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Distribution grids of the future: Planning for flexibility to operate under growing uncertainty

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Contents

Distribution grids of the future: Planning for flexibility to operate under growing uncertainty

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ABSTRACT

In this paper optimal grid design problems are revisited in view of the ongoing transformations in distribution systems. The transformations are those caused by distributed generation, changes in load use, and smart grid operation. These transformations have an expressive impact on the way planning must be carried out. Trends on grid design are advanced to deal effectively with future problems of security of supply in the context of advanced grid operation and demand responsive resources as enabled by grid modernization technologies. Formulations of key optimization problems in grid design are provided together with the required modelling of load behavior. Solution challenges for the key problems are identified and the corresponding stochastic framework for chronological simulation is advanced as favored by a plethora of newly available load-data. Required developments in decision support tools for planning the distribution grid of the future are finally discussed.

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1

Introduction

The electric power system is one of the most complex physical systems created by mankind. Historically, the electric power system has evolved since the late 19th century from a multitude of isolated small-scale direct current (DC) distribution systems to a alternating current (AC) bulk centralized system. The evolution from DC to AC allowed changing voltage levels (with the use of the transformer) and adapting such levels to different purposes: generation, transmission and distribution. Interconnection between isolated systems allowed balancing load/generation between systems to increase load factor and in this way increased generation efficiency and enhanced system stability.

Electrification grew rapidly along the years and as demand for electricity increased power plants evolved to be larger and larger to favor growing generation efficiency with scale. Driven by generation scale, the power transmission infrastructure evolved in tandem to higher and higher service voltages, so as to favor growing delivery efficiency with voltage level. This way, at the end of the 20th century, electric power systems had covered the whole territory of the developed countries, delivering electricity at affordable prices virtually to the entire population.

Being complex, the system naturally evolved over distinctive roles and corresponding liabilities. Generation needed to be planned and managed to match variable demand on different time-scales. The very-high voltage transmission grid infrastructure needed to evolve to be able to accommodate new generation injections and be resilient enough to guarantee (i) that generation outages would not compromise the power delivery capability of the grid infrastructure and (ii) that grid outages would not compromise the power generation stability. The strong interdependence between generation planning and very-high voltage transmission planning was addressed explicitly by composite engineering design approaches since very early and was formulated mathematically as such in the late 80's (EPRI, 1987b; EPRI, 1987a).

Lower voltage grid infrastructures were expanded to deliver power to millions of small customers geographically spread in the territory. Infrastructures expansion was of course dependent on the evolution of the transmission grid as the availability of power to be delivered depended on the availability of a neighbor transmission substation. However, the design of the distribution grid was addressed rather independently from the design of the transmission generation-transmission system as the former was subject to hard constraints when compared to the later: (i) distribution network equipment had to be mass-produced and was naturally standardized into portfolios of few possible choices, and (ii) distribution grid topology needed to comply with the existing topography of the urbanized areas where customers were sited and with the existence of a few if not just one single neighbor transmission substation from which power was available. The weak interdependence between distribution planning and transmission planning and the growing standardization of grid equipment led to distribution design approaches that relied upon predefined grid topology paradigms adapted to areas' load density, required security of supply, and available financial resources (Persoz *et al.*, 1984).

Therefore, the main task of the distribution planner was indeed that of deciding among a few mutually exclusive grid topology options and then adapt the grid design to the available equipment and existing topography of the areas that needed to be served. Yet, there was room for optimization within each chosen grid topology and, since the mid 70's, many authors formulated complex design challenges as optimization problems. The problem was first addressed as a fixed-cost transportation-type of problem, and later as more general mixed-integer programming problems that could include grid topology and security constraints, alongside with grid losses costs (Adams and Laughton, 1974; Wall *et al.*, 1979; Gonen and Foote, 1981; Sun *et al.*, 1982; El-Kady, 1984; Gonen and Ramirez-Rosado, 1987). More complex formulations of the problem were proposed later in the 90's that relied upon advanced heuristics such as evolutionary algorithms and included uncertainty in load growth and load location (Kagan and Adams, 1994; Miranda *et al.*, 1994; Yeh *et al.*, 1995; Carvalho *et al.*, 1998b; Carvalho *et al.*, 1998a; Carvalho *et al.*, 1999a).

In such formulations, energy losses were the main driver for the search for better topologies and adequate equipment. Security of supply was not explicitly evaluated but rather accepted as an outcome of the underlying topology paradigm:

(i) Under purely radial topology paradigms (used for rural areas), security of supply was accepted to be weak as it depended critically on lines and transformers failure odds and corresponding outages.

(ii) Under standby redundant topology paradigms (used for urban areas), security of supply was trusted to be high as it did not depend much on component failures if backup feeding circuits could be triggered quickly and had enough capacity to hold up any island created by an outage.

There was, however, a sound reasoning behind the search for optimal losses designs only, as well as behind the assumption of backup capacity being always sufficient. We will address that in the following but first need to understand what we meant by purely radial and standby redundant topologies. Let us illustrate such topologies and their graph-related representations in Figure 1.1 and Figure 1.2.

