Figure 5. Transient of critical loads: voltage curve under 1-phase earth fault.

The results of this simulation show that data center, even at low UPS capacity, can well safely endure transient one phase earth fault.

After three phase earth fault, the similar transient behavior is exhibited by current and voltage as depicted on Figure 6 and Figure 7 correspondingly. At 0.15 sec power starts falling and by 0.17 sec all three configurations of the UPS manage to stabilize the power. However, the drops are lower. UPS with 100% charge allows voltage and current to drop to about 10% of their nominal values. The UPS with 50% and 20% of charge lets the sag to reach 14.5% and 16% respectively. Even under transient three-phase earth fault, the levels are still within the recommended IEEE 1668-2014 limits.

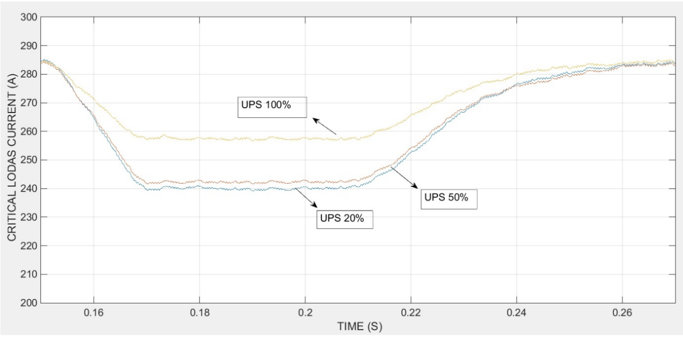

Figure 6. Transient of critical loads: current curve under 3-phase earth fault.

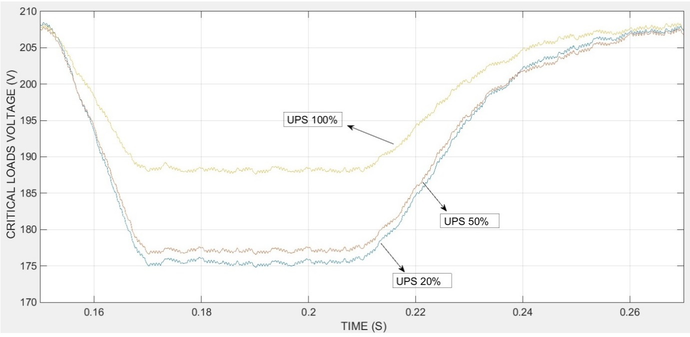

Figure 7. Transient of critical loads: voltage curve under 3-phase earth fault.

The simulation demonstrates that large UPS capacity and its batteries' state of charge is important for safe operation of the data center. Up to 80% of the UPS battery charge can be exploited in demand response applications without threatening reliable operation of the data center. UPS battery can be charged in the period following the demand response action when price of electricity is lower. The decision to provide ancillary services needs to take into account risk of resulting low UPS charge, prediction of data center server utilization and other parameters such as required availability.

B. *Power factor of critical load*

The simulation is carried out in Matlab Simulink, using the model depicted in Figure 3. The state of UPS battery charge is taken at 70%. The size of critical load is changed according to the curve depicted on Figure 2. The several simulations are carried out with the PF of 0.8, 0.9, 0.91 and 0.98.

The results of simulation show that the PF of IT equipment has significant effect on the current and voltage harmonics as depicted on Figure 8 and Figure 9 respectively.

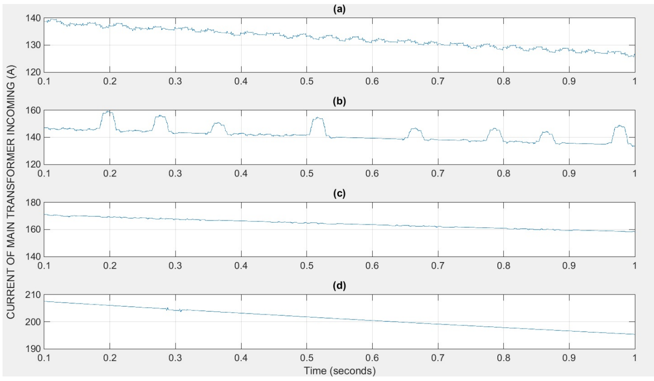

Figure 8. Current of incoming power transformer under various PF of critical load: (a) PF=0.8, (b) PF=0.9, (c) PF=0.91, (d) PF=0.98.

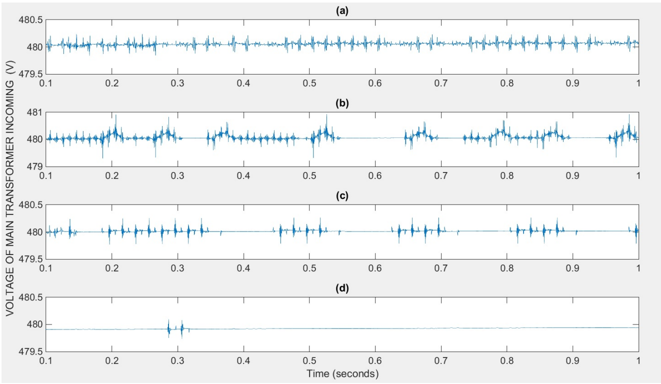

Figure 9. Voltage of incoming power transformer under various PF of critical load: (a) PF=0.8, (b) PF=0.9, (c) PF=0.91, (d) PF=0.98.

At the highest PF=0.98, harmonics of current and voltage waveforms are reduced to the minimum (Figure 8, d and Figure 9,d). As a result data center with high PF will have less power loss and more efficiency, providing high quality power.

There is a noticeable degradation of power quality from PF 0.98 to 0.91 and lower. Servers in data center rarely work at full utilization, i.e. 100% capacity. Typically servers operate at medium utilization [7], exhibiting PF<1. This results in increased power loss, heating of cables and contributes to reduced data center efficiency. Moreover, these harmonic distortions can have effect on power transformer connecting data center to the grid, and therefore on the regional grid. Thus, dynamic PF of data center, fluctuating following server utilization, affects the power grid.

It is important for data center to keep PF as close to 1 as possible throughout the life span of the facility and daily server load.

These results will be taken into consideration when developing dynamic power balancing strategy for the regional networks containing large data centers. Data centers need to monitor their PF while participating in demand response actions, providing ancillary services by either shedding their load or compensating for reactive power.

Conclusion

This paper presents a study on data center power dynamics within the settings of regional grid. The challenging task was developing appropriate models of a data center considering dynamics of various subsystems within the facility. Simulation shows the importance of UPS battery in the events of transient faults occurring in the supplying power network. Proper sizing of UPS system can ensure reliable operation of the data center. Moreover, UPS may unlock the potential of a data center to provide ancillary services for regional network operators. The paper also studied effect of power factor on the power loss and data center efficiency.

Understanding boundaries of safe operation of a data center and its potential is necessary in power management of future smart grid and in automation of data centers themselves.

Immediate future work is to further improve developed models to include dynamic load profile reflecting end user behavior, to extend model of the essential loads considering complete cooling system and to model IEEE 13 node feeder as a regional network.

Building on these results, the next step will be developing an optimal dynamic power balancing strategy for RGO with several data centers and distributed generation. This is an important topic relating to stability and reliability of the grid.

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