Engineering Microgrids With Control Co-Design

Principles, methods, and metrics.

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THE VULNERABILITY OF electrical grids to natural disasters, physical and cyberattacks, and other potential failures has become an increasingly concerning issue. Microgrids can provide the necessary resilience to critical public and private infrastructures while also offering grid-support services and economic and environmental benefits.

Microgrids significantly differ from large electrical grids in their bidirectional power flow, low inertia and associated low damping and stability margins, generation and load uncertainties, energy storage and generator oversizing challenges, and high levels of renewable energy penetration. Advanced microgrid designs need to find highly robust control solutions, with minimum communication requirements and reliable protection systems, all for both single microgrids and clusters of microgrids.

The current microgrid design tools are based on sequential methodologies that deal with steady-state models and economic analysis first, leaving the dynamics and control system design for a later stage. Using a concurrent engineering philosophy, Control Co-Design (CCD) techniques consider dynamic subsystem interactions and control systems from the very beginning of the design process and propose optimal solutions that are not achievable otherwise. This article discusses some CCD methodologies and the associated first principles and metrics to design microgrids with better system dynamics and controllability, which result in lower cost and improved resilience, reliability, and power quality.

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Microgrids

The power grid is about to see one of the largest transformations since Nikola Tesla and Thomas Edison started the first electric networks. The enormously ambitious targets of renewable energy penetration across the globe, the vast proliferation of distributed energy resources (DERs), and the extensive evolution toward electric vehicles (EVs) are demanding a much more flexible and reliable power grid. Simultaneously, resilience is an increasing concern of electricity grids, where the majority of power outages occur at the distribution level.

Microgrids are a potential solution to improve local resilience and reliability, reduce costs, increase renewable energy penetration, and deal with EVs, DERs and flexible network topologies. A microgrid is essentially an independent controllable unit composed of interconnected distributed generators (DGs), loads, and energy storage systems (ESSs), which operate within a well-defined electrical boundary and which can work in either islanded or grid-connected modes. Single microgrids and constellations of microgrids provide resilience to critical public and private infrastructures, facilitating grid support and economic and environmental benefits.

Microgrids differ from large electrical grids in their low inertia and associated low damping, large generation and load uncertainties, storage and generator oversizing challenges, bidirectional power flow, and high levels of renewable energy penetration. The complexity of microgrids often leads to larger investment costs, creating a barrier for widespread adoption.

Advanced microgrid designs need to find robust control solutions for, perhaps, a complete renewable energy penetration, large EV fleets, DERs in flexible network topology configurations, minimum communication requirements, reliable protection systems, good component interoperability properties, plug-and-play options, ancillary services, islanding mode and black-start capabilities, and high resilience against extreme weather events and cyberattacks, all for both single microgrids and clusters of microgrids.

Currently, microgrid design tools are based on sequential methodologies, which deal with the steady-state models and economic analysis first, leaving the dynamics and control system design for later. Using a concurrent engineering philosophy, this article introduces some CCD techniques that consider dynamic subsystem interactions and control systems from the very beginning of the design process, proposing optimal solutions not otherwise achievable.

The new microgrid CCDs look for better system dynamics and controllability, lower cost and improved resilience, reliability, and power quality. In particular, the proposed CCD methodologies endeavor to find new control system solutions with appropriate sensors, actuators, and new plant dynamics and algorithms to achieve key objectives that include, among others, a peak generation reduction and related savings on power generators, the prevention of battery oversizing, increased battery life span, decreased generator and battery maintenance costs, the damping of frequency and voltage oscillations, improved system stability, network topology flexibility, and decreased line-congestion cases.

Grid Inertia

In a conventional generation world, the power grid has a very large rotational inertia composed of the rotors of the spinning generators across the grid. During operation, grid frequency depends on the balance of active power between the generation and the demand. When an imbalance between the generation and the demand occurs, the frequency varies at a rate determined by the inertia of the system.

If that inertia is large, the frequency will respond in a very stable way, with minimum oscillations (see Figure 1); however, as the level of renewable energy penetration increases, and especially with inverter-based wind and solar energy systems, the total rotational inertia decreases significantly. This low-inertia aspect is quite common in microgrids as they typically include a large percentage of solar and wind. In these situations, the generation/demand imbalances will find less rotational inertia and consequently will create more frequency oscillation. At the limit, this can result in an instability phenomena and power outages (see Figure 1).

Over the last decade, there have been many discussions around grid inertia and power system stability, proposing new solutions based on smart grid techniques. They basically try to substitute the conventional mechanical inertia with synthetic inertia to overcome this problem. As the kinetic energy accumulated in the rotors of the conventional generators diminishes, new sources of energy with a similar rapid response time are necessary to decrease the sensitivity of frequency to power imbalances. New power electronics devices, storage systems, topology networks, communications and advanced control solutions are key aspects to finding appropriate solutions for both low-inertia microgrids and the power grid.

Load Sharing and Droop Control

Microgrids behave like a living creature, controlling voltages and frequency across the network with the injection of reactive and active power, respectively. Every time the load changes at any point, the generation also changes, keeping the frequency constant. As the frequency is a global variable (voltage is a local variable), when a frequency change occurs, all the power generators across the microgrid react and inject active power to control it.

The most common control strategy in industry is the proportional–integral–derivative (PID) controller, where the derivative part provides stability and the integral part cancels the steady-state error. This solution works very well in many processes; however, in the scenario in which many power generators regulate the network frequency with PID controllers, by including these integral parts in their algorithms, the generators could fight against each other, producing frequency oscillations and a load-sharing problem (see Figure 2).

