Technologies for Integration of Large-Scale Distributed Generation and Volatile Loads in Distribution Grids

Technologies for Integration of Large-Scale Renewables and Multi-Slot EV Charging Stations in Distribution Grids

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***Abstract*—As fossil fuel reserves are limited in stock and there is an urgent call to reduce the carbon footprint, distribution grids urgently need to move towards heavy use of local and distributed generation of electricity using renewable energy sources. Another promising prospect for the future of the planet is wide adoption of electric cars. However, large-scale integration of these highly volatile resources in distribution grids is challenging: distribution grids may face power quality problems and fuel-based generators may be needed to compensate for high volatility (which defeats the original purpose). Additionally, with the large penetration of solar and wind energy, the grid becomes inverter-dominated (has little inertia) and therefore traditional methods for controlling the frequency, voltage, and congestion of lines are no longer sufficient. In this article, we present different activities carried out in our research groups to tackle above-mentioned challenges in large-scale integration of such volatile resources. These activities range from advance planning to real-time monitoring and operation of distribution grids. We have also developed a software testbed, called T-RECS, for testing software agents before deploying them in the field. Finally, as the reliability and robustness is very crucial in such critical infrastructures, we have developed some reliability solutions that are suitable for use case scenarios typical to distribution grids.**

Keywords—Renewables, Electric Cars, Distribution Grids, Advance Planning, Real-Time Monitoring and Operation

1. Introduction

Solar and wind energy is certainly one promising prospect to reduce the carbon footprint. Contrary to energy generated from burning fossil fuels, solar and wind energy is decentralized, intermittent, variable, and less predictable. Therefore, adding a large amount of such energy in electrical grids has undesirable consequences on the operation of electrical grids: large voltage deviations may happen and line currents may surpass their limits. The addition of EV charging stations will make the problem even worse as the distribution grids are typically not designed for such large and sudden deviations in the load.

Above-mentioned power quality problems can be addressed by grid re-enforcement but the cost is often prohibitive. Dynamic control of resources is an alternative but it has to be economic, reliable, and scalable. Moreover, such control should be pseudo real-time if we need to manage resources with large variability.

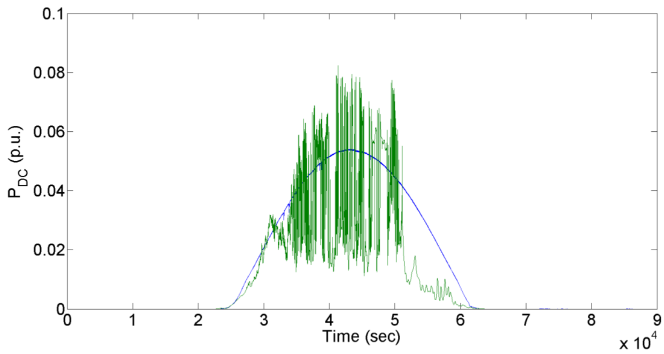

Figure 1: Power injected by solar arrays at the roof of the DESL, EPFL building on one day in the month of November, 2013. Source: Prof. Mario Paolone's lab (DESL, EPFL)

For example, the most extreme case of such resources with large variability is that of solar panels which, during the passage of clouds, can lose or regain most of their power in a few seconds (Figure 1).

A second type of problem caused by the high penetration of decentralized electric power generation concerns the transmission systems. Unlike traditional generators, extreme volatility of decentralized generation is associated with a lack of support to transmission networks for system services (primary and secondary control of frequency and voltage). This leads to an increase in tuning needs for national networks. They have to find ways to compensate for this volatility by employing conventional generators with high flexibility. These generators are typically fossil fuel generators with a negative impact on the environment (CO2 emissions).

Traditional methods of frequency control are no longer sufficient to manage high variability because frequency is very global quantity. It therefore becomes necessary to control directly the active and reactive power of resources in the distribution grids themselves. We already start to see the development of such systems: voltage control in low-voltage network by controlling the active and reactive power of solar

panels [1], and controlling the active power of residential thermal loads using “Demand Response” by an operator [2].
The trends are now rapidly changing not only in terms of distributed generation of electricity but also in terms of load/consumption with the arrival of electric vehicles. As per various studies, the number of electric vehicles (EVs) will significantly rise in next few years. As a result, we will soon see the deployment of large multi-slot charging stations in public or parking places where many EVs (in the order of hundreds or more) can be charged simultaneously. Such a charging station will definitely be a huge load for the local distribution grid. As our current electrical grids were not dimensioned for them, power quality problems may arise if such charging stations are plugged at some arbitrary place in the grid. To deal with these power quality problems, the most environment-friendly solution is to deploy a local generation (PV panels) and storage system (Batteries) along with the EV charging station.

