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PhD Thesis Summary

Hybrid AC/DC solutions for electrical distribution networks: microgrids, direct-current links, electrical energy storage, PV, EV

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1. Critical Literature Review

The rapid transformation of electric power systems—locally and internationally—follows a confluence of forces: legally binding decarbonization trajectories, the European Green Deal and companion packages, accelerating electric-vehicle adoption, the emergence of hydrogen as an energy carrier, distributed and inverter-based generation at scale, and pervasive grid digitalization. The aggregate effect is a pressing need to adapt planning and operation paradigms across all voltage levels.

For over a century, the backbone of power systems has been alternating current (AC). Today, direct-current (DC) technologies are becoming a structural complement rather than a niche, primarily due to advances in power electronics.

There are already developments in which direct-current (DC) technologies have important applications and numerous implementations worldwide, replacing traditional alternating-current (AC) technologies. Worth mentioning here are long-distance transmission of large amounts of power (HVDC), asynchronous interconnection of grids, and the connection of offshore wind farms, all at high voltage.

From a techno-economic perspective, HVDC can outcompete HVAC beyond a corridor-length threshold (≈500 km), or when submarine cables and controllability requirements dominate. Although converter stations raise CAPEX above comparable AC solutions, OPEX is typically lower thanks to reduced losses and superior controllability, yielding competitive lifetime costs.

A similar migration is underway toward medium voltage (MV) and low voltage (LV). In these domains, DC and hybrid AC/DC topologies promise: higher transferable power per corridor (power density), precise and fast controllability of flows, straightforward interfacing of inverter-based resources, and improved cable utilization. Nonetheless, widespread MVDC adoption has lagged: MV grids are often short and ringed, AC equipment is heavily standardized and commoditized, and MVDC protection—especially fast, selective interruption—remains cost-sensitive.

The purpose of the thesis arises from the need for today's power systems to evolve toward smart grids, as motivated by the points described earlier. The main focus of the thesis is the need for smart energy communities—rural or urban, whether connected to the public grid or not—to be supplied with electricity from environmentally friendly sources. Considering that in many cases building new networks is difficult, renewable energy sources require inverters to connect to the AC grid, and a significant share of loads can operate on DC supply, one solution may be the use of hybrid AC/DC networks.

Among the advantages of MVAC worth noting are:

A. Most of the existing medium-voltage network is AC

Although the world's first electric network—built in New York in 1882 by Thomas Edison—was direct current (DC), the technology that came to dominate after the "War of the Currents" was alternating current (AC), starting around 1892, following the invention of the transformer and the asynchronous (induction) machine. At that time, a DC network had to maintain the same voltage level at every point because it was not technically possible to transform voltage with the technology then available, which would have led to high losses and poor investment viability. With AC technology, voltage transformation was possible from the outset, which drove its worldwide adoption. Today, the impediment that once led

to DC being sidelined is no longer an issue. As a result, most consumers are supplied with AC.

B. Need for standardisation

At present, there are numerous important AC standards for voltage levels, frequency, and consequently for equipment. This is also under development for MVDC.

In addition, MVDC can offer the following advantages:

A. Higher power density

In certain cases—such as dense urban/industrial areas where electrification is increasing—it can be difficult and uneconomical to reinforce the network. For non-electrical reasons (environmental, space, etc.), uprating existing cable and transformer capacities or routing new network elements may be difficult or impossible, creating a need to use existing assets and corridors more efficiently. Therefore, converting parts of the network from AC to DC can be considered a solution in this situation, as with HVDC. For MVDC, the voltage range currently considered is 10–70 kV.

B. Improved controllability

A VSC-type HVDC, MVDC, or LVDC link can control power flow and the magnitude of active and reactive power independently of each other. This is not possible on a conventional AC link without additional equipment.

C. Growing number of DC loads

Many residential and industrial consumers are, essentially, DC loads. The rising number of electronics in use and various industrial processes has increased DC demand, which for now is met by converting from AC to DC.

D. Improved integration of inverter-based generators from renewable energy sources

Recent improvements in converter technology have led to the emergence of MMC technology. This is a more advanced, more complex variant of VSC. In an MMC, a valve is composed of a large number of series-connected switches, which makes it possible to obtain a stepped AC voltage by individually controlling the modules.

Back-to-back HVDC links are a type of connection already used in numerous cases, such as linking two grids with different frequencies (Brazil–Argentina, Brazil–Paraguay, Brazil–Uruguay, Japan), two grids with the same frequency but different rules for active power control, or within the same grid to make fault isolation easier or to connect two nodes with an excessively large difference in voltage phase angle.