For this reason, the frequency is typically not directly controlled by PIDs. The conventional solution is a hierarchical control structure, with primary, secondary, and tertiary levels for the short, medium, and long term, respectively (see Figure 3). The primary level is composed of exceedingly simple, first-order algorithms instead of PIDs, known as *droop control*. Although the integral part is not included in the droop control algorithm, and as a result, there is not any specific component at this level to cancel the

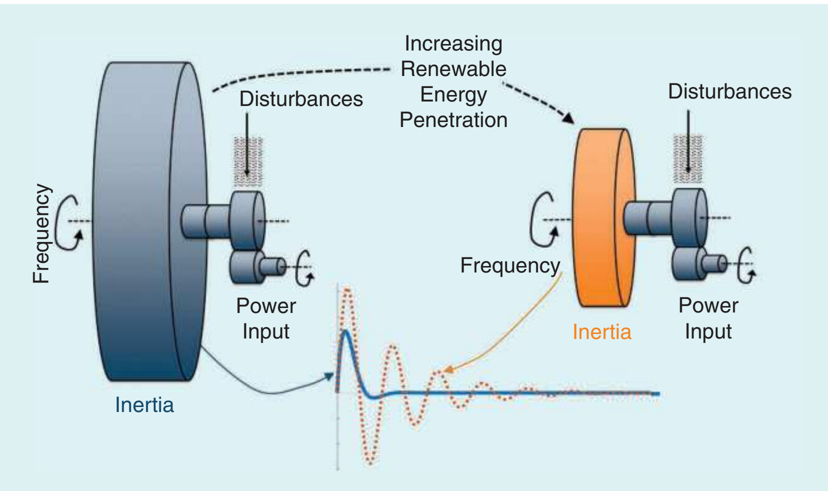

Figure 1. Frequency oscillation, depending on microgrid inertia.

steady-state frequency error, when the number of generators is significant, this error becomes negligible. Also, the secondary level includes a PID algorithm for a steady-state frequency-error cancellation (frequency restoration) in a 10-min horizon.

This droop control (primary) plus PID control (secondary) solution works well in a conventional grid with many power generators. However, this control strategy should be revisited in more sophisticated grids and specially in microgrids with few power generators.

CCD and Microgrid Optimization

Designing the power grid, and in particular microgrids, is a multidisciplinary effort. The key topics include static and dynamic studies, economic analysis, environmental aspects, and statistic considerations. Often, these microgrid designs are developed in a sequential way that relies at least on three steps, as displayed in Figure 4.

Using the appropriate computer tools, a first step considers steady-state calculations (T1.1) and a cost analysis (T1.2), which define and select the generators, loads, storage systems, and networks. Following this, and with additional computer tools, a second step designs the protection systems (T2), including switches, relays, and coordination strategies. Finally, and with other computer tools, a third step studies the dynamic problem and designs the control system (T3), including sensors, actuators, and control algorithms.

As presented in Figure 4, this is an independent and sequential design process that studies the dynamics and develops the control system at a very late stage. Although practical, this sequential approach limits the possibilities of the final microgrid. Every step of this design methodology severely reduces the options of the next step of the process.

Multidisciplinary dynamic systems, like microgrids or the entire power grid, cannot be optimized unless subsystem dynamic interactions and control systems are considered in the system optimization process. A solution is the CCD approach. With a concurrent engineering philosophy, CCD considers the dynamic subsystem interactions from the very beginning of the design process, discussing simultaneously the dynamics of generators, loads,

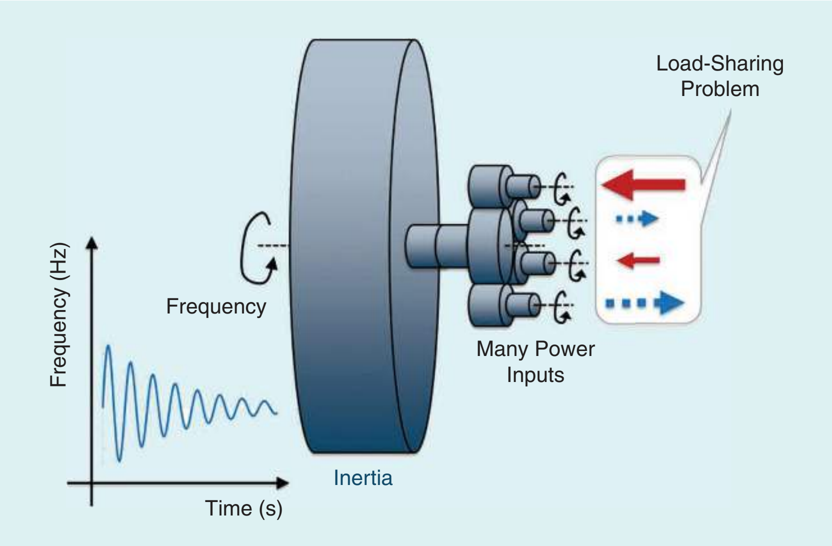

Figure 2. The frequency load-sharing control problem among power generators.

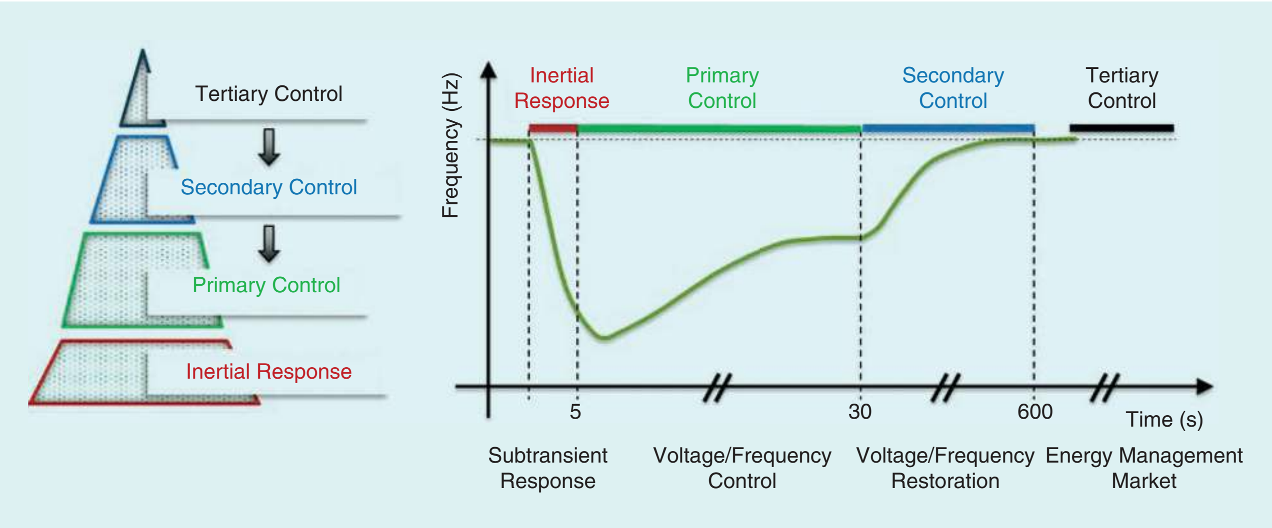

Figure 3. A conventional grid hierarchical control architecture.