With the arrival of large multi-slot EV charging stations, we will also see more peaks in the consumption trends. While charging EVs at such charging stations, we should be able to avoid as much as possible the charging of EVs at peak times of the load in the grid. Moreover, at times when there is large production from renewable energy sources, the charging station should consume more power (for example, by following OpenADR or similar signals). For example, it is probably better to charge the EVs at mid-day when the sun shines the most or during those times when the wind blows. Here it is probably worth to mention that such renewable sources of energy production can vary in terms of their predictability. For example, solar energy is generally more predictable than wind energy. As advance planning is one of the crucial things in integrating large volatile loads/generation, predictability of a resource plays a key role.

In our research groups, we are building solutions for smooth inclusion of such distributed generation and heavy unpredictable loads such as large multi-slot EV charging stations. These solutions range from advance planning, monitoring, and real-time operation of distribution grids. For testing our software agents in silico before their actual deployment in the field, we have also developed a software testbed, called T-RECS. As reliability and robustness are also crucial elements in such critical infrastructures, we have developed some reliability solutions that are suitable in the context of real-time operation of distribution grids. Next sections follow a detailed description of our activities in each of these directions. Last section concludes the paper and gives some future perspectives.

2. Advance Planning

Advance planning is usually the first step in making conventional grids smart. The objectives usually consist in forecasting (usually day-ahead) power consumption/generation for resources with uncertainties. In case of solar generation, forecasting can be done in many ways using various information

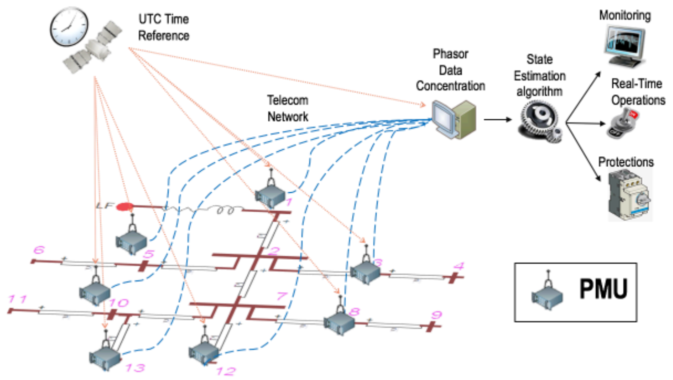

Figure 2: Monitoring infrastructure developed at EPFL campus based on the use of PMUs. Real-time state estimation results are available at [3].

like historical data, weather forecasts, and real-time pictures of sky. In the same fashion, power consumption can be forecasted by finding patterns in historical data. As another example of uncertainties in load, large multi-slot EV charging stations typically do not know the exact arrival and departure time of EVs, type of EVs, and their energy demand at arrival time.

After forecasting, the second step usually is to optimally manage a given set of resources. For example, in case of large multi-slot EV charging stations, an environment-friendly solution is to deploy such charging stations with local generation and storage solutions. By optimally managing all these resources, this solution can also be made economical. In this setting, there can be many optimization objectives: minimize the required capacity of electricity storage, minimize the total import of electricity from the main grid, or simply minimize the cost of electricity purchased from the grid depending on the pricing-scheme. For example, in the above scenario, we can compute the day-ahead optimal power trajectory at the local connection bus where the objective is to minimize the import of electricity from the main grid. The day-ahead power trajectory can be computed periodically (such as every 15 minutes) by taking into account the uncertainties of EV charging station and local generation.

3. Real-Time Monitoring

Having the current state of the grid is a requirement for many ensuing tasks like fault-detection, fault-prevention, and real-time operation of the grid. Therefore, we target that monitoring should be as fast-paced and accurate as possible. This is achieved by our current state-of-the-art monitoring infrastructure, which consists of phasor measurement units (PMUs), a communication network, a phasor data concentrator (PDC), and a state estimator (SE) unit (Figure 2). More details about this real-time state estimation can be found in [4].

