Modeling and Control of DC grids*

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ABSTRACT

This paper discusses the background and main contributions of my PhD thesis entitled "modeling and control of DC grids". The expected advent of multi-terminal HVDC systems and meshed DC grids poses major challenges to the control and operation of our power system. The article describes these challenges and explains how the work has contributed in the field of the development of steady-state and dynamic models to study the future power grid. Furthermore, the article describes new fundamental insights in system interactions that have been analyzed in the thesis.

SAMENVATTING

Dit artikel bespreekt de context en de belangrijkste bijdragen van mijn doctoraatsthesis 'modellering en controle van DC netten'. De verwachte introductie van multi-terminal HVDC systemen en vermaasde gelijkstroomnetten brengt belangrijke uitdagingen met zich mee op het vlak van de controle van het elektriciteitsnet. Dit artikel beschrijft deze uitdagingen en licht de bijdragen van het werk toe aan de ontwikkeling van de benodigde modellen in regimetoestand en voor dynamisch bedrijf. Het artikel beschrijft eveneens nieuwe fundamentele inzichten in systeeminteracties die in het kader van dit werk werden geanalyseerd.

RESUME

Cet article présente le contexte et les contributions principales de ma thèse sur la modélisation et le contrôle des réseaux à courant continu. L'introduction attendue des réseaux multi-terminaux à courant continu pose des défis liés à la gestion de nos réseaux de transport d'électricité. Cet article décrit ces défis et explique comment ce travail a contribué au développement des modèles d'état stationnaire et des modèles dynamiques afin d'étudier le réseau électrique du futur. Cet article introduit également de nouvelles idées sur les interactions des systèmes qui ont été analysées dans la thèse.

Background

The European power system is facing tremendous challenges as a result of the ambitious targets the European Union (EU) has set for its future energy supply: the aim towards a low-carbon economy by 2050, implying carbon-neutrality for the power sector, will impact the way the European transmission system will be redesigned and reinforced in the coming decades. The accompanying massive integration of renewable energy sources in the European transmission system poses major technical challenges in order to guarantee a safe and efficient operation of transmission and distribution grids.

This massive integration of renewable energy sources at the generation side already poses challenges with respect to the operation of today's power system and will set the directions for the transmission grid upgrades. The existing electricity infrastructure was largely built in the 1960s and 1970s by vertically integrated utilities in charge of the different aspects regarding the power supply, i.e. generation, transmission and distribution of electricity. Their regulated monopoly position implied that the entire power system could be perfectly planned using well-established tools: transmission lines were built in accordance with the need for new generation investments which, in turn, were based on electricity consumption forecasts for the years to come. The transmission system was operated based on predefined principles and knowledge of the scheduled merit-order of the power plants covering demand. In light of this, the mere purpose of interconnections between different countries and control zones was to assist neighboring countries in case of need or to facilitate cross-border trade based on long-term contracts.

As a result of the liberalization and unbundling process, transmission system operators (TSO) nowadays have to facilitate the European internal energy market. The interconnections, historically mainly built for reliability purposes, are now serving the liberalized electricity market by allowing for cross-border trade. The European power system is operated ever closer to its limits and investments are needed. Meanwhile, TSOs are faced with an increased public opposition to the construction of new overhead power lines. In light of these conflicting concerns, High Voltage Direct Current (HVDC) technology is a good candidate to reinforce and upgrade the European grid. Contrary to traditional high voltage AC technology, DC links can take the form of long underground cable connections, resulting in a lower expected public resistance and shorter permitting times. The possibility to use long cable connections also makes HVDC the preferred solution to access remote offshore wind resources.

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HVDC-based reinforcements have historically mainly been in the form of interconnections between non-synchronized zones, but they can also take the form of DC links embedded in the existing AC transmission systems. The Alegro HVDC connection between Belgium and Germany will be the first embedded HVDC line connected to the Belgian transmission system. Meanwhile, an analysis from the German grid development plans proposes to upgrade the German transmission system with major HVDC corridors, accompanied by upgrades of the 400 kV AC infrastructure.

Although these reinforcements form essential elements in strengthening the transmission grid, a more fundamental upgrade of the existing grid is required in the long run. The grid upgrades envisaged to accommodate the massive amount of renewable energy sources in the transmission system go well beyond standard system reinforcements used in the past: in the next decades, a North-Sea grid, interconnecting offshore wind farms, is expected to be built. This grid can gradually evolve into a European overlay grid connecting the offshore resources with demand on the continent. The solar energy, concentrated in the south of Europe, will also require similar corridors to link it with demand. This so-called "supergrid" will form a new system of "Electricity Highways" throughout Europe, consisting of energy corridors with power ratings that surpass those of the existing AC grid. Different visions have been proposed for these future grids, and most visions encompass Voltage Source Converter High Voltage Direct Current (VSC HVDC) as preferred technology.