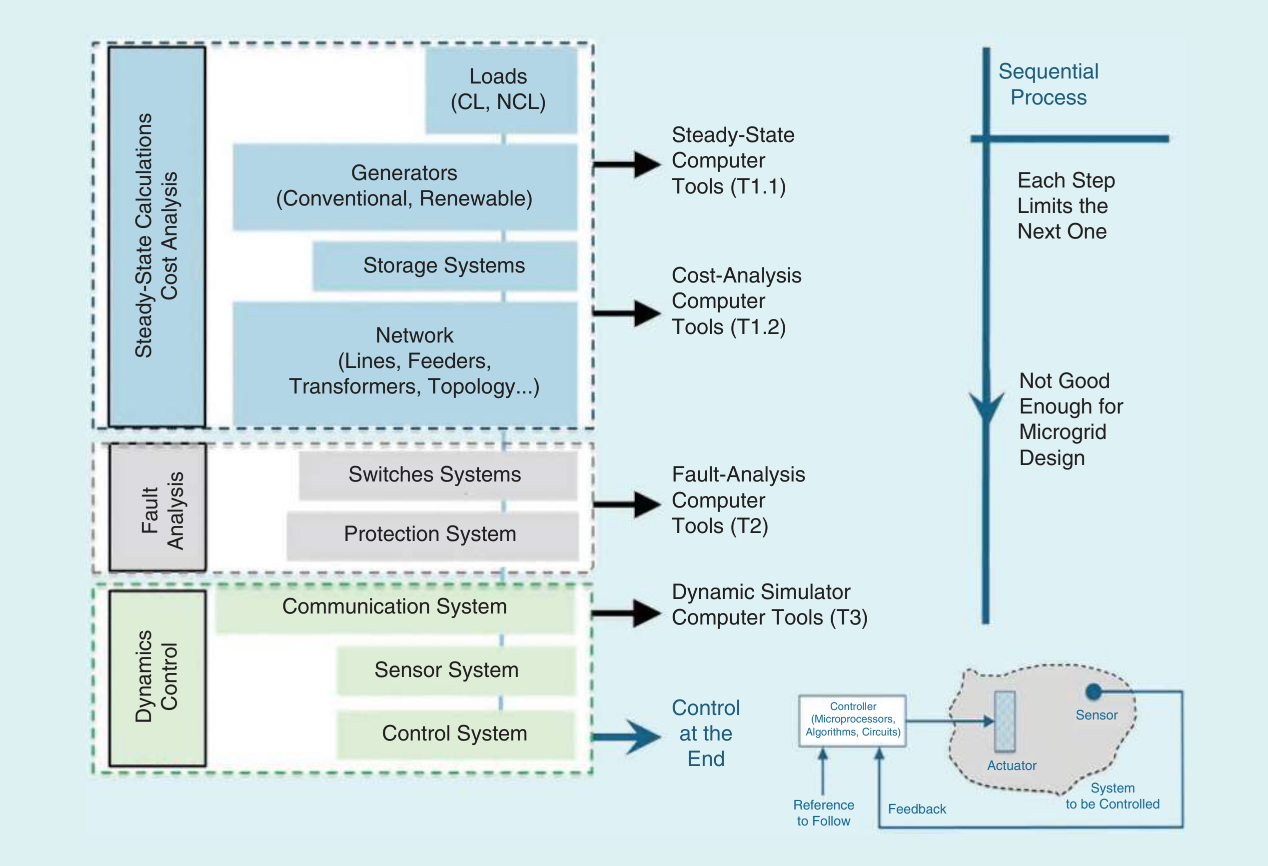

Figure 4. The steps of a conventional, sequential microgrid design process.

storage systems, networks, power systems, protection systems, economics, communication systems, sensors, and control systems (see Figure 5). In this way, CCD proposes optimal solutions that are not achievable otherwise, enabling a more optimal design with better system dynamics and observability and controllability among other advantages, which often results in a lower system cost and improved reliability and resilience.

CCD methodologies are mainly based on engineering, mathematics, and computer science and feature three corresponding areas: 1) (A1) control-inspired paradigms, 2) (A2) co-optimization techniques, and 3) (A3) co-simulation methods (see Figure 6). In addition, the CCD of microgrids typically needs information from five inputs: (i1) microgrid objectives, (i2) predesign of components, (i3) physics-based models, (i4) real data from experiments, and (i5) case studies to validate the design (see Figure 6).

The first input of the process, (i1) microgrid objectives, defines the goals and targets to be achieved by the microgrid or cluster of microgrids. Usually, these objectives are formally defined in terms of

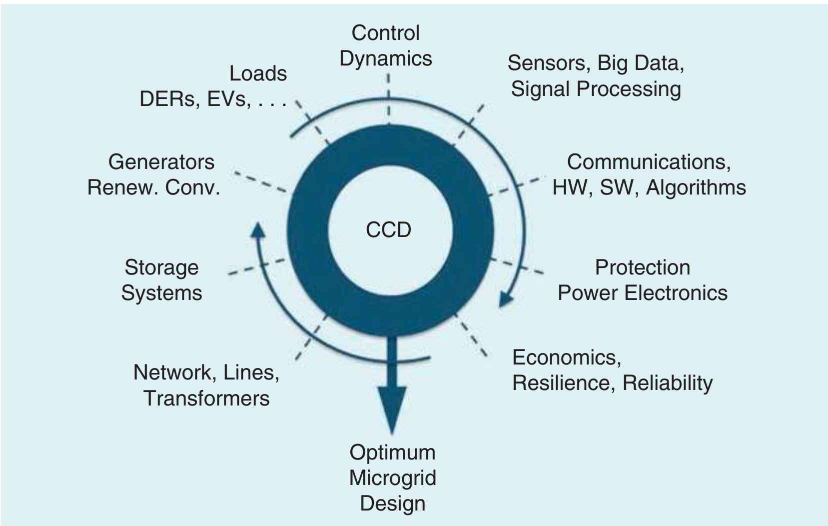

Figure 5. The CCD of a microgrid. Renew.: renewable; Conv.: conventional; HW: hardware; SW: software.

numerical metrics, which include a variety of characteristics, such as reliability, resilience, performance, dynamics, controllability, observability, efficiency, robustness, survivability, life span, economics, environmental impact, and interoperability (see the "A Metric Space for Microgrid Design Guidance" section).

The second input, (i2) predesign of components, proposes an initial design of the relevant components of the microgrid, including the generators, loads, storage systems, networks, switches, transformers, and so on. The third input, (i3) physics-based models, outlines the mathematical models that describe the dynamics of the components and the interconnections defined in the second input, including subtransient, transient, and steady-state dynamics, and the high-, mid-, or low-fidelity models of the electromagnetic and mechanical aspects, the economic characteristics and so forth.