4. Real-Time Operation (Commelec Framework)

With the monitoring infrastructure, we have a real-time (with a reactivity of the order of a fraction of a second) operation framework, called Commelec. It sends active or reactive power

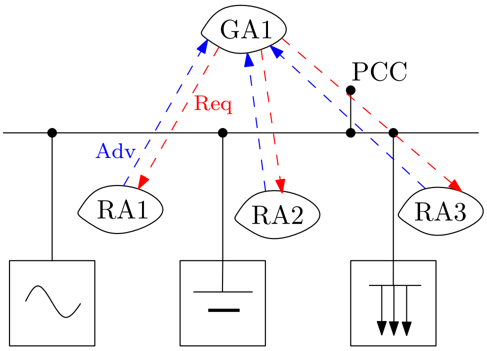

Figure 3: Structure and principle of Commelec protocol. Resource Agents (RAs) send advertisement containing the state of resources under control to the Grid Agent (GA) and GA sends power setpoint requests to the RAs.

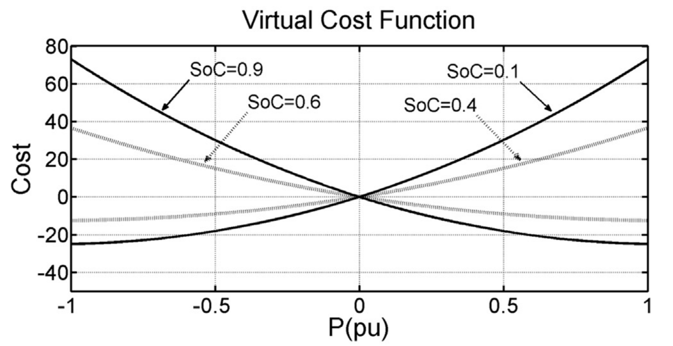

Figure 4: Virtual cost function for the active power used by battery agent as a function of state of charge (SoC).

setpoints to the resources involved in balancing the network. As, in most cases, it is not enough to control only the reactive power but also the active power, it is necessary to have some form of energy storage. These storage solutions can be: supercapacitors for the very short-term storage (of the order of a second), batteries for the short term (hours / days), and fuel cells / hydrolyzers for the longer term (weeks / month). It should be noted here that the cheapest storage in the minutes / hours dynamic is the manipulation of demand, mainly thermal loads (heating, hot water, refrigeration, air conditioning) which offer a huge virtual storage capacity.

We have developed a real-time operation framework, called "Commelec", with the support from "SNSF – NRP 70" Energy Turnaround Project [5] and "SCCER-FURIES" project [6]. With the Commelec framework [7-8], a grid controller (Grid Agent or GA), implemented on a microcontroller, is responsible for managing an electrical network, for example a building or a district. It receives information on the status of different resources (a solar panel controller, a building or a battery) under control by their respective resource agents (RAs) (Figure 3). GA sees the state of the electrical grid for which it is responsible and sends power setpoints every 100 milliseconds to resource agents, so as to maximize overall utility while keeping the grid in a stable and secure state.

4.1 Simplified functionality due to its Universal Protocol

The first essential feature of Commelec is the use of a universal protocol, which is independent of the hardware. Thus, the battery agent BA, when it informs its network controller GA1 of its internal state, does so using an abstract (virtual) cost function and does not use a battery specific language (figure 4). When the battery is almost full, e.g., for a charging state equivalent to 0.9, the cost function indicates a preference to generate power (positive power domain, right part of figure 4) rather than to consume (negative power domain, left part of figure 4) and conversely when the state of charge is low. It is therefore not necessary to expose to the grid controller all the internal characteristics and variables of each battery or resource.

Another system, e.g., the Intelligent Building Agent, sends similar messages. These messages differ only in the value of the cost function, which can also change for each message every 100 milliseconds. The work of the network controller is therefore always the same: to calculate the total cost gradient including a penalty term to keep the electrical network in a safe state, to perform a step of minimization with a gradient descent, and send the corresponding power setpoints to different agents.

4.2 Separation of Concerns

In particular, all network controllers are identical and there is one code to develop for all power grids, regardless of their size and specificity. In addition, this code is small and can be validated by rigorous development methods. Only agents, such as the battery agent, for example, must be specific to the nature of the system they represent. But, in return, they perform simpler functions.