The figures show small-scale grids. The scale is intentionally very small to illustrate some fundamental topology properties of distribution grids. In reality, electrical power distribution grids are composed of thousands of nodes, most of which correspond to load points, and

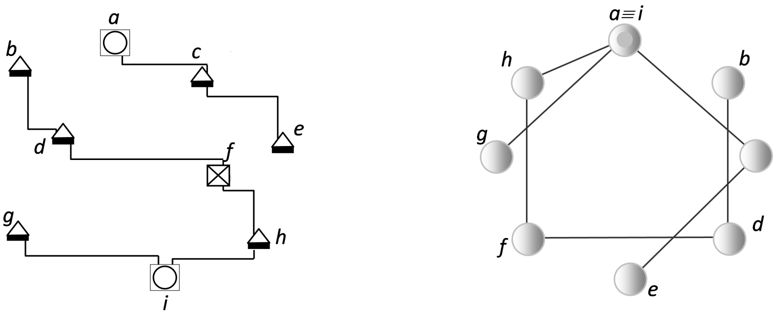


Figure 1.1: Schematic representation of a purely radial electrical distribution grid (left) and its correspondent graph topology (right). The figure shows a small-scale grid with two substations (power delivery points at busbars a and i), six load points (busbars b, c, d, e, g, and h), and a link-box or switching station (busbar f). In the graph representation, the two (injection points are represented by a single node (the tree root $a \equiv i$).

thousands of branches, most of which correspond to electrical cables or lines. The other nodes correspond to power delivery points or connecting points, and the other branches correspond to transformers, link boxes or switching busbars. Regardless of grid scale, from a topology perspective the physical grid infrastructure can be represented by a graph G.

In normal operation, each node of the graph is connected to a single power delivery point through a unique path. The operating grid configuration is therefore radial and connected. Thus, from a topology perspective the operating configuration of the grid can be represented by a spanning-tree T of the graph G.

In purely radial topologies, as represented in Figure 1.1, the graph of the physical grid infrastructure G coincides with the spanning-tree T used as the operating configuration. The graph being acyclic, the infrastructure does not allow for alternative operating configurations, and any branch permanent outage leads to a long standing operating outage that requires branch repair to be resolved.

In standby redundant topologies, as represented in Figure 1.2, the spanning-tree T used as the operating configuration is just one possible

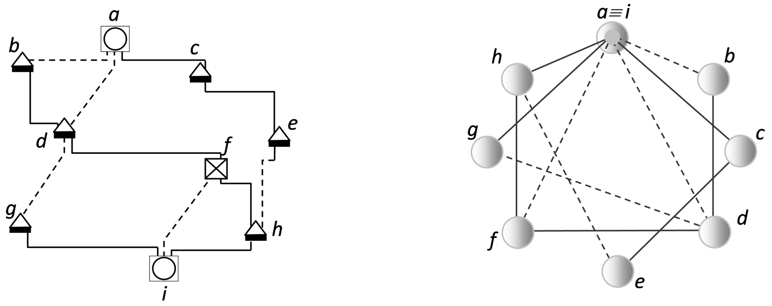


Figure 1.2: Schematic representation of a standby redundant electrical grid (left) and its correspondent graph topology and spanning tree solution. The figure shows a small-scale grid with two substations (power delivery points at busbars a and i), six load points (busbars b, c, d, e, g, and h), and a link-box or switching station (busbar f). The dashed lines identify the grid branches not used by power-flow purposes. In the graph representation, the two (injection points are represented by a single node (the tree root $a \equiv i$), the spanning-tree arcs are represented by solid lines, and the co-tree arcs are represented by dashed lines.

spanning-tree T of the graph G that represents the physical grid infrastructure – usually called the *normal* operating configuration. Being just one possible configuration, the infrastructure allows for its reconfiguration under any branch permanent outage. For a given branch outage, reconfiguration is achieved by switching-on any co-tree arc of G in the fundamental cycle that includes the arc of the outage. This way, standby redundant topologies avoid long standing operating outages as they enable switching-on the graph arcs not used in normal operating configurations by closing the Normally Open (NO) switches. Figure 1.3 illustrates an outage and the subsequent reconfiguration.

For reconfiguration to be feasible, the backup circuit must have headroom capacity to hold up new load, as switching transfers load from the branch under outage to the switched-on branch. Referring again to Figure 1.3 and to the outage of branch $d-f$, note that after switching-on branch $d-g$, load in feeder $i-g$ increases by $L(d) + L(b)$, where L denotes the load function of each node. Such quantity, $L(d) + L(b)$, was

