

Making DC Optimal Power Flow-Based Expansion Planning AC feasible: Application to Senegal

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Abstract—This article examines the physical feasibility of DC-OPF based solutions when applied to power system planning. Although widely used for its computational efficiency, the DC-OPF framework overlooks key constraints of the AC model, which can lead to solutions that are not operationally viable. To address these shortcomings, a rehabilitation methodology is developed to ensure the full feasibility of the solutions obtained. The proposed methodology is validated on a power grid representative of an emerging country, namely Senegal. Such power systems are characterized by rapid demand growth, a sparse grid, and limited automatic control devices, making feasibility issues particularly critical. The results demonstrate that explicitly accounting for AC feasibility significantly improves the robustness and practical applicability of the planning results.

Index Terms—AC feasibility, Direct Current Optimal Power Flow, Energy Transition, Planning Electrical System.

I. INTRODUCTION

Power system planning is a central issue to support the energy transition in developing countries. It aims to determine, at a lower cost, the necessary investments in generation and transmission in order to guarantee security of supply and the successful integration of renewable energies. Given the massive integration of renewable energies, it has become essential to explicitly integrate transmission grid models into overall planning models [1] [2]. The economic analysis often relies on DC-OPF, a simple and fast method for optimizing large-scale investments. However, its simplifying assumptions (small angles, neglected losses, constant voltage) may limit the technical validity of the results when compared to actual AC system operation. At the same time, AC Optimal Power Flow (ACOPF) provides a more accurate representation of electrical behavior, taking into account reactive flows, active losses, and voltage stresses. However, their numerical complexity limits their use for long-term planning. This study proposes an iterative methodology that combines DC-OPF with AC power flow analysis to validate and refine grid investment decisions, ensuring that they are compatible with the physical constraints of the grid and their feasibility under AC operating conditions. More specifically, this work proposes:

- a multi-period optimization framework based on DC-OPF to plan investments in generation, storage, and power grid reinforcement;

- an AC Power Flow validation step to assess the physical feasibility of power grid investments and identify discrepancies; and
- an AC - DC-OPF iterative loop designed to optimize investments in the power grid and ensure efficient management of reactive power flows in order to ensure the overall technical feasibility of the power system.

This hybrid approach improves the reliability of power grid planning by combining the computational efficiency of DC models with the precision of AC analysis. It demonstrates that the simplifications inherent in DC models are no longer appropriate, particularly when applied to emerging power grids, and highlights the need of physical validation in long-term planning. The power system of Senegal is considered as a case study in order to illustrate and validate the proposed methodology.

II. LITERATURE REVIEW

Historically, long-term power system planning has relied on DC Optimal Power Flow (DC-OPF) for its computational efficiency. However, this linearized framework, by neglecting losses, reactive power, and voltage variations, often yields economically "optimal" solutions that are physically unfeasible under AC constraints [3]. To manage renewable energy (RE) variability, the recent literature advocates for a multidimensional approach that integrates infrastructure coordination [1] [4], high temporal resolution for extreme weather events [5] [6] and spatial resolution to capture RE correlations and transport constraints [2]. The structural limitations of DC models are under increasing scrutiny. Studies demonstrate that neglecting losses can underestimate infrastructure needs by 15–25% [7], while the geometric distance between DC and AC feasibility regions highlights significant operational risks [8]. Furthermore, PyPSA-Eur platform developed by [9] has demonstrated the relevance of the DC-OPF for large-scale continental analyses, while highlighting the need for additional AC validation to ensure technical feasibility.

The question of the physical validity of DC investment decisions thus remains a major subject of research. The massive integration of renewable energy sources exacerbates these limitations. As shown [10], the decentralized nature of

renewables radically alters voltage profiles, making the DC-OPF constant magnitude approximation obsolete. In [11], the authors showed that the errors introduced by DC linearization increase with the grid load rate and penetration of renewable energy sources, compromising the relevance of the model in highly variable contexts.

This work highlights that, while the DC model remains a relevant tool for strategic planning, it becomes less reliable for operational use and for systems subject to significant voltage and reactive power constraints. The applicability of DC-OPF results depends on the power system context: in developed systems, which are typically dense and well controlled, DC approximations tend to be more reliable. However, in power systems of emerging countries, which are often weaker and subject to stronger voltage constraints, their accuracy may be reduced. This calls for more rigorous physical validation. The study proposes a method that combines DC-OPF and AC-PF within a feedback loop to account for physical constraints. Applied to the Senegalese power system, it improves investment decision-making and provides a reproducible framework for a similar power system.

III. METHODOLOGY

This approach is based on three main steps, as shown in Fig. 1: DC-OPF planning, AC analysis, and corrective feedback.