These applications, adapted to a multi-terminal structure, can also be employed at the level of medium-voltage networks, increasing flexibility and the degree of control for distribution network operators, as well as the level of interconnection between different operators, including across countries. These elements also contribute to the transformation of distribution network operators into system operators, complementing the role of transmission system operators.

The simplest MVDC or LVDC connection that can be introduced in a dense urban area is the back-to-back link, known as a “soft open point” (SOP). This replaces the traditional concept of a “normal open point” (NOP), represented by the classical sectionalizing switch in a looped medium- or low-voltage network. Unlike an NOP, an SOP actively directs the power flow between the two connected branches, contributing to network stability. With an SOP, the

network can be operated either radial or looped. An example of such a link has been implemented in the United Kingdom.

Islanded/isolated networks (electrical and/or geographic) and consumers located far from the grid often suffer from imbalances between generation and load. Near-shore islands are sometimes supplied from the mainland via an AC link, but there are situations where even this cannot compensate for the voltage drop on the island by injecting reactive power, and other methods may be uneconomical. In such cases, a technically and economically viable solution can be a two-terminal MVDC link between the mainland and the island, similar to a conventional HVDC link.

Rural communities located far from the public grid can be connected to it via an MVDC link, which has lower losses than a conventional AC link. The DC link can also be extended down to the low-voltage level using DC–DC conversion. The entire (micro)grid of the locality—hybrid, with DC and AC elements—could also operate islanded if it has sufficient generation and storage capacity and nonessential loads are dispatchable. Another case is the opposite of the one described, where an isolated network produces much more than it consumes and this energy must be exported.

A valuable example is the ANGLE-DC project, which repurposes a 33 kV AC link between North Wales and the island of Anglesey. Anglesey has evolved from a network with no generation, dependent on Great Britain's grid, to one with over 80 MW installed, most of it from variable renewable sources. Urban regeneration projects have also led to increased demand. For exporting/importing electricity to the island, the thermal and permissible voltage limits of the existing 33 kV AC link would today be exceeded. The traditional solution would have involved reinforcing the network with new distribution capacity. The approach considered, however, was to convert the existing connection into an MVDC one, without replacing any component, of ±27 kW DC, a value calculated for converting a double-circuit link in which the insulators withstand a DC voltage equivalent to the AC peak phase-to-earth voltage.

Another example is the supply of an offshore platform near Wenchang, China. It was initially fed via a submarine MVAC cable link. Overvoltages occurring when re-energizing the platform gradually damaged the cable insulation. As the diesel generators on the isolated platform were insufficient, expensive to operate, and noisy, the platform was reconnected in a pilot project via a new MVDC link of ±15 kV, 8 MW.

While MV networks share many characteristics with HV networks—despite certain differences—their modelling and steady-state calculations are carried out in the same way. The main difference that arises in LV networks and affects how they can be modelled is the imbalance present between phases. The cause of this situation is single-phase consumers, especially high-power ones such as single-phase chargers for electric vehicles and single-phase heat pumps, as well as single-phase distributed generation, for example single-phase inverters. One method for analysing such networks is to include the neutral conductor in addition to the three phases. In studying a low-voltage hybrid AC–DC network, these imbalances should be manageable on the AC side by the converters. To date, there are multiple works that analyse control and management methods for converters in networks. Moreover, after the modelling and research stages, these technologies must also be commercially available in order to implement hybrid low-voltage AC–DC networks—a problem that does not arise at MV.

The calculation of short-circuit currents for DC auxiliary installations in power plants and substations is addressed in IEC 61660. The first part of this standard deals with the calculation of short-circuit currents in DC networks. The second part analyses the impact of DC short

circuits on various equipment. The final part is a technical report presenting different approaches to short-circuit current calculation using a correction factor σj.

The second technology is the solid-state circuit breaker. On its main branch there is a power semiconductor S (IGBT or IGCT), whose role is to interrupt current flow when a fault occurs. Upon fault detection, the semiconductor switches off and the current passes through the secondary branch. On this branch there is a suppressor circuit consisting of a diode connected in parallel with a resistor, and a capacitor.

The role of the suppressor is to rapidly reduce the fault current value, together with the varistor, which has the same use as the one employed in the mechanical breaker. The advantages of this option are the speed of fault clearing and the low risk of failure due to the absence of moving parts. Because the power semiconductor device is placed directly in the current path during normal operation, the losses of this breaker are significant. In addition, there is the complicated design of the series connection of power semiconductor devices required to reach the blocking voltages of an MVDC line.

Nevertheless, research into silicon-carbide (SiC)–based semiconductors, with higher nominal blocking voltages than current silicon-based technologies, could reduce the number of semiconductors needed to achieve the required blocking voltage, lowering the complexity and price of these devices.