The fourth input, (i4) real data, provides information from experiments to assist with the analysis of the microgrid, validates the models, and reduces the inherent model uncertainty. The fifth input of the CCD process, (i5) case studies, proposes key cases to test the microgrid, including grid-connected and islanded cases, different levels of renewable generation and electricity costs, a variety of faults in key points of the network and the communication system, variations of the network topology, extreme weather cases, a transition among system states, and cases defined by the standards.

With this information (i1 to i5), the CCD methodology develops the optimization of the microgrid. The first CCD method, known as *control-inspired paradigms* (A1), proposes new design solutions based on a practical engineering understanding of dynamics and control. Based on control engineering principles, this approach uses physics-based low-/mid-fidelity models in frequency and time domains and tools like Bode and Nichols diagrams and Root locus. With the appropriate power electronics, sensors, and control algorithms and looking at the dynamics of the microgrid, it proposes solutions that optimize aspects like controllability; observability; stability; damping; time delays; multi-input, multi-output coupling; integrity; fragility; actuator-sensor colocation; control authority; nonlinearities; and others.

The second CCD method, known as *co-optimization* (A2), uses a formal mathematical methodology with the nonlinear low-/mid-fidelity dynamic models of the microgrid and multivariable-constrained optimization theories and iterative processes. The third CCD method, *co-simulation* (A3), uses multiscale, multiphysics, high-/mixed-fidelity dynamic models of the microgrid in an iterative simulation process, frequently with methodologies that include Monte Carlo algorithms, data-based models, or machine learning techniques.

Each method provides some benefits but also has some limitations. In

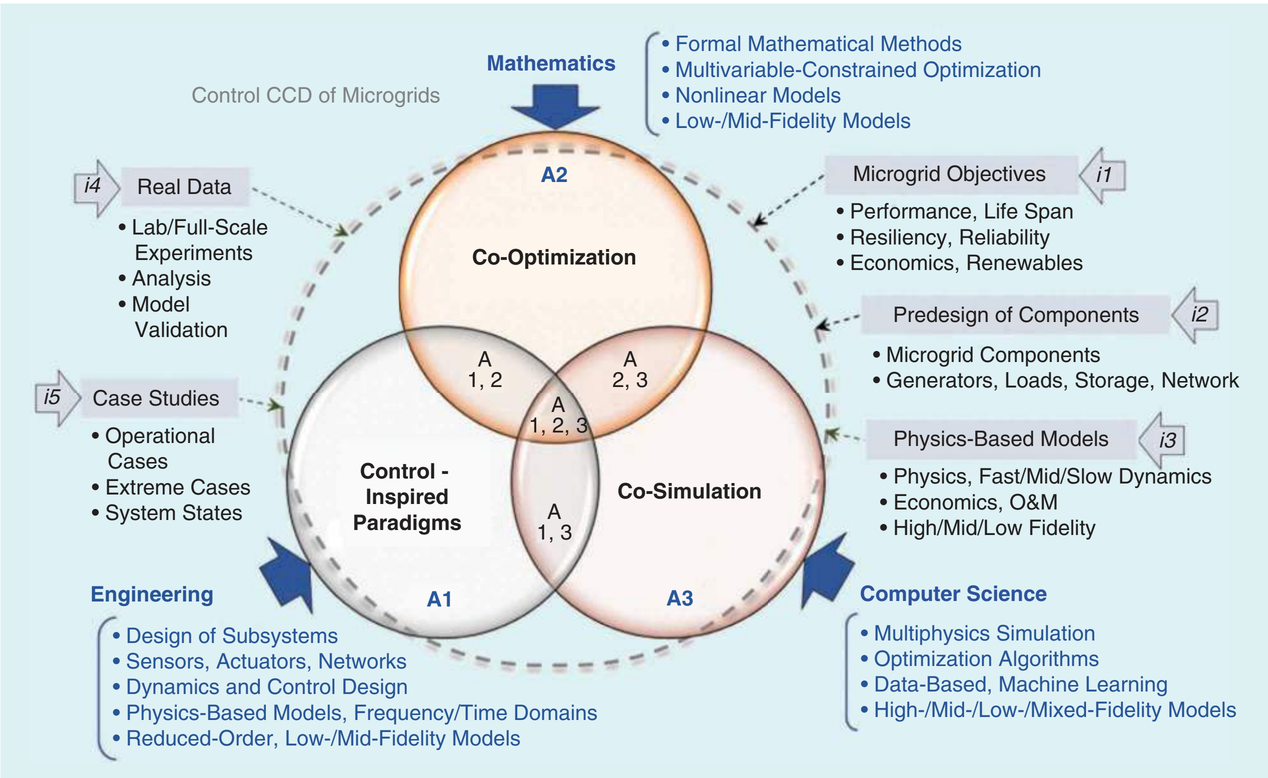

Figure 6. The CCD methods. O&M: operation and maintenance.

theory, the co-optimization method (A2) is able to find a global-optimum solution; however, it is often quite difficult to model all the complex aspects of the system, or it fails to converge into a practical solution. At the same time, the co-simulation method (A3), combined with physics-based models and machine learning techniques, is very attractive for some cases. However, this method has difficulties in finding creative solutions outside of the information contained in the original data. Finally, the control-inspired paradigms method (A1) is the one that is able to keep an engineering understanding of the microgrid during the design process, especially when appropriate control engineering tools are applied. Studying the dynamic interaction among the components, this approach is able to propose new mechanisms, actuators, sensors, and control solutions to modify the system's dynamics to achieve the design objectives.

These three methods (A1–A3) and five inputs (i1–i5) give a comprehensive picture of the current CCD philosophy; however, that systematic approach was not so well understood when it was first proposed (see Figure 7). The first CCD notions are probably buried in the pioneering designs of Charles Brush and the Wright brothers. In 1887, Charles Brush (Cleveland, Ohio) designed and tested the world's first automatically operating wind turbine for electricity generation, and in 1903 (Kitty Hawk, North Carolina), the Wright brothers designed and tested the world's first heavier-than-air powered airplane. Both applied a CCD control-inspired paradigm (A1) method.

Many years later, starting at the end of the 1980s, a new CCD co-optimization (A2) method was introduced. It formally proposed a simultaneous mathematical co-optimization of the parameters of both the controller and the plant of the system, both with a fixed structure. These new ideas were soon known as *integrated structure/control design* and were first applied to airplane structures, flexible robots, and spacecraft. With the extraordinary improvement of computing capabilities and new artificial intelligence algorithms over the last few years, new CCD co-simulation (A3) methods have been proposed.