Future technical challenges

The operation of multiple converters in a meshed structure poses several challenges. Whereas the operation and control of a small multi-terminal HVDC (MTDC) system with a limited number of terminals is still relatively similar to a two-terminal system, DC grids ask for totally different approaches. This paragraph aims at pinpointing the main technological challenges on the road ahead for DC grids to become a reality. Meanwhile, it acknowledges that apart from my academic work on DC voltage control and power flow control dealt with in greater detail in the next section, there are other challenges which are still subject to research.

Fast-acting fault clearing

Unless the converter has blocking capabilities, a DC fault is fed by the converters in the grid through the anti-parallel diodes. Unlike AC systems, the fault currents are not limited by reactive line impedances, which causes a steep rise of the current and a rapid decrease of the voltage. Furthermore, the converters' power electronics are not able to withstand high overcurrents and must be protected. The interruption time of the breakers needed to quickly interrupt such a current, has to be in the order of only a few milliseconds. Unlike in AC circuits, there are no zero current crossings, which makes breaking a DC current more difficult. At present, different concepts are under development in research and industry. With the advent of the first hybrid HVDC breaker prototypes, practical and reliable DC breakers can be expected in the near future.

Grid protection coordination

The fast rising time of the DC short circuit current does not only pose challenges on the design of the DC breaker, but is also challenging from the point of view of the protection coordination. Furthermore, standard AC protection techniques such as impedance relays cannot be used. The protection system should have a number of requirements, such as a fast fault detection, small clearing times, selectivity in opening only those breakers needed to extinguish the fault current, and redundancy. Fast rising times and high steady-state fault current values make that the breakers have to operate on the rising slopes of the fault current, which is hampered by reflections appearing at intersections and other places where the characteristic cable impedance changes. New protection techniques have to be developed, which can be combined with converter support during the fault, e.g. by using full-bridge modules which can be blocked in case of a DC fault.

Communication requirements

Communication will surely be required for the operation of the DC grid, but it remains to be seen to what extent it is needed from the point of view of grid control and protection coordination. The main challenge with communication is that it introduces other failure modes. This is why it has been argued that protection devices that are not relying on the communication in case of failure of a communication link should be developed. The converter control can either be based on local measurements only (e.g. voltage droop control based on a local voltage measurement) or on a common signal that is communicated to all converters in the system. In the latter case, a backup control based on local measurement (which could have more relaxed control settings) needs to be present, in order for the scheme to operate in case of a communication failure. Other than the arguable communication needs for control and protection, a slower communication is required to deal with off-line calculated setpoint values and changes.

Multi-vendor interoperability

Whereas current-day point-to-point VSC HVDC schemes are primarily developed and designed by one single industrial player, a DC grid will require a multi-vendor approach, allowing for different manufacturers to develop products which can be connected to or installed in a DC grid. This poses challenges with respect to the interoperability of different types of converters, from different manufacturers, each with their own control strategy and/or implementation. An easy integration and interoperability could be impeded by the fact that most aforementioned aspects are subject to patents and protected designs, and that usually, only generalized models are available, which do not necessarily fully represent the actual converter layout and control schemes, since these are usually not distributed. Such intellectual property considerations pose considerable challenges with respect to the development of generic converter models. This aspect also raises questions to what extent the control behavior and responses to various grid phenomena can be standardized, without having full knowledge of actual converter layouts, time constants and component values. This holds especially with the introduction of new converter topologies such as the MMC, for which simplified models are currently still under development. For these reasons, the issues related to multi-vendor interoperability might become key challenges for a future DC grid to be controlled and operated in a reliable manner.

Voltage level standardization

Another challenge arises from the definition of the voltage level of a DC grid. In point-to-point connections, the selection of the link's voltage level is usually a result of an economic optimization taking into account the project's specific needs and the voltage levels supported by the manufacturers. In a DC grid, the selection of the appropriate voltage level is less evident for different reasons. DC grids will not be built in one single round, and the selection of the voltage level has to allow a stepwise development. When initiating the DC grid by building point-to-point connections that can be interconnected afterwards, the voltage levels should ideally be the same in order to avoid expensive and lossy DC/DC converters. The selection of a system voltage is also hindered by the fact that the available voltage and current ratings of XLPE cables and VSC converters are not yet in the order of magnitude of the levels aimed for when considering a DC overlay grid with higher ratings than the existing infrastructure. However, the ratings might be sufficient to develop an offshore grid. Using DC overhead lines or mass-impregnated cables would already allow higher ratings and XLPE cables for higher voltage and power levels are under development at the time of writing.