As HVDC technologies extend into the MVDC and even LVDC domain, new possibilities arise for distribution networks. The major advantages are especially for dense urban areas, isolated consumers, and the integration of renewable energy sources. The possibilities include creating entirely DC distribution networks or hybrid AC/DC ones to leverage the advantages of both technologies.

Existing pilot projects from the past few years now focus on practically demonstrating the advantages of these types of networks, which until recently were found only at a theoretical level or within research projects.

However, certain obstacles must be overcome for the large-scale implementation of hybrid networks. The main obstacles are the lack/insufficiency of standards, adapting circuit breakers for MVDC and LVDC, the emergence of commercial solutions for electronic transformers, and investment costs.

2. Original contributions

After a critical survey of current applications and directions in the field—from MVDC/HVDC comparisons and the diversity of topologies and uses to the challenges of standardization, interruption, and transformation—the conclusions are translated into operational steps on a hybrid AC–DC test network. This move clearly and explicitly establishes the analysis approach, selection criteria, and complete simulation toolkit, so that the hypotheses derived from the research starting point can be verified, advancing the state of knowledge in MVDC.

A first step is to create a medium-voltage hybrid AC–DC test network, building on existing test networks. Thus, after examining the test networks proposed by IEEE and CIGRE, the IEEE-33 network was chosen as the basis for developing the required hybrid network.

A second important step is to use the QSTS (Quasi-Static Time Series) method alongside a steady-state program, so that dynamic evolutions of the network state are captured as chains of quasi-static states governed by numerically implemented control loops. These control loops represent the automations that, in reality, act almost instantaneously to keep the network within limits. Given that in a medium-voltage network variations in generation and load are felt more strongly and more rapidly, a simple steady-state study would not have been sufficient to assess the changes brought by hybridizing the network.

For steady-state analysis, the open-source OpenDSS program was used, which allows nodal powers to be provided as input vectors—i.e., values corresponding to each time interval (one hour, one minute, one second, etc.). OpenDSS streamlines the computation of all results, presented as a time series, by using the results of the previous steady-state as inputs for the new steady-state at the next moment in time. In this way, the number of iterations to convergence is reduced and the time series is obtained more quickly, enabling the QSTS method to be implemented with it, together with the adaptations needed to simulate the control loops.

Thanks to the implementation of voltage regulators, PQ buses could be converted into PV (P–V) buses—an approach that corresponds to how voltage regulation operates in practice.

A first control method implemented and studied is a PID-loop voltage regulator. It contains two main blocks:

- a block that compares the process variable with a reference value, whose output is the error relative to the setpoint;
- a transfer function that takes the previously obtained error as its input and produces an output via a PID-type transfer function.

PI (proportional–integral) and PID (proportional–integral–derivative) control are the most commonly used in practice. The thesis summarizes several aspects of the general PID block, including proper tuning of the PID parameters. If the controller includes only the proportional component K_P, there is always a residual steady-state error. The integral component ensures that, after some time, the residual error gradually decreases and ultimately reaches zero, effectively correcting the leftover error from previous iterations. The derivative component (also called differential) provides a faster response.

The way in which the PID constants are chosen is, for most situations, an iterative process. First, K_P is chosen, witch $K_I = 0$ (infinite integral time) and $K_D = 0$ (no derivate response), after which for a K_P held constant, K_I is chosen and, afterwards, with both values kept constant, K_D is chosen. The procedure may involve further retuning of the previously chosen constants until the transfer function's response is as desired for a step disturbance applied to the system.

If output noise needs to be reduced due to input noise (random variations of the input superimposed on the useful signal), the function can be modified to include a low-pass filter (LPF).

Tests demonstrated the effectiveness of this type of voltage regulator implemented between two time instants that can be considered quasi-static. For fine tuning, multiple values of the proportional, integral, and derivative components were explored empirically. Although the derivative component helped achieve a rapid response, it led to oscillations; therefore, it was dropped, and the resulting controller is of the PI type.

In the model, one or more equilibrium nodes are identified on the DC side (U = constant), which act as "providers" of inertia in the DC network—functionally equivalent to the equilibrium node in the AC network, traditionally represented by the strongest generator. This

allows the balance between load and generation to be maintained during abrupt power variations.

The first hybrid AC–DC test network created was a 10-node AC network—a subnet of the IEEE-33 grid—to which a DC link was added to tie an area of increased generation to one of increased consumption.