Finally, in 2018, the U.S. Department of Energy/Advanced Research Projects Agency—Energy (ARPA-E) started a number of large efforts in CCD. The Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servocontrol (ATLANTIS) program proposed a CCD approach to find radically new designs of floating offshore wind turbines, and the Submarine Hydrokinetic And Riverine

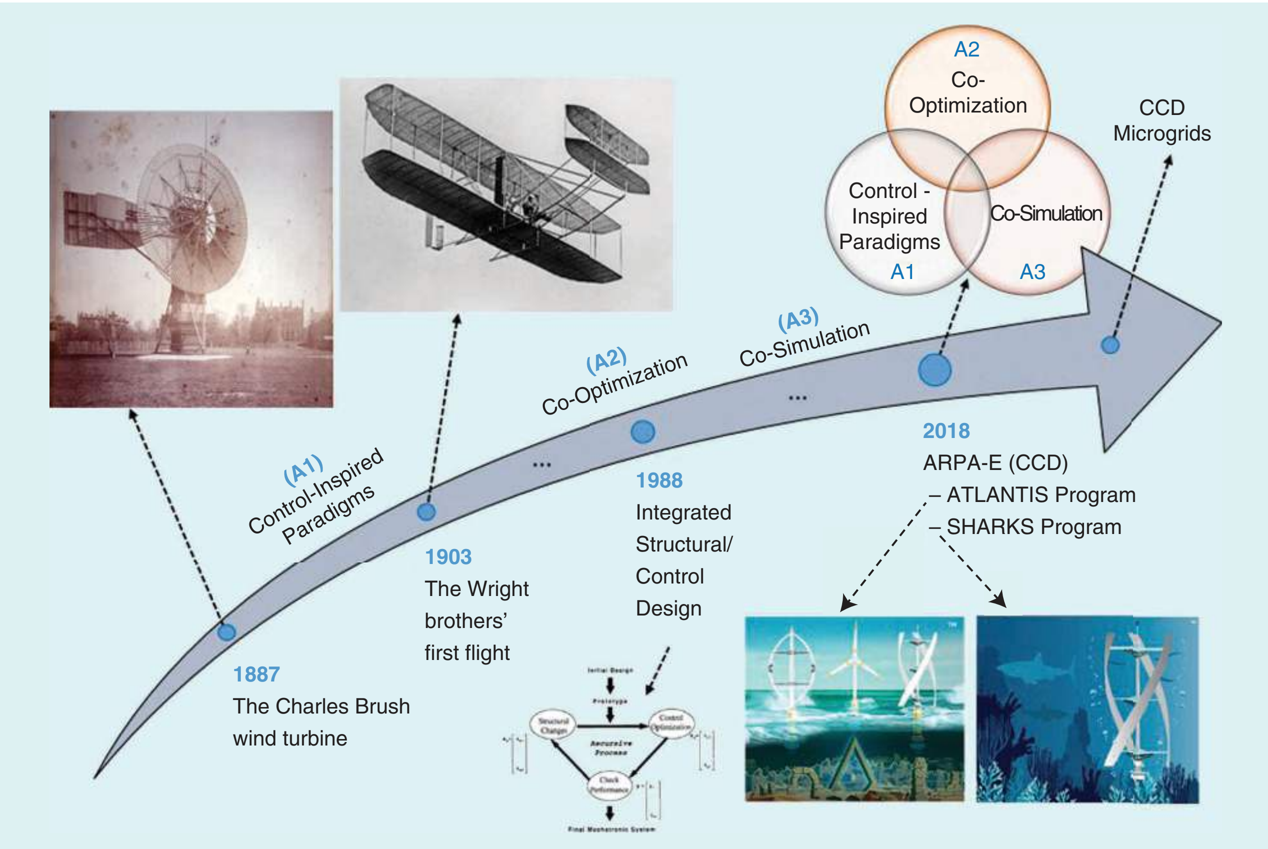

Figure 7. CCD: The story of an idea.

Kilo-megawatt Systems (SHARKS) program proposed a CCD approach to find completely new concepts of tidal and riverine energy converters. The highly coupled dynamics of these systems make them ideal candidates for the CCD approach (see Figure 7).

Similarly, the extremely coupled dynamics present in microgrids make them an ideal candidate for the CCD approach. Microgrids are composed of many subsystems that interact dynamically, including conventional and renewable generators, power electronics, flexible loads, EVs, ESSs, control, communications, and protection systems. The higher the subsystem dynamic interactions, the more needed the CCD methodology. The design of optimal microgrids, composed of electromechanical systems, cyberphysical systems, and techno-economic solutions with disparate mathematical descriptions, require multiple areas of expertise in a CCD framework (see Figure 5).

As shown, the three CCD methods involve a concurrent and iterative engineering effort that redesigns the components, networks, and control solutions of the microgrid at each iteration of the optimization process. The combination of the three methods, with the engineering creativity of the control-inspired paradigms (A1), the mathematical co-optimization techniques (A2), and the co-simulation campaigns (A3), will definitely open the door to radically new optimal designs of microgrids.

A Metric Space for Microgrid Design Guidance

Metrics play a key role guiding research and technical innovation. This section proposes a new metric space to apply the CCD methodology to microgrids. Metrics quantify the performance of microgrids and facilitate a graphical understanding that guides optimal designs and operations.

Figure 8 depicts a conceptual picture of the metric space. It is composed of two orthogonal metrics: M1 and M2. The first metric (M1) measures the resiliency and reliability of the microgrid under a set of tests. The resiliency is computed as the availability of the microgrid to maintain the energy supply under some predefined events, and the reliability is calculated as a dynamic margin in terms of frequency and voltage damping of the microgrid to those events. The second metric (M2) is a technoeconomical evaluation of the microgrid, which includes costs and grid services. Putting both metrics in an orthogonal space, it is easy to 1) estimate the performance of existing microgrids; 2) define the objectives with bounds that represent a tradeoff between the two metrics (see the dashed line), with the areas of interest where an optimal design should land; and (3) find a path to guide the research and innovation efforts to accomplish those objectives.