PhD contributions

The primary focus of my PhD is on the control of DC grids and encompasses a detailed analysis of distributed voltage control. The work includes a detailed study of the steady-state and dynamic control aspects, as well as the influence of the DC grid layout on the distributed control. Furthermore, the influence of the DC system control on the AC system power flows and the AC transient stability is assessed. In what follows, the main contributions are discussced, referring to a selection of publications. During my PhD, I have had the opportunity to be involved with different stakeholders through different CIGRÉ working groups and my academic work has benefited greatly from these experiences. I would also like to acknow-ledge that this work would never have been possible without the help from amongst others my PhD promoter prof. Ronnie Belmans, as well as from the fruitful discussions with prof. Dirk Van Hertem.

Power flow and DC voltage control

Contrary to two-terminal schemes or MTDC schemes with a small number of terminals, a DC grid ideally has a decentralized control of the DC voltage. The system voltage in a DC grid is usually attributed a role similar to the frequency in an AC grid. Similar to the frequency, any power imbalance is reflected in an increase or decrease of the DC system voltages. However, there are two major differences when making this comparison:

– whereas the AC frequency is a global measure that can be considered to be almost the same in the entire interconnected AC system, the DC system voltage is different for all nodes in the DC network as a result of the resistive voltage drops in the lines;
– as a result of the small time constants related to the energy storage in the cables and capacitors (10–100 ms), the control of the DC voltage proves to be challenging from the point of view of traditional AC system dynamics.

The absence of a substantial amount of energy storage elements equivalent to the inertia in AC systems makes DC voltage variations much faster than AC frequency variations. These fast dynamics therefore result in very fast converter setpoint changes when considered from a traditional AC system stability perspective. In essence, the voltage in the system only varies as a result of a current imbalance in the DC system, which causes the cable capacitances and converter capacitors to discharge in case of any deficit. It is thus possible to either use the DC current or the power as output for the controllers. In the PhD thesis, a systematic classification is presented for DC voltage converter control characteristics and how these characteristics can be combined into different grid control strategies. The details have been published in [1]. It is discussed how a general distinction can be made between centralized and distributed control methods to limit this DC voltage variation and how different charac-teristics can be combined, resulting in more advanced converter control characteristics. Figs. 1–3 respectively depict the converter outage and the principles of a centralized control vs. a distributed control.