A. Step 1 - DC-OPF Optimization

The Senegalese power system is modeled in PyPSA as a multi-period investment optimization [12].

$$\min \sum_p \frac{1}{(1+\rho)^p} \left(\sum_{l,p} c_l F_{l,p} + \sum_{n,s} c_{n,s} \bar{g}_{n,s,p} + \sum_{n,r} c_{n,r} \bar{h}_{n,r,p} + \sum_{n,s} w_t \sum_{n,s} o_{n,s} g_{n,s,p,t} \right) \quad (1)$$

subject to:

$$\sum g_{n,s,p,t} + \sum h_{n,r,p,t} - \sum h_{n,r,p,t} f_{l,p,t} + \sum K_{n,l} = \sum d_{n,p,t} \quad (2)$$

$$\text{with: } f_{l,p,t} = \sum (BK^T)_{li} \theta_{i,p,t} \quad (3)$$

$$g_{n,s,p,t}^{\min} \bar{g}_{n,s,p} \leq g_{n,s,p,t} \leq g_{n,s,p,t}^{\max} \bar{g}_{n,s,p} \quad (4)$$

$$|f_{l,p,t}| \leq \alpha_l F_{l,p} \quad (5)$$

$$0 \leq h_{n,r,p,t}^+ \leq \bar{h}_{n,r,p,t} \quad (6)$$

$$0 \leq h_{n,r,p,t}^- \leq \bar{h}_{n,r,p,t} \quad (7)$$

$$0 \leq \text{soc}_{n,r,p,t} \leq H_{n,r} \bar{h}_{n,r,p,t} \quad (8)$$

$$\text{soc}_{n,r,p,t} = \eta_{\text{loss}} \text{soc}_{n,r,p,t-1} + w_t (\eta_{\text{ch}} h_{n,r,p,t}^- - \eta_{\text{dis}}^{-1} h_{n,r,p,t}^+) \quad (9)$$

The objective function (1) minimizes the total cost of the power system, including the discounted CAPEX of transmission lines ($c_l F_{l,p}$), generation units ($c_{n,s} \bar{g}_{n,s,p}$) and storage facilities ($c_{n,r} \bar{h}_{n,r,p}$), as well as the hourly OPEX ($o_{n,s} g_{n,s,p,t}$). Here, $\rho = 3\%$ is the discount rate for the investment periods (2030, 2035, 2040, 2045 and 2050), and w_t represents the weight of representative snapshots.

The model is subject to nodal power balance (2), where g , h , and d denote generation, storage dispatch, and demand at node n , respectively. Transmission flows $f_{l,p,t}$ are linearized in (3) using the susceptance matrix B , the incidence matrix K , and voltage angles θ . Operational constraints include generation limits (4), and thermal line capacities (5) adjusted by a security factor α_l . Storage dynamics (6)–(9) are governed by the state of charge (*soc*), the charging/discharging powers (h^-/h^+) and efficiency factors (η), ensuring temporal consistency across the horizons. To balance accuracy with computational complexity, the time dimension is reduced to 20 representative days per period [13]. This sample is augmented with extreme days (peak load, minimum demand, and maximum RE production) at an hourly resolution.

B. Step 2 - AC power flow analysis

1) *Formulation*: The transition from DC-OPF to AC Power Flow (AC-PF) makes it possible to verify the operational viability of planned investments. This stage extracts optimized capacities ($\bar{g}_{n,p}$, $\bar{h}_{n,p}$, $F_{l,p}$) and active power setpoints for generators ($g_{n,s,p,t}$), storage ($h_{n,r,p,t}$) and loads ($d_{n,p,t}$) from Step 1. While the DC model only considers reactance (X), the AC model incorporates resistance (R), transverse susceptance (B), and transformer parameters. Reactive power demand ($Q_{n,p,t}^{\text{load}}$) is introduced by assuming a constant power factor ($\cos \varphi = 0.9$) relative to active loads.

2) *AC feasibility criteria*: The system is considered AC feasible if the following criteria are met.

- Voltage Constraints: $0.95 \text{ p.u.} \leq V_n \leq 1.05 \text{ p.u.}$
- Thermal constraints of the lines: $I_{l,p,t} \leq I_{l,p}^{\max}$
- Generator capacity constraints:

$$0 \leq g_{n,s,p,t} \leq g_{n,s,p}^{\max} \quad (10)$$

$$Q_{n,s,p}^{\min} \leq q_{n,s,p,t} \leq Q_{n,s,p}^{\max} \quad (11)$$

A "Distributed Slack" approach is used, distributing the active and reactive power differences of the power system between production units in proportion to their nominal power [14]. Generators other than slacks are modeled by keeping their active power constant and setting a voltage setpoint. Storage units are integrated into the model with a constant power allocation over the time interval considered, acting as injector or absorber nodes depending on their state of charge.

C. Step 3 - Violation Remediation

1) *Remediation of Line Violations*: These violations reflect a mismatch between the distribution of active flows from the DC-OPF and the actual capacity of the network in AC mode, in particular due to losses and voltage-power coupling effects, thus proving insufficient investment in the lines concerned. The mitigation strategy relies on an iterative feedback loop consisting of:

- investment freezing: maintain generation and storage capacities at their DC-optimized levels;
- line derating: tighten constraints on critical branches by reducing the admissible flow coefficient α_l in (5).