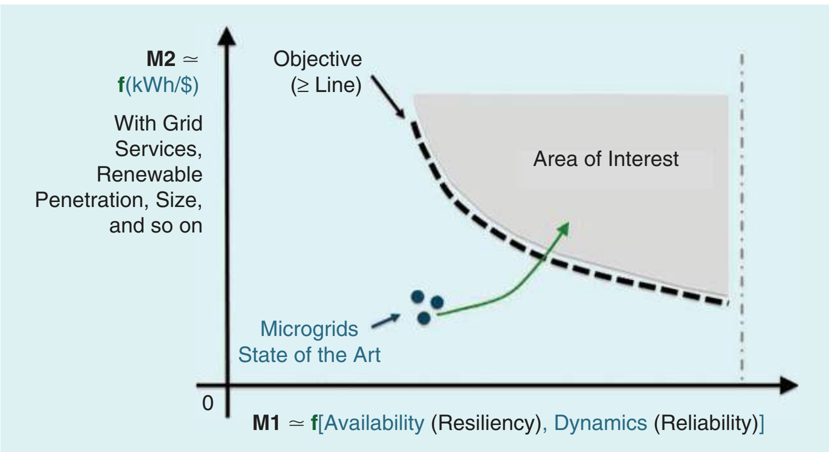

Figure 8. The metric space required for microgrid design and optimization.

The metric space captures some of the key aspects of the CCD philosophy for the microgrids introduced in the previous section. In particular, it describes the dynamics and control aspects with the M1 metric, and the steady-state calculations and cost analysis with the M2 metric.

The M1 metric is composed of two functions, f_1 and f_2, as shown in (1). The first function f_1 is a second-order polynomial of the availability A_y, and the second function f_2 is a second-order polynomial of the dynamics D_y, as presented in (2) and (3).

$$\mathrm{M1} = f_1(A_y) + f_2(D_y) \quad (1)$$

$$f_1(A_y) = \alpha_2 A_y^2 + \alpha_1 A_y + \alpha_0 \quad (2)$$

$$f_2(D_y) = \beta_2 D_y^2 + \beta_1 D_y + \beta_0. \quad (3)$$

The availability A_y measures the number of load losses under some contingencies during the set of tests, as shown in (4).

$$A_y = 1 - \frac{\beta_c \sum_{k=1}^{nc} z_c(k) + \beta_p \sum_{k=1}^{np} z_p(k) + \beta_d \sum_{k=1}^{nd} z_d(k)}{(n_c + n_p + n_d) n_{co}}, \quad (4)$$

where the load type (tiers) are classified as critical "*c*," priority "*p*," and discretionary "*d*," being the number of customers of each load type n_c, n_p, and n_d, respectively, the number of load losses z_c, z_p, z_d, respectively, the number of contingencies in the study n_{co}, and the weight of each respective load β_c, β_p and β_d, with $\beta_c + \beta_p + \beta_d = 1$. A typical weight scenario of each respective load can be defined as: $\beta_c = 0.36$, $\beta_p = 0.33$, and $\beta_d = 0.31$.

There are many practical ways to define the set of tests and predefined events or contingencies that evaluate availability and damping. As an example, a test composed of five periods in sequence, with five contingencies per period and 5 min between contingencies was chosen. The five periods are 1) (S1) microgrid connected to the grid for

30 min, 2) (S2) islanded mode due to planned disconnection for 30 min, 3) (S3) reconnecting to the grid-connected mode for 30 min, 4) (S4) islanded mode due to unplanned disconnection for 30 min, and 5) (S5) reconnecting to the grid-connected mode for 30 min. The five contingencies are 1) major synchronous generator fault, 2) major renewable energy generator fault, 3) distributed energy storage fault, 4) main line fault, and 5) communication system fault. In summary, the tests last a total of 150 min, with a total of 25 contingencies.

A load loss is counted every time that the system falls outside of the voltage/frequency area, demarcated by "Zone B" in Figure 9, as defined by the IEC 60034-1 standards, or every time that the system does not satisfy the requirements of the IEEE Standard 1547—2018, *Power Quality in Voltage and Frequency*, including 1) rapid voltage change, 2) voltage flicker, 3) total rated-current distortion, 4) transient overvoltage, 5) voltage ridethrough, and 6) frequency ridethrough.

According to some initial evaluations, current microgrids suffer approximately four losses out of the 25 contingencies proposed here (initial case = 20%). In this context, a potential target could be roughly one loss out of the 25 contingencies (target case = 4%), and a maximum/optimal case of zero losses out of the 25 contingencies (maximum case = 0%).

Additionally, the dynamic factor D_y of the M1 metric represents the decay of the oscillation, or relative damping of the microgrid, when a disturbance enters the network and the control system reacts to reject it. This is measured both in voltage D_v and frequency D_f under the same contingencies defined previously and as shown in (5)–(7), with $0 \le D_v \le 0.5, 0 \le D_f \le 0.5$,

$$D_y = D_v + D_f \quad (5)$$

$$D_v = 0.5\left(1 - \frac{1}{n_{co}}\sum_{r=1}^{n_{co}}\left(\frac{1}{n_{po}}\sum_{k=1}^{n_{po}}\frac{O_{v2}(k)}{O_{v1}(k)}\right)_r\right) \quad (6)$$

$$D_f = 0.5\left(1 - \frac{1}{n_{co}}\sum_{r=1}^{n_{co}}\left(\frac{O_{f2}}{O_{f1}}\right)_r\right), \quad (7)$$

where n_{po} is the number of test points and n_{co} is the number of contingencies. The *relative damping* is defined as the second overshoot O_2 (or undershoot) divided by the first overshoot O_1 (or undershoot), O_2/O_1, for both frequency (O_{f1}, O_{f2}) and voltage (O_{v1}, O_{v2}), considering always $0 \le (O_2/O_1) \le 1$ (see Figure 10).

Typically, with a PID controller tuned using a classical Ziegler–Nichols method, the relative damping (O_2/O_1) is 25%. In this context, an initial relative damping of about 20%, a potential target of 5% and a maximum of 0% are defined.