4.3 Composability

Composability is the second essential feature of Commelec: the GA1 network controller in Figure 3, which, for example, controls an EPFL building, is itself controlled by a higher-level network controller, for example, the controller. their campus of the EPFL. In this interaction, the controller GA1 and the entire network of the building it controls appear as a single resource, somehow a battery of a special kind. The campus controller thus sees only a small number of systems, which keeps it simple and small (and therefore reliable). This composability property can be repeated at multiple levels, making it easy to manage systems of any size.

This property has another positive effect: it simply allows to realize the much-desired concept of "dispatchable feeder" with and without frequency control and primary/secondary reserves. In fact, the campus controller can send a power instruction to the building controller GA1, for example by asking him to reduce his consumption by x kW. The controller GA1 will incorporate this setpoint into its optimization function and, depending on the state of the systems it controls, will try to approach the setpoint. For example, the reduction will be possible if the heating of the buildings can be delayed for a few moments or if a battery has a sufficient state of charge. The building can therefore appear as a controllable electrical resource; and by composability, the entire campus too. In extreme cases, the software makes it possible to automate the islanding operation, that is to say the disconnection / reconnection to the electrical grid from the main grid. In the

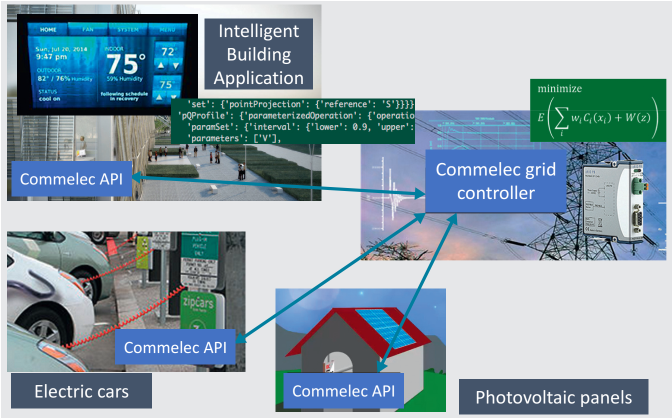

Figure 5: Application Programming Interface (API) of Commelec allows to simply connect an intelligent building control system, an EV charging station, and photovoltaic panels; all these systems therefore can actively contribute to the management of electric distribution networks.

long run, it is a city or a portion of the country as a whole that can enjoy this flexibility of the electricity grid - a breakthrough that will allow for a strong penetration of renewable energies.

4.4 Commelec API

In practice, the deployment of Commelec requires that certain critical resources, such as heating for a building or a battery, respond to the instructions of an electrical network controller. Developers of building management systems or electric cars however do not need to know the details of Commelec, thanks to its programming interface (API) which is freely available [8]. They can simply interface with the control system of electrical networks (Figure 5). In a way, the Commelec API provides the "operating system" of an active power grid.

4.4 Implementation/Demonstration

The Commelec control framework has been tested on the experimental electrical network of EPFL's Distributed Electrical Systems Laboratory (DESL). In a first step, it reproduces a Cigré1 benchmark of low voltage electrical distribution network. It incorporates:

- 40 kW of solar panels;
- Leclanche Li-titanate battery of 25kW and 25kWh;
- 75 kW and 2 kWh supercapacitors;
- 15 kW fuel cell and 6 kW hydrolyser connected to 30 bar hydrogen and oxygen storage system with a capacity of 2.5 MWh;
- a heat pump;
- and a building emulator connected to the hot water network with a heat output of 55 kW.

The first tests for the automatic control of this test network by the Commelec software took place in the autumn of 2015. In a second step, the test network is extended to few buildings of EPFL's electrical department (medium voltage grid). With Commelec, we have also successfully tested the islanding (automatic disconnection / reconnection) of DESL microgrid to the main grid. Outside EPFL network, Commelec is successfully tested at EMPA NEST building [10] and is now being deployed by few utilities in Switzerland and outside.

5. T-RECS TESTBED

A recurrent requirement for software-based real-time monitoring and operation software agents is to test them as they are in silica before their actual deployment in the field. Monitoring and operation performance of such software-agent based solutions is influenced by software non-idealities such as crashes and delays, and message losses and delays due to the underlying communication network. Therefore, to study the effect of these non-idealities, we developed T-RECS: an open-source virtual commissioning system or software testbed.