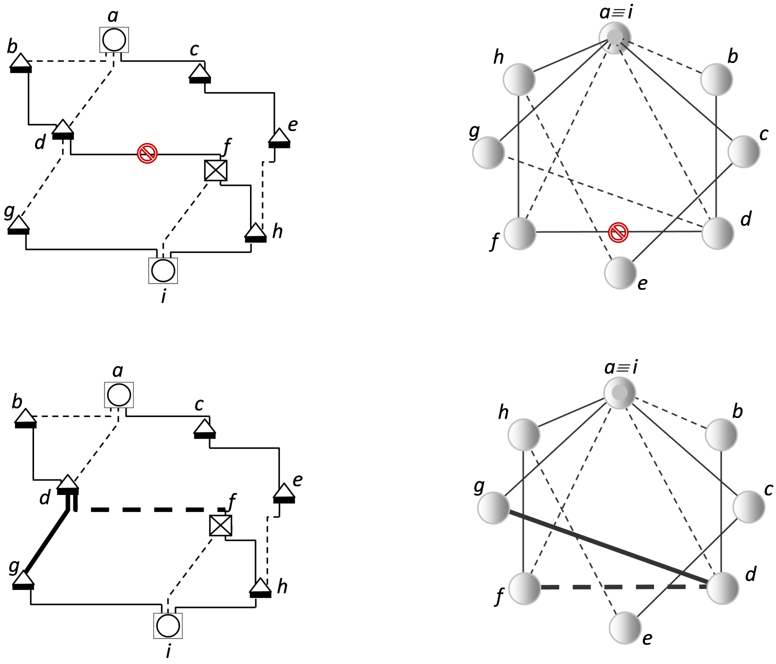


Figure 1.3: Representation of an outage in branch $d - f$ (red circle) in both the schematic representation of the electrical grid and its correspondent graph (top figures) and the subsequent reconfiguration achieved by switching-on branch $d - g$ (bottom figures). Note that $d - g$ is a co-tree arc of the normal operating configuration topology (top figures) that defines a fundamental cycle $d - f - h - i - g$, which includes the outage arc $d - f$.

served by $d - f$ before the outage, and needs to be served by feeder $i - g$ after reconfiguration. If not possible, other switching operations need to be considered. Note that there are several alternative possibilities to restore power to nodes b and d after the outage of $d - f$, i.e., other co-tree arc of G in the fundamental cycle that includes $d - f$. Such arcs are $a - b$ and $a - d$ (besides $d - g$).

So, when designing standby redundant distribution grids, sufficient capacity should be guaranteed not just for normal-configuration grid loading but also under contingency configurations' loading. Several contingency configurations may exist for the same outage, each with its backup capacity requirement. So, grid design is also about planning contingency configurations and their capacity requirements in order to guarantee at least one feasible reconfiguration for each possible outage. This is much more complex than planning for optimal losses only (Carvalho and Ferreira, 2005; Carvalho *et al.*, 2007b; Carvalho *et al.*, 2007a).

Yet, backup capacity planning was implicitly ignored in the past. The reason is simply pragmatic. The outcome of optimal losses design led to grids with such a high capacity (for normal operation configuration) that backup capacity was always guaranteed. We will see why in the following.

1.1 Paradigm change: from maximum efficiency to minimum capacity

For a given normal operation configuration, the cross-section area of the conductor equipment determines its resistance, and therefore determines the grid Joule losses in its lifetime given a load profile evolution in such lifetime. The optimal tradeoff between the cost of equipment investment and the Joule losses cost is determined by the well-known Kelvin's law (Persoz *et al.*, 1984; Semenza, 1924), which states that the cost of the energy lost in each equipment should equal the interest on the capital cost and the depreciation of the equipment.

As conductor equipment variable costs with cross-section area are typically small, Kelvin's tradeoff led to current densities that were also very small when compared to the maximum allowed for each conductor cross-section area. Optimal current densities being small guaranteed enough headroom in normal operation configuration for backup capacity after any reconfiguration to be also guaranteed (Persoz *et al.*, 1984; Curcic *et al.*, 2001). This is the reason why in the past the outcome of optimal losses design could guarantee enough backup capacity. But will that stand in the forthcoming planning horizon? We believe not.

So what is that that is changing? Is there something disruptive in the horizon of grids lifetime? No, there is not. Is there something dramatically different regarding the evolution of interest on the capital cost and on the depreciation rate of grid assets in the near future? Also not. Although there are important changes foreseen for the future load. Such changes are driven by *The Future of Electricity New Technologies Transforming the Grid Edge* (2017):

- A sharp decrease in costs of distributed energy resources (DERs) like distributed generation, and also a possible decrease in distributed storage costs;
- A growing electrification of large sectors of the economy such as transportation and heating.

In this scenario, from the grid side perspective, perceived load (net load) is expected to change substantially.

- DERs penetration will decrease load factor substantially, reducing the underlying energy of the load profile (Denholm *et al.*, 2015) (e.g., when high solar generation decreased net load during daytime, changed profiles were designated duck curves).
- New loads such as electrical vehicles, heat pumps, etc., will increase profile's peak at hours of low generation (Tovilović and Rajaković, 2015) (e.g., immediately after the morning or evening commute when solar generation is ramping up or down).