Given that a DC network lacks the mechanical rotational inertia that provides an instantaneous response to disturbances and thus prevents system degradation through voltage changes (especially voltage drops)—as happens in AC networks with respect to frequency—in a DC network a similar inertia effect is provided by capacitors coupled to the DC busbars at certain nodes, especially at DC generators, in our case at the equilibrium node. Thus, the DC equilibrium node is a voltage source whose value is in fact the voltage maintained on the DC bus—i.e., on the DC-bus capacitor—which can react instantaneously to disturbances by supplying the required current, while its voltage decreases gradually as energy is drawn. The capacitance value calculated and used was tested so that it can preserve the quasi-static character for each time step studied.

The effect of the DC-bus capacitance is formalized as “electrostatic inertia” (HELS): the energy stored in a capacitor slows the degradation of voltage during fast events—an effect validated both theoretically and through QSTS runs with short time steps. The first test set validated this form of “electrostatic inertia.”

In this way, the transition from surveying the state of the art of MVDC networks to applied research is made without breaks: notions about the controllability of DC networks and assisting AC networks via DC, the increase in distributed generation, and the advantages of hybridization are reflected in the simulations performed. The subsequent test sets continually add new elements to validate these and the operation of the hybrid network as a whole.

The next test set targeted operating regimes with active power P demanded at an AC node. The power requested from the converter is no longer equal to the variation of P; rather, it represents a nodal active power used to maintain the node voltage at a reference value that must remain within permissible limits (±5%).

Building on the created hybrid prototype and the QSTS method integrated with a steady-state program, the analysis extends to a complex MV network that includes two multi-terminal DC subgrids with four and eight nodes, respectively, with the capability to regulate voltage via P and/or Q at the AC nodes. From this point in the original research, the emphasis shifts from validations on simplified configurations to assessing coordination and validating the concept on a broadened architecture in which power flows can follow alternative paths and be redistributed through the DC networks.

Next, the mathematical operating model of bidirectional converters is described for the two operating modes: AC–DC and DC–AC. The implementation details of the previously described controls are also provided.

The following test set demonstrates the usefulness of voltage control via P, Q, or a combination of the two components, which are quantified in terms of control effectiveness given the limitations of network components, and in terms of overall network efficiency.

The sensitivities dU/dP and dU/dQ are quantified in the next set of tests for representative nodes, which justifies using P-based control as a practical tool at medium voltage, complementing the classic Q-based regulation used in high-voltage networks. A comparison between the two control methods and their complementarity is shown in the tests performed, with the result that both methods—or a combination of them—are suitable. Their behavior is

influenced by the specific network, so the control must be adapted case by case to obtain the best solution with minimal losses.

The case studies compare the control methods and show how load sharing among converters, the placement of equilibrium nodes, and the constraints within the two types of networks influence voltage stability.

Scenarios with varied subsets and parameters are then explored to test the robustness of the developed method and highlight its relevance.

For the tests performed, power balances are also checked to identify differing losses due to the various control types used. It can be shown that these losses are within normal limits; however, fine-tuning the control helps significantly reduce losses.

Subsequently, the network's operation is studied as a whole, in which, in addition to conventional consumers and generators, there are renewable-energy-based generators with intermittent output and storage installations.

An important introduction regarding the control used is the voltage droop characteristic. Similar to frequency droop, "droop" here means the ratio between the relative voltage deviation and the relative change in active power that results, in steady state, in response to the voltage deviation, expressed as a percentage. The relative voltage deviation is referenced to the nominal voltage, and the relative change in active power is referenced to the maximum capacity or to the actual active power at the moment the relevant threshold is reached. To avoid activation for insignificant voltage deviations, a deadband was also used. Note that a scheduled power of 0% corresponds, for example, to a BESS initially operating at zero terminal power, but capable of providing control both when the nodal voltage drops below the lower deadband threshold and when it rises above the upper deadband threshold. This mode of operation is used in the scenarios presented in the thesis. The observable result is that the choice of voltage droop is specific to each system case, and QSTS–steady-state techniques can simulate the system evolution well for various droop settings, making them a useful tool in this area.

The scenarios in this test set include ramp disturbances, step changes, and sloped variations. Starting from a single node that can provide droop-based control, with different droop values, the simulations also cover the interactions that arise when multiple nodes have voltage droop control, using identical or different droop curves, each implemented with a low-pass filter and with power limits that are more or less restrictive. Important observations in these tests concern the interactions of two nodes tasked with voltage regulation via droop, including how to minimize negative interactions. One such example is reducing episodes where one node brings the voltage back within limits while the other either amplifies the first node's effect excessively or attempts to counteract it.