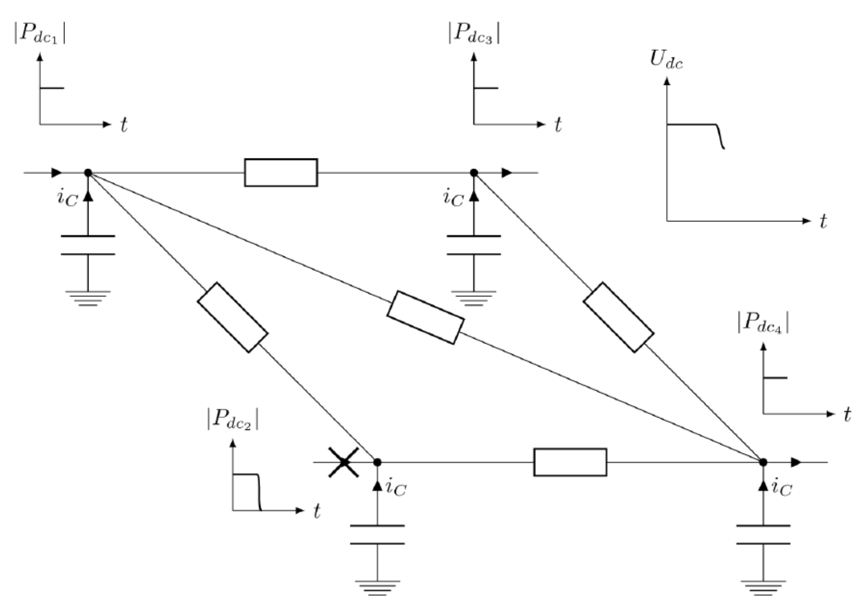

Fig. 1: DC voltage control – converter outage

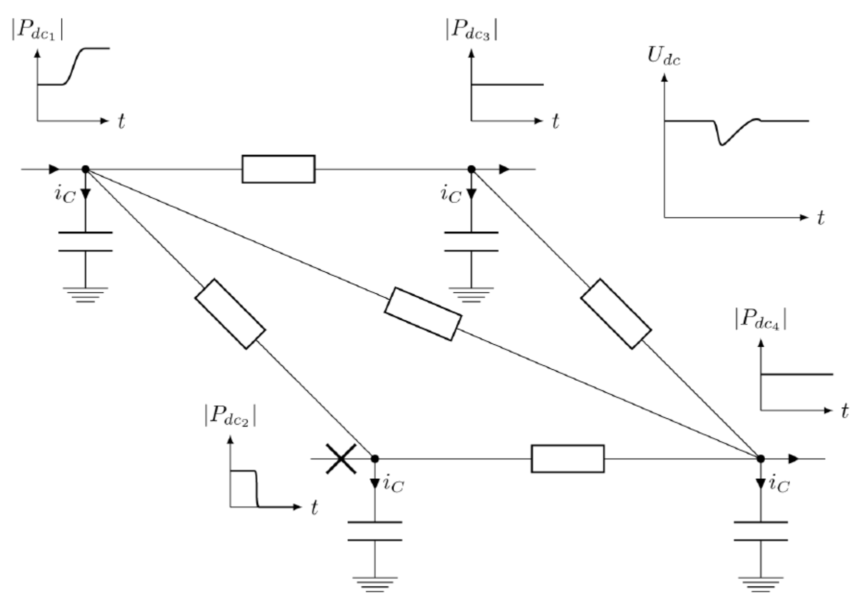

Fig. 2: Centralized voltage control (voltage margin control)

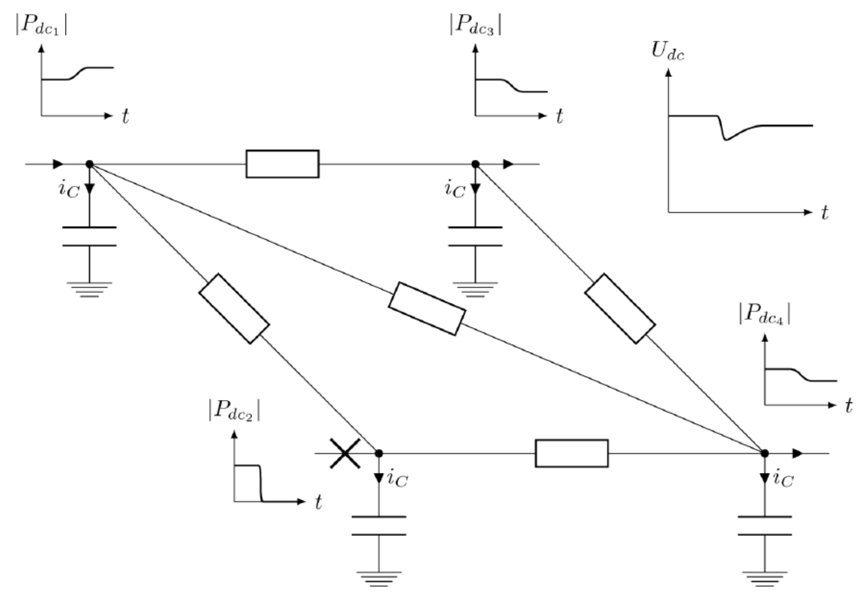

Fig. 3: Distributed voltage control (voltage droop control)

The pictures show the overall system control after an outage of a converter that was injecting power into the DC system (converter 2). For the purpose of illustration, the voltage difference between nodes in the network has been left out of the analysis. The arrows at the converter terminals determine the power direction, i.e. converters 1 and 2 initially inject power into the DC network (rectifier mode) and converters 3 and 4 extract power (inverter mode). As a result of the power imbalance caused by the outage of converter 2, the capacitances in the DC circuit (converter capacitors and cable capacitance) discharge, which causes the DC voltage to drop (Fig. 1).