Under the foreseen changes in future load profiles, a new paradigm emerges. The paradigm of *lower energy delivery under higher peak requirements*. Under such paradigm, lower losses will be expected whilst higher capacity will be needed. Under lower expected losses, Kelvin's optimal tradeoff will lead to higher current densities. The optimal conductors' cross-section area will therefore be reduced and might not guarantee backup capacity anymore.

Figure 1.4 illustrates Kelvin's optimal tradeoff between cost in grid investments and Joule losses costs. The bottom figure is obtained for a profile with the same shape and half the peak demand of the top figure. The optimal cross-section area S^*, for half the energy would be exactly half

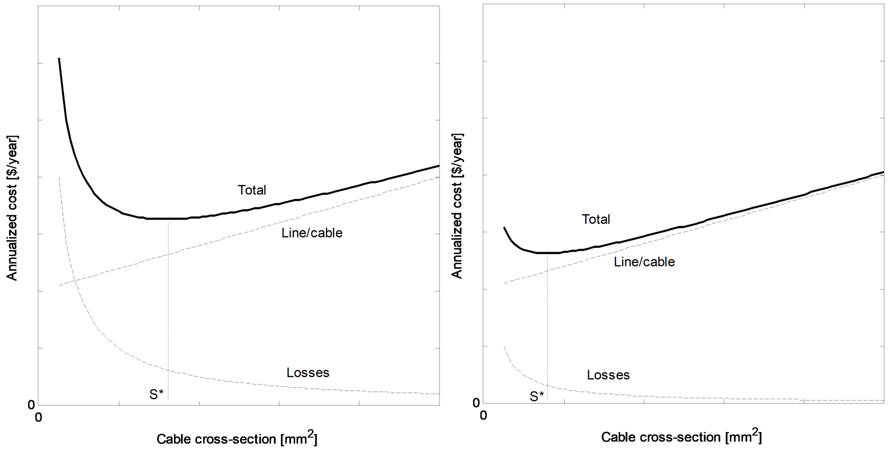


Figure 1.4: Illustration of the optimal tradeoff between the cost of the energy lost and the interest on the capital cost as a function of conductor cross-section area. Two cases are illustrated for a given load profile (left) and half such given profile (right) to show dependence of the optimal cross-section area on profiles underlying energy.

of the original cross-section area. Under profile shape changes, including the change into duck shapes, the optimal cross-section S^* will not be exactly half the original but will be substantially lower than the original.

This is especially dramatic if, at the same time, peak demand increases as a consequence of new loads such as electrical vehicles and heat pumps.

A similar effect on optimal cross-section areas would be expected if profiles would not change but energy costs would drop instead (note that the tradeoff is between costs). But are we expecting energy costs to drop? We believe so, as the penetration of DERs has already reduced electricity wholesale spot prices by displacing coal and gas fired generation and is expected to continue doing so (Browne *et al.*, 2015; Clò *et al.*, 2015; Vos, 2015; Dillig *et al.*, 2016; Paraschiv *et al.*, 2014; Würzburg *et al.*, 2013). If wholesale prices decrease, variable costs of energy ($/kWh) will also decrease, and losses costs are also expected to decrease.

Together, the effects of *low energy delivery* and *low energy costs* will lead to optimal conductors' cross-section areas that will no longer guarantee backup capacity. And in time, the needed security of supply investments will need to be carefully justified before regulators and public policy makers.

Justification obligations will force design objectives to change in order to explicitly address capacity adequacy. Therefore, in the foreseen future, grid design objectives need to undertake a significant change from maximum efficiency (losses are a measure of inefficiency) into minimum capacity, where minimum means necessary and sufficient to guarantee security of supply.

This change in objectives will impact significantly into engineers' mindset and make traditional planning tools obsolete. The reason is that capacity minimization demands for risk assessment in order to quantify grid's adequacy under critical situations and efficiency maximization only requires average representative scenarios to be found. And critical situations are hard to characterize as they have to be found with probabilistic consumer/generation modeling in order to be representative, and need to take into account the available means to mitigate their consequences, including the means enabled by future demand side response (DSR).

In the following, we will address the future design trends and describe the main challenges in more detail.

1.2 Design trends

In a time where DERs call to provide a range of new grid services, including energy but also capacity and voltage control services, utilities need to deploy a grid infrastructure that enables the new business models around such services while keeping the operation safe and secure. And utilities need to do this under the new paradigm of *low energy delivery* and *low energy costs*, which does not allow investing enough in capacity based on energy efficiency objectives alone. Therefore, utilities need new objectives to ensure a timely deployment of their infrastructure.

Security of supply

New objectives will depend on the participation of the utility in the business models of the future. However, whatever the utilities' participation in the future business will be, utilities will have to invest in sufficient capacity to guarantee a safe and secure operation of the electrical grid. So, *minimal capacity*, in the sense of the capacity necessary and sufficient to guarantee a safe and secure operation of the system, will become the primary objective of future grid design.

Investment in capacity will therefore require careful justification about its necessity. Capacity is sufficient when it guarantees enough headroom under any probable outage, but to be necessary it requires such headroom to be minimal in the sense that it should match as much as possible the maximal power-flow under such outages. Let us exemplify the difference between necessity and sufficiency with the case of Figure 1.3.