Deviations from expectations are documented and explained in context (topology, converter limits, X/R ratio), defining the domains of validity for the control strategies. From this point, the results not only confirm the initial ideas but also provide a basis for best practices for coordinated operation in MVDC networks coupled with and co-modeled alongside MVAC.

The validated results for—and with the help of—medium-voltage hybrid electrical networks create the premises for a natural extension toward multi-vector systems, in which a local gas network interacts with the hybrid grid through P2G (power-to-gas) and G2P (gas-to-power) conversions, creating a so-called "Gas Valley."

Under conventional conditions, electrical and natural gas networks are not explicitly coupled.

It should also be noted that, to operate, the natural gas network requires electrically powered equipment such as pressure-boosting pumps/compressors. However, this is not considered a systemic interaction, only a functional one, in which the equipment behaves like any ordinary load.

At the same time, gas-fired power plants inject electricity into the power system using natural gas supplied by the gas network, but this situation is also not generally regarded as an interaction between the two systems; they are analyzed separately.

With the large-scale introduction of renewable sources—whose output depends on natural conditions (solar irradiance, wind presence)—generation from these sources is generally not synchronized with system demand, requiring various measures such as energy storage, a method considered among the most effective. In natural-gas networks, the storage issue is addressed by gas storage facilities as well as by the quantity of gas already present in the network (linepack), which can serve as significant storage.

Short-term storage is increasingly present through the use of Li-ion batteries, whose deployment is growing. However, for long-duration (interseasonal) storage, Li-ion batteries become impractical, necessitating complementary solutions.

Converting electricity from renewable sources into hydrogen is considered an absolutely necessary complementary solution to cope with the significant differences between summertime photovoltaic generation and wintertime electricity demand, when renewable output drops appreciably.

Methane storage is considered to have a potential tens of times greater than that of electricity, and hydrogen storage could approach similar characteristics as its storage technologies improve and become cheaper.

In the future, a complete switch to hydrogen is possible, but it would require redesigning gas pipelines, gas turbines, and storage systems—measures that can be very costly and risk slowing the energy system's transformation.

As a technical alternative, further converting hydrogen into CH_4 via the Sabatier reaction could provide fully green methane. In the Sabatier reaction, carbon dioxide (CO_2) is captured from the atmosphere to produce CH_4, and when this methane is burned, the same amount of CO_2 is released back into the atmosphere. This process is "circular," not increasing CO_2 emissions over the full cycle.

It is important to mention that although this is still a transfer of power through a conducting medium, gas power flow has its own particularities. Important aspects differentiate the steady-state behavior of such a network from that of electricity. First, gas is compressible—its volume changes significantly with variations in temperature and pressure. Moreover, gas is governed by characteristics different from those of electricity, such as mass, volume, density, pressure, temperature, viscosity, etc. Although some of these parameters can be partially mapped to electrical ones, a simulation using the same mathematical model would yield unsatisfactory results. To date, the approach proposed in the literature is similar to the sequential method used for hybrid electric networks, with the difference that the gas network itself continues to be simulated using its own mathematical model.

Accordingly, the architecture and mathematical model are explicitly introduced for the P2G interfaces (electrolyzer, Sabatier methanation unit) along with storage of the resulting gas, and for G2P (combined-cycle turbines, fuel cells), so that energy flows can be directed to the appropriate energy vector at the right time, with the aim of increasing the integration of

electricity from renewable sources by making maximum use of existing infrastructure, thereby increasing system flexibility.

The first tests validate the support that P2G components can provide at midday in summer, as well as the contribution of G2P components on a summer evening.

The interseasonal P2G–GS (gas storage)–G2P cycle is analyzed to demonstrate the usefulness of such coupling: surplus electricity in summer is converted to gas, stored, and then reintroduced in winter as electric power (1 MW, 4 h/day), with aggregate overall efficiency and utilization metrics calculated step by step. The models quantify the available chemical energy (H_2, CH_4, or their mixture) as well as the effects on the electrical network's operating regime during critical periods, highlighting benefits for flexibility and resilience.

The technological and economic trade-offs of H_2–CH_4 blends are analyzed alongside the alternative of full conversion via the Sabatier reaction to "green" methane, with implications for emissions and infrastructure requirements.

In parallel, specific costs (electrolyzer, green-CH_4 chain, transport and storage) and the dependence of the "Gas Valley" gas price on the electricity price are evaluated for distinct investment scenarios. These simulations show that choosing a "Gas Valley" model based solely on hydrogen or on a hydrogen–CH_4 mix essentially depends on investment, transport, and storage costs for hydrogen and for CH_4, factors also influenced by the existence and adaptability of current infrastructure.