Based on all of these cases (initial, target, and maximum) for both availability A_y and dynamics D_y, and to have a well-balanced M1 metric according to the expressions given by (1), the parameters of the polynomials of (2) and (3) are $\alpha_2 = 468.75$, $\alpha_1 = -718.75$, $\alpha_0 = 300$ and $\beta_2 = 500$, $\beta_1 = -775$, and $\beta_0 = 325$. The contributions of the availability and

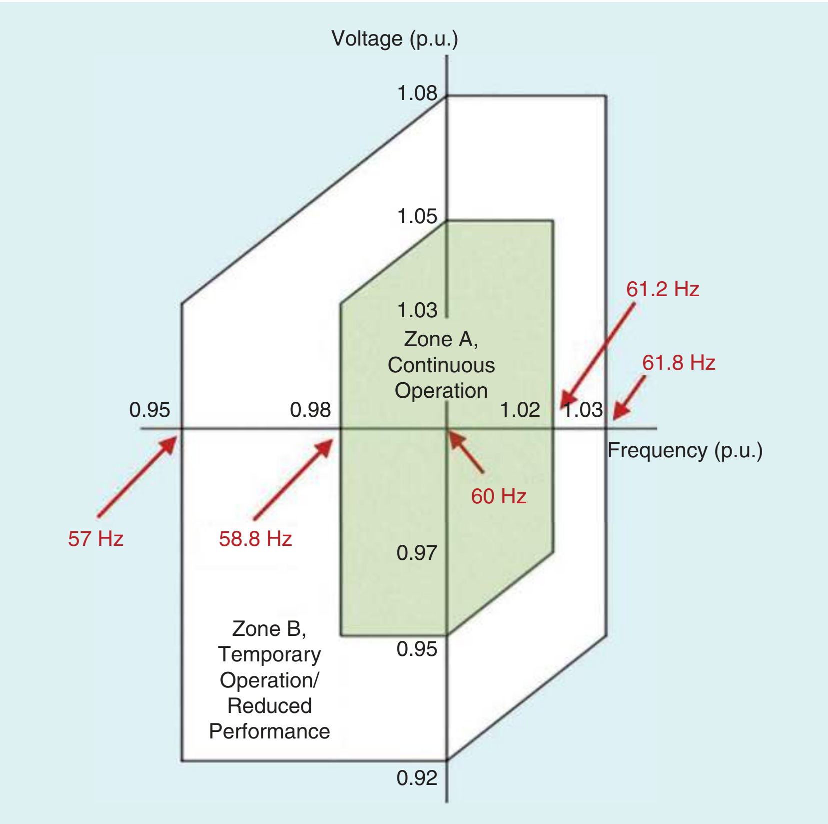

Figure 9. The voltage-frequency limits for power generators and transformers according to IEC 60034-1.

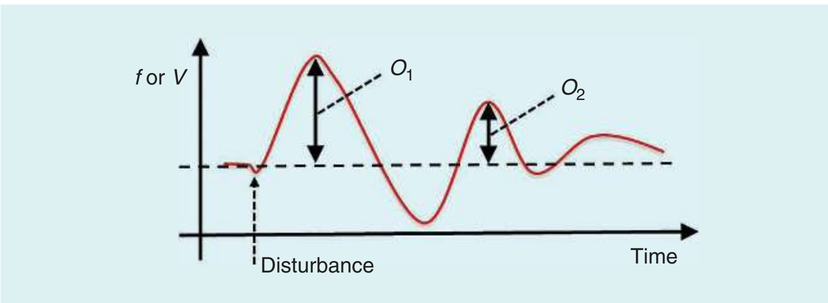

Figure 10. The frequency and voltage oscillations.

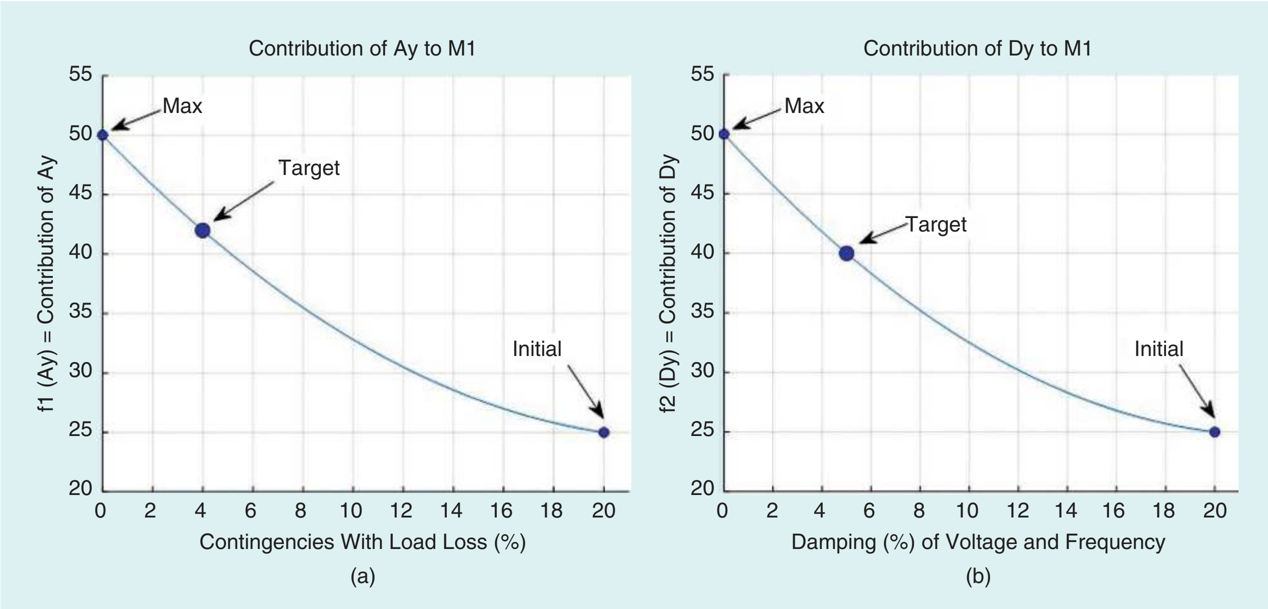

Figure 11. The contributions of the (a) availability (A_y) and (b) dynamic (D_y) factors to the M1 metric. Max: maximum.

dynamic factors (A_y and D_y) to the M1 metric are shown in Figure 11, with

$$M1_{\text{Initial}} = 50, M1_{\text{Target}} = 82, M1_{\text{Max}} = 100. \tag{8}$$

The M2 metric of the metric space gives a technoeconomical evaluation of the microgrid, similar to the inverse of an extended well-known levelized cost of energy (LCOE), as shown in

$$M2 = \frac{ED}{FCR\ CapEx + OpEx}, \tag{9}$$

where

- ED: the *annual energy delivered to the loads* (in kWh/year), including the energy delivered to critical, priority, and discretionary category loads: $ED = ED_c + ED_p + ED_d$.
- CapEx: the *capital expenditures of the microgrid* (in \$), including the DERs, renewable energy resources (not dispatchable); DGs (dispatchable); ESSs; noncontrollable loads; controllable loads, which can be shifted or curtailed; electrical network (lines, transformers, and so on), control systems; protection systems; and communication systems.
- FCR: *fixed charge rate* (in one/year), which includes the cost of money, taxes, and amortization and depends on the lifetime of the project.
- OpEx: the *operation and maintenance expenditures* (in \$/year), including
  - frequently recurring labor and materials costs, components replacement (O&M)
  - fuel costs (FC)
  - energy purchases from other grids to the microgrid; this becomes a negative number