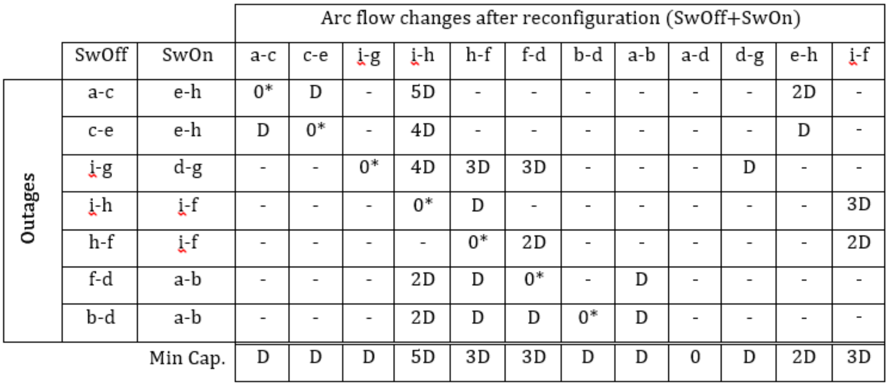
In the grid of Figure 1.3, there are two delivery buses (primary substations), six load buses, one connection bus, and twelve branches (cables or lines) from which seven are energized. Let us define a graph $G = (A, N)$ as a pair of sets: one set of nodes N for the grid buses, and one set of arcs A for the grid branches defined between the nodes of N. Let us assume that all loads are equal, i.e., $L(i) = D, i \in \{b, c, d, e, g, h\}$. Assuming that probable outages are outages of arcs only (i.e., that substation outages are very rare), and that all arcs have the same existing capacity, $C(ij) = 5D, \forall ij \in A$, then the existing capacity is sufficient to guarantee standby redundancy.

Note that the outage of arc $a-c$ needs to be resolved by switching-on arc $e - h$, and that under such configuration arc $i - h$ will carry a flow of $5D$. Therefore, the capacity of $5D$ is necessary for arc $i - h$, but it is not necessary for the other eleven arcs.

Let us simulate outages in each and every energized arc, and calculate the necessary capacity requirements under each outage for all possible switching-on reconfiguration operations. We do this by selecting the switching-on operation that minimizes the power-flow in the back up circuit. Results of the minimization are shown in Table 1.1 for each arc possible outage in the grid of Figure 1.3.

If one looks for the maximum flows in each arc under all analysed post-contingency reconfigurations (examining the columns of Table 1.1), minimum necessary capacity can be determined for each arc (values shown in the last row of Table 1.1). Note that such minimum is zero for the co-tree arc $a - d$, meaning that the arc is not necessary for backup.

Table 1.1: Power-flows under optimal reconfiguration after an outage in the grid of Figure 1.3. Optimal reconfiguration is understood as minimal capacity backup requirements.



			Arc flow changes after reconfiguration (SwOff+SwOn)											
	SwOff	SwOn	a-c	c-e	i-g	i-h	h-f	f-d	b-d	a-b	a-d	d-g	e-h	i-f
Outages	a-c	e-h	0*	D	-	5D	-	-	-	-	-	-	2D	-
	c-e	e-h	D	0*	-	4D	-	-	-	-	-	-	D	-
	i-g	d-g	-	-	0*	4D	3D	3D	-	-	-	D	-	-
	i-h	i-f	-	-	-	0*	D	-	-	-	-	-	-	3D
	h-f	i-f	-	-	-	-	0*	2D	-	-	-	-	-	2D
	f-d	a-b	-	-	-	2D	D	0*	-	D	-	-	-	-
	b-d	a-b	-	-	-	2D	D	D	0*	D	-	-	-	-
		Min Cap.	D	D	D	5D	3D	3D	D	D	0	D	2D	3D

The same could be said about co-tree arc $i - f$ if one would be willing to reinforce the capacities of arcs $a - b$ and $b - d$ to $3D$ and $2D$, respectively, and select different switching-on operations. Consider Table 1.2 where we selected different switching-on operations for outages $i - h$ and $h - f$, and note that by doing so the minimal capacity of arcs $a - b$ and $b - d$ increased while minimum capacity of $a - d$ became zero.

Consider the previous two alternatives for minimizing capacity: (i) building a co-tree arc $(i - f)$ with a capacity of $3D$, or (ii) reinforcing a co-tree arc $(a - b)$, from D to $3D$, and also reinforcing a tree arc $b - d$ from D to $2D$. The overall needs of capacity sum up to the same total value of $21D$. So, depending on the sizes of the branches and their corresponding costs, the optimal solution might be one investment alternative or the other. Or neither…

We have assumed that the normal-operating configuration was static, i.e., that the spanning tree T of the graph G was optimal as we did not consider changing it. But was it optimal? To answer that we need to know what the objective is. If it is capacity alone, them T is not optimal as we may find a different T for which the capacity requirements are lower. Take Figure 1.5 where the original configuration and a new configuration are shown.