Extending the principles of a two-terminal VSC HVDC link to a MTDC system, Fig. 2 shows how all but one converter can control their power injection, whilst one converter (often referred to as 'slack' converter) controls the DC voltage. As the loss of the DC voltage control cannot be tolerated, in reality, this centralized control principle is extended to allow for a (centralized) backup control by changing the constant power characteristics at converters 2 to 4 into a so-called voltage margin characteristic. Doing so, one of these converters can take over the voltage control in case converter 2 fails to control the voltage (e.g. converter outage or power limit hit). Though a valid option for small MTDC schemes, the voltage margin control poses a number of challenges when used in a meshed DC system with a large number of terminals due to the responsibility of primarily one converter at a time for balancing the entire DC grid and a more and more complex coordination of the margin settings when then number of converter increases.

As an alternative to voltage margin control, the voltage droop control has been developed. The idea of the control is to provide a distributed balancing in case of a converter outage. Other than the aforementioned voltage margin control, which uses a PI controller to control the DC voltage by one converter at a time, the voltage droop control method involves different converters controlling the voltage at their bus simultaneously by means of a proportional controller.

Fig. 3 schematically depicts the control actions taken by the three droop-controlled converters after an outage of converter 2. Contrary to the situation with voltage margin control, converters 3 and 4 also decrease their power taken from the DC grid. Converter 1 still increases its power injection, but to a lesser extent than was the case with the voltage margin control. Another difference results from the use of a proportional controller, which implies a steady-state voltage deviation after an outage. The offset can be accounted for by providing a secondary voltage control, which changes the droop control setpoints.

Steady-state system interactions

The introduction of HVDC grids and MTDC systems is challenging from the point of view of steady-state interactions with existing AC systems. The fast DC voltage control described in the previous section and the corresponding power changes in the converters will not only change the power flows in the DC system, but will also cause a change of power flows in the interconnected AC systems. The thesis develops an accurate steady-state model for VSC MTDC systems and its interaction with AC systems. The power flow algorithm uses a sequential method, meaning that AC and DC systems are solved sequentially while iterating between them: when solving

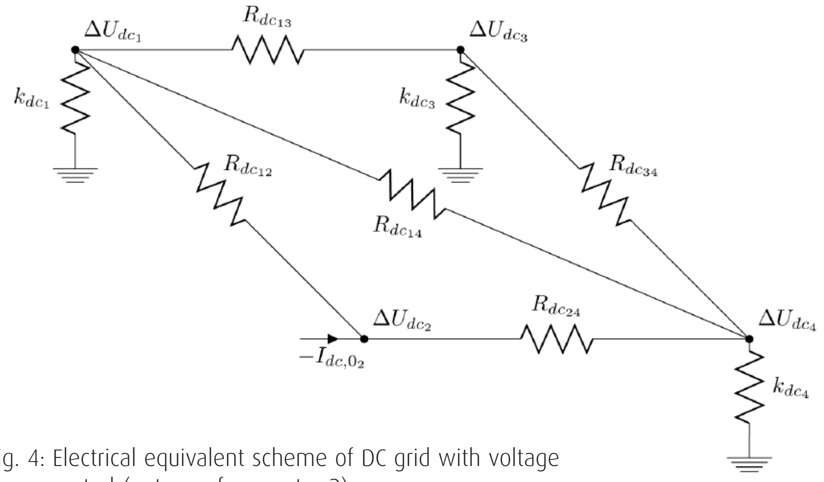

Fig. 4: Electrical equivalent scheme of DC grid with voltage droop control (outage of converter 2)

the AC system, the DC grid variables are kept constant and the converter interaction with the AC system is modeled by means of standard PQ- and PV-buses. Similarly, the AC grid quantities are kept constant when solving the DC grid. As published in [2], it is possible to model the converters as constant power buses or as a constant voltage bus, thereby implicitly extending the operational principles of two-terminal VSC HVDC schemes. Alternatively, a distributed voltage control can be represented in the algorithm, as published in [3]. This allows to study the steady-state effects of the voltage droop control on the power flows in the hybrid AC/DC system. The algorithm has resulted in the development of an open-source software package MatACDC [4], which is currently being used in the CIGRÉ B4.58 working group to study steady-state system interactions in the CIGRÉ DC grid benchmark test system.

Another important aspect of the voltage droop control is the influence of the voltage drops throughout the system on the power sharing after an outage. This influence has been derived analytically and the results have been published in [5]. The analysis shows that the droop control can in fact be regarded upon as an equivalent resistive load at the DC side (Fig. 4), with the resistances equal to the droop constants (current-based droop control). Using this model, it is shown that from a steady-state perspective, a trade-off exists when selecting the converter gains. On the one hand, the steady-state voltage deviations after a contingency have to be limited and kept within reasonable bounds. From a control perspective, on the other hand, the aim is to obtain an optimal power or current redistribution after a converter outage, preferentially set by selecting the appropriate gains and not by the characteristics of the DC system. The analysis shows that a set of gain values can only be scaled to a limited extent without altering the relative power sharing of the different converters. It has also been shown that the DC grid has a tendency to solve deficits locally. This means that converters that are electrically close to the converter facing an outage have a natural tendency to take a higher share of the power sharing when using similar droop settings. This can be advantageous from the perspective of the AC system stability when the converters that are electrically close at the DC side are also electrically close at the AC side.