The following aspects are important when using a Gas Valley (GV) to support a hybrid network:

- The electricity used for P2G conversion can be used to produce hydrogen, methane, or a mixture of the two;
- The 2400 kW used on summer days for P2G conversion does not affect the electric grid during periods of abundant renewable generation—the issue studied in S1;
- The 1000 or 2000 kW produced on winter days via G2P conversion improves the operating regime of the hybrid electric network studied in S2;
- For the input data presented, summer P2G operation provides a significant power contribution in winter, evidenced by a 4-hour period of 1000 kW electricity production on 74 days;
- Higher winter output values can be determined by the method presented, by adjusting inputs such as P2G power as well as the number of operating hours and days;
- The chapter systematizes a simplified mathematical model for the gas microgrid—generically called a "Gas Valley"—to enable interaction studies with the (conventional and/or hybrid) electric network focusing on various aspects.

The efficiency over a full P2G–GS–G2P cycle in the case studied is 34,4%, which is low compared with typical efficiencies of individual devices. Nevertheless, such an efficiency should be accepted as a viable solution—one of the future options to help achieve carbon neutrality by integrating renewable electricity into the gas sector.

This framework integrates existing knowledge on steady-state studies of power systems into a multi-vector logic, enabling the design of energy communities that can benefit from additional flexibility across vectors and seasons.

The overall aim of the thesis, integrating the research efforts, is to provide an analysis framework—**Hybrid and Multi-Energy Grids Dynamic Analysis Framework using QSTS-**

LF technologies—covering hybrid AC and DC electrical networks and methane/hydrogen gas networks. The proposed analysis environment addresses dynamic evolution using QSTS techniques in combination with a steady-state (load-flow) program.

3. Conclusions

This doctoral thesis is dedicated to a topic of major importance for the future evolution of power systems, namely hybrid medium-voltage networks. It inventories both the theoretical arguments for hybridization—transfer capacity, controllability, integration of distributed and variable generation, integration of DC producers and consumers—and the technical and regulatory barriers—DC protections, switching devices, state of standardization—presented in Chapter 1. From this analysis emerged the need for a unified testing framework that translates conceptual statements into verifiable hypotheses and transferable best practices, especially at the distribution level, where impedance ratios and generation profiles significantly change how controls are implemented compared to high voltage.

A key finding was the lack of recognized hybrid test networks that are sufficiently detailed to allow rigorous comparisons between methods, topologies, and control strategies. Reference AC networks exist, but turning them into AC/DC test systems—with convertible lines, strategically placed converters (or where siting allows), control nodes, and reconfiguration options—largely remains the task of each individual researcher, complicating reproducibility and aggregation of results. In this context, in Sections 2.2, 2.3, and 2.4, this work adopts and extends an IEEE distribution model, IEEE-33, organizes it into zones with islanding potential, and adds alternative transfer paths via DC networks so that resilience and coordination studies are possible without losing the original topology. The role of the new lines and how they are operated (reinforcement, meshing, bypass routes) are specified to support credible operating scenarios, starting from a network operating outside satisfactory limits.

The choice of simulation method followed two main criteria: to faithfully capture evolutions induced by variable load/generation profiles, and to naturally integrate automation functions between two simulation steps. The Quasi-Static Time Series (QSTS) method, presented in Section 2.2.1, meets these requirements thanks to its ability to integrate with a steady-state (load-flow) solver. This enabled the creation of a new, integrated analysis method that models the network's dynamic evolution as a chain of steady-state points and allows "closing the loop" with discrete regulators (PI/PID) at nodes that in reality would use automation to maintain voltage levels. In addition, using an established load-flow program (such as OpenDSS), presented in Section 2.2.2, ensures accessibility and reproducibility—essential qualities when the objective is to establish a reusable workflow for future researchers.

The test network was designed to strike a balance between operational realism and research clarity/quality: an easily understood topology, zones that can be separated to create new situations, alternative power-flow paths, and clear AC/DC interface points. Within this architecture, converters with distinct roles were introduced: some impose a voltage level on the DC bus ("equilibrium node"), others regulate voltage at AC nodes via modulation of active and/or reactive power. These are described in Section 2.3.5. By explicitly listing these roles and their connections, the network becomes a configurable "testbed" for studies of control and power-flow distribution in a multi-terminal AC–DC structure.

The simulation method and the quality of the test network were validated incrementally. First, the agreement was shown between the evolution of the DC-bus voltage supplied from a capacitor and analytical predictions for controlled discharge scenarios, presented in Section

2.2.2.2: the QSTS results correctly indicated the moments when voltage thresholds were reached and showed that the time step can be chosen fine enough for each increment to be considered quasi-static. This validation ensures that the notion of “electrostatic inertia” introduced by the DC-bus capacitance is correctly captured by the model and can be used in strategies to damp disturbances caused by power variations.