Table 1.2: Power-flows under optimal reconfiguration after an outage in the grid of Figure 1.3. Optimal reconfiguration is understood as minimal capacity backup requirements.

			Arc flow changes after reconfiguration (SwOff+SwOn)											
	SwOff	SwOn	a-c	c-e	i-g	i-h	h-f	f-d	b-d	a-b	a-d	d-g	e-h	i-f
Outages	a-c	e-h	0*	D	-	5D	-	-	-	-	-	-	2D	-
	c-e	e-h	D	0*	-	4D	-	-	-	-	-	-	D	-
	i-g	d-g	-	-	0*	4D	3D	3D	-	-	-	D	-	-
	i-h	a-b	-	-	-	0*	D	D	2D	3D	-	-	-	-
	h-f	a-b	-	-	-	-	0*	0	D	2D	-	-	-	-
	f-d	a-b	-	-	-	2D	D	0*	-	D	-	-	-	-
	b-d	a-b	-	-	-	2D	D	D	0*	D	-	-	-	-
	Min Cap.		D	D	D	5D	3D	3D	2D	3D	0	D	2D	0

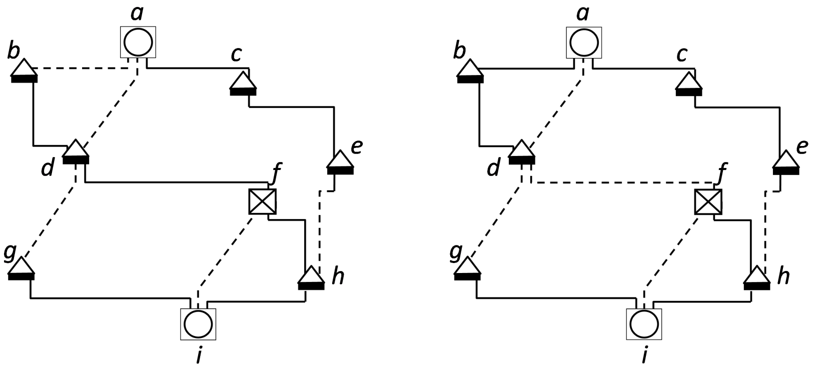


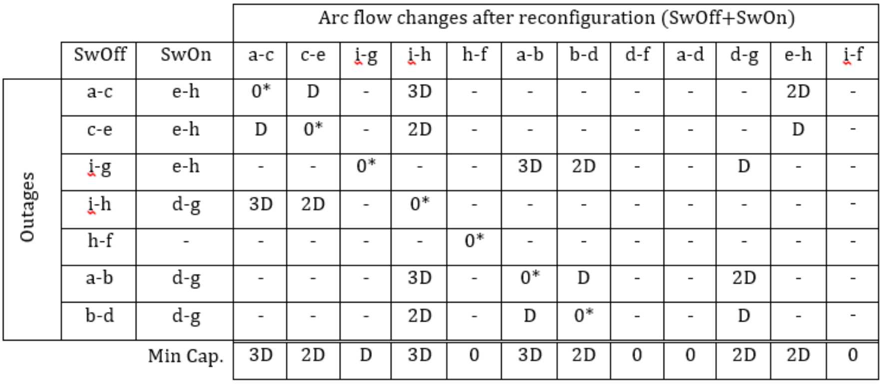
Figure 1.5: Schematic representation of the original standby redundant electrical grid and its correspondent normal operating configuration (left-hand-side figure) and a new normal operating configuration of the same grid (right-hand-side figure).

For the new configuration used for normal operation, the capacity requirements are now lower. It is easy to see that under any outage, arc capacity needs are never higher than $3D$ and that the total capacity now sums up to $18D$, instead of $21D$. Table 1.3 shows the results on capacity requirements for the new operating configuration.

With this small example, it becomes clear that capacity requirements are hard to assess and consequently hard to minimize. Requirements depend on both the normal-operating configuration and on the chosen normally-open switches used for reconfiguration. From the topology perspective, capacity is a function of the spanning tree T and of the co-tree arcs of the graph G used to reconfigure the spanning tree.

Capacity assessment is complex and requires complete exploration of post-contingency reconfiguration possibilities to optimize backup switching selection (Castro *et al.*, 1980; Aoki *et al.*, 1987; Nahman and Srtbac, 1994; Nara *et al.*, 1992; Toune *et al.*, 2002; Baran and Wu, 1989; Morelato and Monticelli, 1989; Wu *et al.*, 1991; Popovic and Ciric, 1999; Liu *et al.*, 1988; Carvalho *et al.*, 2007b). Being the principal optimization objective of future grid design, capacity assessment and minimization will need to be addressed explicitly by decision support tools of the future.

Table 1.3: Maximum flows under optimal reconfiguration after an outage in the new configuration of the grid of Figure 1.5. Optimal reconfiguration is understood as minimal capacity backup requirements.