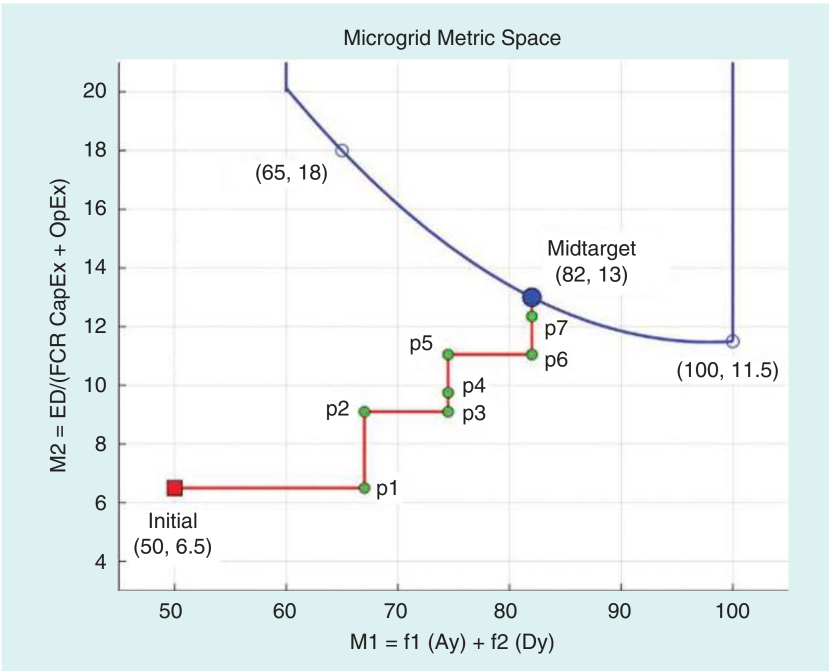

Figure 12. The trajectory guidance provided by the metric space for research task selection. ED: energy delivered; FCR: fixed charge rate; OpEx: operation and maintenance expenditures; CapEx: capital expenditures of the microgrid; Ay: availability factor; Dy: dynamics factor.

TABLE 1. **The proposed tasks needed to reach the microgrid objective in Figure 1 (see "U.S. Department of Energy, Office of Electricity: Microgrid portfolio of activities" in the "For Further Reading" section).**

Points	M1 Per Unit	M2 kWh/US$	Segment	Tasks
Initial	50	6.5	—	—
p1	67	6.5	Initial to p1	A_v from an initial 20 to 4% of load losses
p2	67	9.1	p1–p2	Capital Expenditures reduction increases the initial M2 by 40%
p3	74.5	9.1	p2–p3	D_f from an initial 20 to 5% of the relative damping
p4	74.5	9.75	p3–p4	O&M cost reduction increases the initial M2 by 10%
p5	74.5	11.05	p4–p5	Fuel Costs reduction increases the initial M2 by 20%
p6	82	11.05	p5–p6	D_v from an initial 20 to 5% of the relative damping
p7	82	12.35	p6–p7	Energy Purchases reduction increases the initial M2 by 20%
Mid Target	82	13	p7–Midtarget	Provided Ancillary Services increases the initial M2 by 10%

for energy sells from the microgrid to other grids (*EP*)
- ancillary services provided to the macrogrid or other microgrids, being (*AS*)

$$OpEx = O\&M + FC + EP - AS. \quad (10)$$

Defining the microgrid objectives with a boundary line, which represents a balance between resiliency/reliability (M1) and energy cost (M2), Figure 12 depicts an example of how the metric space provides guidance to select the appropriate trajectory with tasks to accomplish these objectives. It illustrates a given microgrid with an initial position of M1 = 50 (A_v = 25, or 20% of load losses; D_v = 12.5, or 20% of damping; D_f = 12.5, or 20% of damping), M2 = 6.5 (extended LCOE = 0.1538 US$/kWh), and proposes eight steps to achieve the Mid Target, with M1 = 82 (A_v = 42, or 4% of load losses, D_v = 20 or 5% of damping, D_f = 20 or 5% of damping), and M2 = 13 (extended LCOE = 0.07692 US$/kWh) (see Table 1).

Conclusion

As a way to improve the resilience of the power grid and increase the level of renewable energy penetration, this article discussed some CCD methodologies and the associated metrics that design microgrids with better system dynamics, observability, and controllability. This may well result in lower cost and improved resilience, reliability, and power quality. To that end, a new generation of optimum microgrids needs the research community to develop 1) CCD computer tools that combine steady-state calculations, cost analysis, dynamics, and control; 2) new advanced control architectures and algorithms beyond the droop control strategies; 3) new sensor systems that expand microgrid observability and situation awareness; and 4) new power electronic devices that improve system controllability.

Disclaimer

The opinions in this article are those of the author alone and have not been reviewed or endorsed by ARPA-E/Department of Energy.

For Future Reading

S. Parhizi, H. Lotfi, A. Khodaei, and S. Bahramirad, "State of the art in research on microgrids: A review," *IEEE Access*, vol. 3, pp. 890–925, June 2015. doi: 10.1109/ACCESS.2015.2443119.

"Office of electricity: Microgrid portfolio of activities," U.S. Department of Energy. http://energy.gov/oe/services/technology-development/smart-grid/role-microgrids-helping-advance-nation-s-energy-syst-0 (accessed July 2021).

M. Garcia-Sanz, "Control co-design: An engineering game changer," *Adv. Control Appl.*, vol. 1, no. 1, pp. 1–10, 2019. doi: 10.1002/adc2.18.

M. Garcia-Sanz, "A metric space with LCOE isolines for research guidance in wind and hydrokinetic energy systems," *Wind Energy*, vol. 23, no. 2, pp. 291–311, 2020. doi: 10.1002/we.2429.

"Advanced Research Projects Agency—Energy (ARPA-E): ATLANTIS Program on floating offshore wind energy," U.S. Department of Energy, Jan. 2019. Accessed: July 2021. [Online]. Available: https://arpa-e.energy.gov/technologies/programs/atlantis

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