Next, nodal controllability on the AC side was verified via control loops that track voltage at representative nodes, as described in Section 2.3.3. Comparing scenarios showed that modulating either active or reactive power yields robust stabilization, with differences depending on topology, converter placement, and the load/generation profiles used. Sensitivity analyses justified, for medium voltage, using P-based control as a practical tool (alongside classic Q-based regulation), especially where the DC interface provides additional degrees of freedom for redistributing flows. The conclusion is not absolute but context-dependent, and can be adapted both in future studies and in real applications. In networks with impedances and loadings similar to those studied, P-based control can perform as well as Q-based control, and weighted combinations are a natural path to optimization.

As complexity increased, the network included multiple multi-terminal DC subgrids, with additional converters placed at key nodes on the AC side, chosen both to solve network issues and empirically. Each node has a defined role: maintaining voltage on the DC network, on the AC network, and enabling bidirectional power transfer. This expansion allowed assessment of control-loop coordination, limitations of flows on alternative routes, and trade-offs between voltage stability and overall losses, while the QSTS framework remained stable and transparent for cross-scenario comparisons—elements presented in Section 2.3.6.

After consolidating the electrical portion, the work integrated a generic gas network, aptly named “Gas Valley,” presented in Section 2.4. It was designed to be modular and parametric and is coupled to the hybrid electrical network through two interfaces: conversion of electricity into hydrogen/green methane (P2G)—based on electrolysis and, optionally, the Sabatier reaction—and conversion of gas back into electricity (G2P)—based on gas turbines and fuel cells, as presented in Section 2.4.2.1. The model includes gas storage and an interface to the public gas network similar to that of the electric grid, so that flows can be directed in both directions and the appropriate vector can absorb production surpluses or cover consumption peaks depending on season and operating context. The clear definition of components and their relationships makes “plug-and-play” coupling of the gas network to the electrical framework possible. An important aspect of this coupling is that it is a real-world phenomenon that typically is not modelled; the two network types are usually considered separately.

Building on this foundation, Section 2.4.4 presents seasonal simulations that link periods with abundant renewable electricity generation to periods of increased demand. P2G enables storing energy over time via the gas vector; storage extends its usefulness; and G2P brings it back into the electrical network when it is most needed and direct electricity-storage methods would not suffice. The operational result is the flattening of troughs and reduced stress during critical periods, without burdening the electrical infrastructure by leveraging existing infrastructures. In addition, calibrated G2P injections can support voltage regulation and reduce the need for corrective actions in the hybrid network at any time of year. Cost sensitivity analyses highlight the dependence of Gas Valley gas prices on electricity costs and on specific equipment investments, recommending multi-criteria optimization of H_2/CH_4 proportions and installed capacities.

The advantages of multi-vector integration can be summarized on three levels. Technical, a new kind of flexibility in volume and duration that electrical storage can deliver only with difficulty; electrostatic inertia in the DC network and the ability to reroute flows through new lines and toward gas provide damping and maneuverability in the face of fast variations or seasonal profiles. Operational: energy communities can build scenarios in which energy is shifted between vectors and time intervals, increasing resilience to disturbances and enabling more efficient use of existing infrastructure. Economic and climatic: blending hydrogen with methane reduces emissions without radical infrastructure changes, and the Sabatier reaction creates the premises for a near-circular CO_2 cycle. The choice between options depends on site topology and resources, equipment prices, regulation, and energy-price dynamics; these elements are presented in Section 2.4.4.

The contribution of the work crystallizes into several practical results: (i) explicit criteria for designing hybrid test networks (topology, zones and reconfigurations, alternative routes, placement of converters and definition of their roles); (ii) a protocol for the integrated QSTS–LF method—from data selection and implementation of control loops to robustness checks and theory-versus-simulation confrontations; (iii) a nuanced analysis of medium-voltage voltage regulation based on specific sensitivities, motivating the use of P control, Q control, or a combination thereof depending on topology and context; and (iv) a generic gas-network model interconnected with the electrical grid, capable of supporting techno-economic and resilience evaluations within a multi-vector logic.

Natural directions for continuation include validations, refinement of storage and transport models as a function of pressure/volume for the gas network, exploration of alternative conversion technologies, and the definition of integrated performance indicators for planning and operating multi-vector energy communities; integration of the heat vector; and identification of new scenarios where studying interconnection improves the resilience of future networks. Through these extensions, the proposed framework can facilitate the transition from simulation to pilot implementations and, subsequently, to model-assisted operation in interconnected hybrid AC/DC networks coupled with gas networks and beyond.