			Arc flow changes after reconfiguration (SwOff+SwOn)											
	SwOff	SwOn	a-c	c-e	i-g	i-h	h-f	a-b	b-d	d-f	a-d	d-g	e-h	i-f
Outages	a-c	e-h	0*	D	-	3D	-	-	-	-	-	-	2D	-
	c-e	e-h	D	0*	-	2D	-	-	-	-	-	-	D	-
	i-g	e-h	-	-	0*	-	-	3D	2D	-	-	D	-	-
	i-h	d-g	3D	2D	-	0*	-	-	-	-	-	-	-	-
	h-f	-	-	-	-	-	0*	-	-	-	-	-	-	-
	a-b	d-g	-	-	-	3D	-	0*	D	-	-	2D	-	-
	b-d	d-g	-	-	-	2D	-	D	0*	-	-	D	-	-
		Min Cap.	3D	2D	D	3D	0	3D	2D	0	0	2D	2D	0

Capacity and load modeling

Capacity requirements depend on load requirements and load requirements may be hard to estimate. Outages are imminently unpredictable. So, they may occur in critical loading situation. Capacity, seen as a guarantee of supply, needs to be assessed under such critical loading situations to identify possible grid congestions. But what is a critical loading situation? And how congestions translate into capacity violations?

These questions are hard to answer. In distribution grids, loads are strongly asynchronous and peaks are not time-coincident. As outage events occur in time, the times of critical loading have to be well characterized. In order to accurately characterize critical loading situations, one must rely upon probabilistic load modelling (Mori and Jiang, 2009; Cao and Yan, 2017; Yu *et al.*, 2009; Allan *et al.*, 1981; Allan *et al.*, 1976; Hu and Wang, 2006; Su, 2005; Morales and Perez-Ruiz, 2007; Willis and Northcote-green, 1985; Hajian *et al.*, 2013; Zhang and Lee, 2004; Schellenberg *et al.*, 2005). However, typical probabilistic analysis results such as statistical moments for line currents and nodal voltages are not sufficient to assess capacity adequacy. What can one say about capacity adequacy of arc $i - g$ with information on the moments of loads b, d and g? Let us assume that loads b, d and g are normally distributed random variables with the same expected value μ (first order moment) and the same variance σ^2 (second order moment). Under a contingency of arc $a - b$, by switching-on co-tree $d - g$, the power-flow in $i - g$ is the sum of the loads of b, d and g. What do we know about such sum? Can we say that the expected value of the flow is 3μ and the variance is $3\sigma^2$? If so, then the maximum flow with 97.25% guarantee would be below $3\mu + 2\sqrt{3}\sigma$. But we cannot say that because loads b, d and g are not independent. Loads and some kind of generation such as solar PV are usually strongly correlated with each other.

The dynamic nature of consumers and generation is difficult to model because it has to mimic different behaviors with heavy time dependencies. To ensure a good characterization of load and generation and take into account the existing correlations and time dependencies simultaneously, many studies resort to simulations based on realistic consumption/generation profiles. These realistic profiles can be gathered from advanced metering infrastructures (AMI) or be synthetically created (Machado *et al.*, 2017; Zhao and Guan, 2016; Ferreira *et al.*, 2013; Wang *et al.*, 2012; Abowd and Lane, 2004; Chen *et al.*, 2010; Sobu and Wu, 2012; Poland and Stadler, 2014; Gafurov *et al.*, 2015; Bartels *et al.*, 1992; Aigner *et al.*, 1984; Richardson *et al.*, 2010; Widén and Wäckelgård, 2010; Capasso *et al.*, 1994; Yao and Steemers, 2005; Armstrong *et al.*, 2009; Train, 1992; Widén *et al.*, 2009).

The planning tools of the future need to emulate load dynamics and allow chronologic simulation to identify congestions and capacity violations. That requires chronologic power-flow analysis, which must rely upon dynamic load modelling and simulation.

Congestions and short-term flexibility

We now may know how to identify critical loading situations but still cannot tell how severe the situation is. Severity can be assessed by answering the later question, i.e., how congestions translate into capacity violations.

Not all hypothetical congestions have to be seen as capacity violations. A line ampacity violation of 10% that occurs once a week and stands for 15 minutes is not the same that a violation of 100% once every 10 weeks, despite both having the same expectation. Also, a line ampacity violation of 10% that occurs once a week and stands for 15 minutes is not the same that a violation of 10% that occurs just in a particular week of the year but stands for 13 hours in a row. Line ratings are dynamic, so, context is critical to define a capacity violation based on probabilistic assessment of congestions: it is not sufficient to determine the probability of congestion; it is necessary to know the maximum congestion value and understand whether such congestion is long-standing but episodic or short-term but periodic. Chronologic simulation is essential to understand context.

If critical operation conditions are found to be episodic, then they might be able to be forecast. If so, capacity adequacy needs to be assessed under flexible demand paradigms. Engaged customers under DSR contracts can reduce consumption or increase generation if asked to do so in advance. Depending on the contracts, customers might respond to direct calls from the grid operator to reduce or increase power or respond to price signals published by local markets ahead of time (e.g., dynamic tariffs). Such price signals can also be used to resolve short-term periodic congestion by incentivizing customers to reduce consumption at periods of high congestion risks.