Dynamic system interactions

The lack of sufficient energy storage equivalent to the system inertia in an AC system, makes that the DC voltage variations are an order of magnitude faster than the frequency variations in AC systems. Consequently, a major part of the research on DC voltage control deals with the system dynamics. In the thesis, a new detailed dynamic converter control model is introduced. The details have been published in [6]. The developed converter model includes internal current and voltage limits and has a cascaded control scheme that allows for both voltage margin control and voltage droop control. This makes the model ideally suited? for the dynamic study of DC grids. The salient features of the model are the full representation of converter limits and the fact that it can be easily reconfigured to combine different converter control modes, such as DC voltage droop, constant power and constant DC voltage control. It is shown by simulations how the limits influence the dynamics and what the effects are of neglecting converter limits and DC grid current dynamics. The results indicate that reduced order models approximate the detailed model well. The model has been implemented and tested using *MatDyn*, an open-source electromechanical simulation toolbox and has been thoroughly tested against an implementation in the commercially graded power system software EUROSTAG. Details can be found in [6].

Using this dynamic model and the steady-state models from MatACDC, the thesis discusses both the steady-state and dynamic implementation of alternative droop control schemes. Simulation results show that the major difference is mainly reflected in the steady-state values after a contingency, rather than the dynamic system response, which is primarily determined by the DC grid dynamics, the converter control parameters and the actual control layout. The general control strategies have been combined to obtain different droop-based control schemes including a constant power and current deadband or alternatively constant voltage characteristics to combine the behavior of a centralized voltage control for minor power variations with a distributed control for major events (e.g. converter outages). To account for the steady-state offset caused by the droop control action, the thesis presents a secondary voltage control strategy, which aims at restoring the voltage profile after a contingency. It is demonstrated that the overall DC voltage profile can be changed with relatively small changes to the converter power settings.

When analyzing the effect of this control on the AC system, the observation was made that the fast change of the power flows in the AC system as a result of a distributed DC voltage control can possibly trigger AC system instability. The influence of the converter power sharing after a contingency on the AC system transient stability is investigated by analyzing the input directions causing the smallest effect on the system outputs due to disturbances at the DC side. The methodology is based on singular value decomposition and multi-input multi-output (MIMO) system analysis. The details have been published in [7]. Due to the voltage droop control, the outage of a converter results in a system-wide power rescheduling by different other converters. By analyzing the AC system response, it is shown that the power rescheduling can also be optimized from the point of view of the AC system dynamics. In general, it is preferred to balance the power deficit or surplus caused by the outage locally, but a challenge arises from the fact that the droop settings determine the power sharing for each possible outage in the DC system and that different outages can result in a different optimal power sharing and corresponding droop settings.

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Jef Beerten received the M.Sc. degree in electrical engineering (Summa cum laude) and the Ph.D. degree (Summa cum laude with congratulations from the Board of Examiners) from the University of Leuven (KU Leuven), Leuven, Belgium, in 2008 and 2013, respectively. In 2011, he was a Visiting Researcher at the EPS Group, KTH Royal Institute of Technology, Stockholm, Sweden. From April 2014 until March 2015, he was a Visiting Postdoctoral Researcher at the Power Systems Group, Norwegian University of Science and Technology (NTNU), Trondheim, Norway. Currently, he is a Postdoctoral Researcher with the ELECTA/Energyville division of KU Leuven. Dr. Beerten is an active member of both the IEEE and CIGRÉ. He has been a contributing member of the CIGRÉ B4.52 working group on HVDC grids feasibility and is the secretary of B4.58 on power flow and DC voltage control in meshed HVDC grids and the convener of WG B4.64 on the impact of AC system characteristics on the performance of HVDC schemes. His research interests include power system control and dynamics, the grid of future and multiterminal VSC HVDC and HVDC grids in particular. His research has been funded by a Ph.D. fellowship from the Research Foundation—Flanders (FWO). Currently, he holds a Postdoctoral Fellowship from the FWO.