They key feature of T-RECS is that it allows to test existing software without modification by running them in software containers. The communication network among these software containers is emulated using Mininet framework. As the communication network is emulated, it allows for real packets being exchanged between software agents as is the case in the real-world. The electric resources in the grid are simulated and the grid is modeled in the phasor domain.

We are currently using T-RECS to test Commelec software agents before deploying them in electric grids of different utilities we are working with. This allows us to study if Commelec software agents are bug-free and if they are able to achieve their desired objectives. More details about T-RECS and its design can be found in [11].

6. RELIABILITY

To achieve a control system that takes into account electrical networks, buildings, loads, and distributed generation systems such as solar panels, etc., the challenge becomes, as for any process control system on a very large scale, to ensure its reliability and robustness. Such systems must withstand hardware failures and software bugs.

To tackle reliability in communication networks with stringent delay constraints, multiple fail-independent paths are necessary. However, existing solutions such as parallel redundancy protocol (PRP) only work for local area networks. Such a limitation on scalability, coupled with lack of security, and diagnostic inability, renders PRP unsuitable for reliable data delivery in smart grids. To address this issue, we developed a transport-layer design: IP parallel redundancy protocol (iPRP). Besides unicast, iPRP supports multicast, which is widely using in smart grid networks [12].

For Commelec style controllers where setpoints have real-time constraints (implementing a setpoint after its deadline, or not receiving setpoints within a deadline, can cause failure), delay faults can cause setpoints to violate their real-time constraints. To address these delay faults, we developed a fault-tolerance protocol, called Axo, that guarantees safety and improves availability [13].

7. Conclusion

The formidable challenges posed by strong penetration of decentralized production and large multi-slot EV charging stations can be solved by a combination of the following activities: advance planning, real-time monitoring, and real-time operation of electric grids. In our two laboratories, we are working on each of these directions of activities. We have already built a set of technologies that can help integrating large volatile distributed renewable energy sources (solar, wind) and loads (multi-slot EV charging stations). We continue working in these research directions and now actively trying to make a positive impact by bringing our research work to the industry.

References

[1] D. Georges, A. Coutarel: Voltage Regulation in LV Networks with PV Installations (Régulation de la tension dans les réseaux BT avec installations PV). Bulletin SEV/AES 5/2014, pp 29-32, 2014.

[2] For example: Swisscom Energy Solutions www.tiko.ch

[3] https://smartgrid.epfl.ch

[4] M. Pignati and al., "Real-time state estimation of the EPFL-campus medium-voltage grid by using PMUs," in Innovative Smart Grid Technologies Conference (ISGT), IEEE PES, 2015.

[5] NRP70 Research Program http://www.nrp70.ch/en

[6] Swiss Competence Center for Energy Research – Future Swiss Electrical Infrastructure. http://sccer-furies.epfl.ch

[7] A. Bernstein, L. E. Reyes Chamorro, J.-Y. Le Boudec and M. Paolone: A composable method for real-time control of active distribution networks with explicit power set points. Part I: Framework. Electric Power Systems Research, Vol. 125, pp. 254-264, August 2015.

[8] L. E. Reyes Chamorro, A. Bernstein, J.-Y. Le Boudec and M. Paolone: A composable method for real-time control of active distribution networks with explicit power set points. Part II: Implementation and validation. Electric Power Systems Research, Vol. 125, pp. 265-280, August 2015.

[9] See https://github.com/LCA2-EPFL/commelec-api and https://smartgrid.epfl.ch/?q=node/14

[10] https://smartgrid.epfl.ch/?q=node/22

[11] Jagdish Achara, Maaz Mohiuddin, Wajeb Saab, Roman Rudnik, and Jean-Yves Le Boudec. T-RECS: A Software Testbed for Multi-Agent Real-Time Control of Electric Grids. In 22nd IEEE International Conference on Emerging Technologies and Factory Automation. IEEE, 2017.

[12] M. Popovic, M. M. Maaz, D.-C. Tomozei, and J.-Y. Le Boudec. IPRP: "Parallel Redundancy Protocol for IPv6 Networks," Technical report, EPFL, 2014

[13] Maaz Mohiuddin, Wajeb Saab, Simon Bliudze, and Jean-Yves Le Boudec. Axo: Masking Delay Faults in Real-Time Control Systems. In Industrial Electronics Society, IECON 2016-42nd Annual Conference of the IEEE, pages 4933–4940. IEEE, 2016