It is likely that, in the future, congestion management approaches will rely upon DSR as enabled by information and communications technologies (ICT). Therefore, when designing future grids one needs to consider DSR as a possible control mechanism to mitigate congestion risks (Hazra *et al.*, 2012; Kumar and Sekhar, 2012; Ibars *et al.*, 2010; Moradi *et al.*, 2008; Shayesteh *et al.*, 2008; Ilic *et al.*, 2013; Carvalho *et al.*, 2014). But how could this flexibility of demand be included into a design approach for capacity minimization?

As contributors to the supply guarantee, customers are capacity enablers. The variable part of their load can be seen as headroom for contingent loading. Customers' capacity headroom can be enabled for a price (as contracted) much like infrastructure headroom is enabled by assets reinforcement (as invested). However, from the design perspective, asset investments contribute to capacity in a very different way from that of customer DSR contracts. The reason is that asset investments have a lifetime of 20 to 30 years — they represent long standing reliable capacity enablers —, and DSR contracts have short validity periods, as customers may necessarily be able to exercise their rights to terminate such agreements.

As short term capacity enablers, DSR contracts must be seen as temporary capacity providers and be used to postpone long standing grid reinforcement decisions (Dias and Carvalho, 2018). They should not be seen as a substitute for traditional grid reinforcement but just as a way to mitigate congestion risks and defer investment in grid assets. Under considerable uncertainty about grid load and generation evolution, such flexibility in investment timing might have a high optionality value (Correia *et al.*, 2008; Muñoz *et al.*, 2011; Samper and Vargas, 2013). Therefore, the planning tools of the future need to be able to evaluate not just capacity needs but also optimal timing for capacity investments under the flexibility enabled by DSR to defer some of such investments.

1.3 Organization of the paper

In the rest of the paper, we will elaborate on the identified features of design support technologies necessary for planning the distribution grids of the future. We intentionally ignore futuristic views of the future distribution operation such as those that rely upon large behind the meter storage capabilities, generalized microgrid operation or generalized meshed operation paradigms. The reason is that technology is not mature enough for such operation paradigms to be competitive and, even if they would be competitive, their impacts would be so disruptive that foreseeing an evolution from the actual practice would be very risky. Therefore, we dedicate the rest of the paper to elaborate on the evolution of grid design features necessary to respond to the emerging and already very challenging problems the industry faces today. Such features have been identified in this chapter to be those of:

- Capacity adequacy assessment and optimization under given load scenarios.
- Load modeling and chronologic simulation to identify critical congestion scenarios.
- Congestion mitigation and reinforcement deferral with flexibility enabled by DSR.

We will dedicate one chapter to each of the identified features.

In Chapter 2, we formulate the distribution planning problem as an optimization problem that explicitly includes security of supply costs, besides energy losses and capital costs. We evolve from the previous definition of capacity as a qualitative guarantee of security of supply to a quantitative definition by introducing load shedding. Emphasis is put on the evaluation of security of supply and on how such evaluation depends on post-contingency reconfiguration possibilities and backup switching selection. Necessary evolutions of computational applications that support decision-making are envisaged and main challenges are identified.

In Chapter 3, we describe the necessary evolution of load modeling and chronologic simulation to embrace an explicit risk-controlled probabilistic decision-making approach. We start by discussing the requirements of specific data analytics tools necessary to explore the large volumes of metering data aiming at segmenting customer profiles into typical consumption/generation profiles, and on the developments necessary to characterize such profiles and extract representative behaviors to be modelled as stochastic processes. Then, we focus on the evolution of the computational applications that support decision-making necessary to input representative consumption/generation behaviors as parameters of stochastic processes and use such input in power-flow simulation to identify critical consumption/generation congestion scenarios.

In Chapter 4, we reformulate the distribution planning problem as a problem of finding the optimal timing for previously identified capacity reinforcements. Emphasis is put on the modelling of flexibility as enabled by ICT and the smart grid, namely the future observability and controllability made available to empower demand response capacity. The focus of optimization is put on the valuation of such flexibility as a mean to defer traditional grid capacity investments by contributing to mitigate potential grid congestions. The fundamentals for finding tradeoffs between investment deferral benefits and demand response cost are provided, and the necessary evolutions of the decision support computer applications are envisaged. Because the scope and validity of DSR contracts and corresponding costs are very uncertain, tradeoff analysis should be multi-objective to avoid summing reinforcement capital costs with contract operational costs. Therefore, future computer applications must rely upon the capability of solving multi-objective optimal-timing problems in horizons where congestions scenarios are credible. We discuss the challenges related to the capability of solving such multi-objective problems and the benefits of finding Pareto-optimal solutions on investment deferral benefits and DSR participation costs.

In the closing Chapter 5, the design support technologies presented are discussed as necessary building blocks of the future planning approaches. A perspective on future evolution of grids is presented identifying the opportunities enabled by ICT and pointing out the underlying risks of business-as-usual planning approaches.

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