Contributions of the Thesis

In this thesis, building on the current state of research, original contributions were made to advance knowledge of hybrid medium-voltage networks. Chapter 1 reviews the existing literature to aggregate current knowledge on technologies for medium-voltage direct-current (MVDC) networks and on how equipment, applications, etc., established at high voltage (HV) can extend down to MVDC or even LVDC. These insights were tailored to anticipate the field's future needs and constitute **Contribution I** of the thesis.

As a natural continuation of the literature review, the need was identified to build a hybrid (AC and DC) medium-voltage test network that would enable complex analyses of the interaction between the AC grid and multiple DC grids. This network was developed starting from the classic IEEE-33 test grid: initially with a relatively small number of AC nodes and a DC link consisting of two nodes (converters) and one line, then increasing the number of nodes throughout Chapter 2, reaching 25 AC nodes and two DC networks—the first with four nodes (converters) and three lines, and the second with eight nodes (converters) and eight lines. This constitutes **Contribution II** of the thesis.

Using the hybrid test network, a modeling method was developed by integrating QSTS techniques with steady-state (load-flow) programs, employing evolution steps with periods

under 1 s. An approach was devised to describe a hybrid AC–DC network by highlighting elements specific to steady-state applications.

To this end, a requirements analysis and a systematization of the types of interaction objects between an AC node and a DC node were carried out so they can be readily represented and integrated into load-flow calculations—the basis of the QSTS-LF technique. The following objects were systematized: (a) an AC–DC converter with a voltage source (acting as an equilibrium node) on the DC side; (b) a DC–AC converter with added active- or reactive-power control on the AC side to regulate the nodal voltage at the converter's AC connection node, with Q-based voltage regulation emulating the function of a FACTS device of the STATCOM type. This constitutes **Contribution III**.

Through simulations on the hybrid network developed in the thesis, a comparative analysis was performed of voltage-level control in the medium-voltage AC network—either via active power P at the terminals of the converters coupled to the AC side, via reactive power Q supplied by a STATCOM (or equivalent) connected at the same node, or via a combination of both. Network tests using QSTS showed that the minimum losses in the chosen network are obtained with a combination of P and Q control at the regulating node, a solution that differs from current practical approaches based solely on Q control. This constitutes **Contribution IV** of the thesis.

In the QSTS simulations, specific automations and SCADA elements related to AC–DC interaction were integrated. Among the implemented automations, aspects of DC-grid "inertia" were highlighted, which slow the degradation of the DC-side voltage level. In this way, the dynamic evolution of hybrid AC–DC networks could be analyzed. This constitutes **Contribution V** of the thesis.

The various power variations studied included step and ramp variations, which are specific to electric vehicle charging stations and to distributed renewable producers, elements which are more and more present in MV grids. These elements have the potential to make significant to the operation of these grids. This represents **Contribution VI** of the thesis.

To extend the regulation concept into the DC network, a voltage-droop function was implemented that regulates output power as a function of terminal voltage. The function can be applied to a converter, a generator, or a storage unit. Similarly, it can also be implemented on the AC network, complementing the classic frequency-droop function. This is **Contribution VII** of the thesis.

Voltage-control concepts for multi-terminal DC networks were also analyzed as a combination of local droop-based control and a secondary control that improves voltage levels at critical nodes via more complex algorithms. Functional analyses of this mixed DC-voltage control were successfully carried out using the QSTS technique. This is **Contribution VIII** of the thesis.

Starting from the hybrid network and the usefulness of considering and analyzing multi-vector energy networks**,** a generic "Gas Valley" model was proposed. It provides a simplified description of the interaction between hybrid AC–DC networks and a generic gas-network model containing hydrogen, green methane, or a mixture of the two (described by a mixing parameter). The specific modeling requirements for this type of network were analyzed, and the interaction objects were systematized: the P2G converter and the G2P converter. This is **Contribution IX** of the thesis.

As a general contribution, the thesis demonstrated the applicability of QSTS techniques to analyzing the dynamic evolution of hybrid AC–DC medium-voltage networks, advancing

various modeling and control aspects that enable the study of such networks. This is **Contribution X**.

Finally, the thesis addressed a timely research topic on hybrid AC–DC medium-voltage networks which—by adding other energy vectors such as gas—helps consolidate the knowledge needed for their future modeling and implementation, for example in building complex, fully fledged energy communities. This joint approach—an MV hybrid AC–DC electric network interacting with a gas network (methane, hydrogen, or a combination thereof)—is considered **Contribution XI** of the thesis.