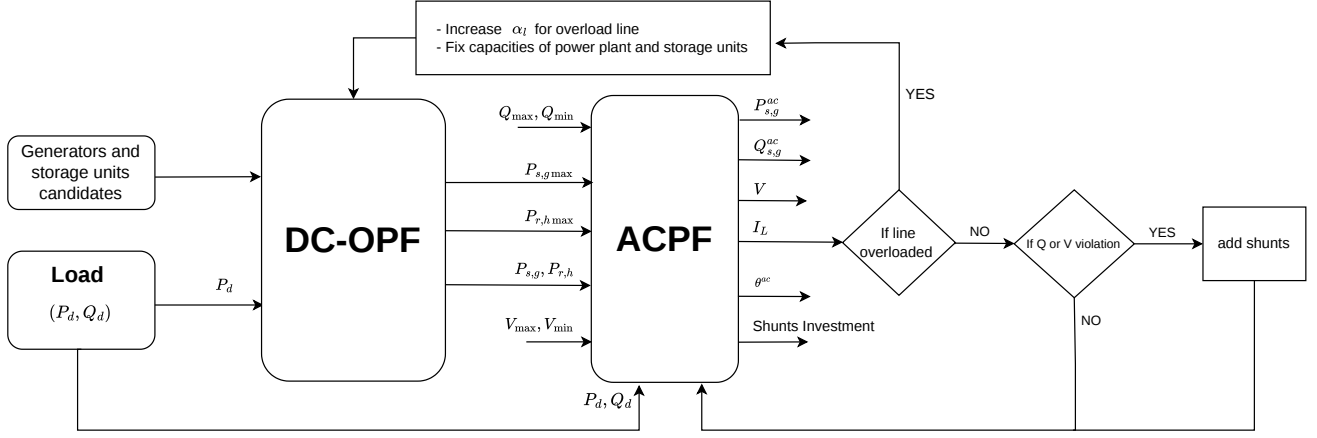


Fig. 1. Flow chart of the approach

The reduction in transit capacity acts as a penalization of congested corridors, forcing the model to invest more on these lines, and making it possible to anticipate AC constraints within the linearized framework of the DC-OPF. At the same time, some investments may be deemed irrelevant. In this work, these are the lines for which the DC-OPF proposes reinforcement, but whose maximum load rate remains below 30%. For these corridors, investment is ignored until it becomes relevant for the following years.

2) *Remediation of voltage violations and reactive power imbalances of generators:* Voltage and reactive power violations are assessed as indicators of local reactive imbalances. These discrepancies are typically driven by the capacitive effects of long-distance transmission, the reactive deficits of high-demand centers, and a systemic lack of localized voltage regulation resources. Reactive power limit violations are observed on slack buses, which compensate when generators reach their limits. The required compensation is determined for each investment year based on the maximum deviation between the required reactive dispatch and the admissible limits. Remediation of voltage violations is based on a heuristic approach. For each investment period, it is implemented by adding local compensation devices. Their sizing is proportional to the magnitude of the deviations and limited by a maximum capacity $Q_{\max}$:

$$Q_{sh,n,p} = \left(\frac{V_{n,p}^{\max} - 1.0}{V_p^{\max} - 1.0} \right) \times Q_{\max} \quad (12)$$

This method remediates violations without having a significant impact on the overall dispatch.

IV. RESULTS AND DISCUSSIONS

A. Analysis of DC-OPF results in the AC-FP analysis before correction

1) *Production investment:* The evolution of the energy mix and the associated investment trajectory are consolidated in Table I. To provide a transparent view of the grid's expansion, the values represent the total installed capacity per technology,

while the figures in parentheses specify the new capacity commissioned during each period. The DC-OPF model invests more in renewable energy in the first years of investment, investments in gas-fired power plants start in 2040. This evolution accounts for the decommissioning of existing plants.

TABLE I
EVOLUTION OF THE ENERGY MIX AND NEW INVESTMENTS (MW)

Technology	2030	2035	2040	2045	2050
Gas	1567 (-)	1537 (-)	1383 (70)	1610 (541)	1958 (677)
Solar	592 (544)	1049 (642)	1451 (595)	1794 (655)	2022 (404)
Wind	496 (369)	1137 (700)	1652 (562)	2030 (585)	2272 (264)
Hydro	442	442	442	442	442
Hfo	30	30	-	-	-
Diesel	50	-	-	-	-

2) *Analysis of Network Investments in AC Power Flow before remediation:* The investments in lines (Table II) are classified into 3 categories according to the AC power flow results:

- Relevant: when an investment is made and the line is more than 30% loaded but never overloaded,
- Irrelevant: when an investment is made when the load rate of the line's does not exceed 30% of its nominal capacity,
- Insufficient: when an investment is made or not, but the thermal limit of the line is anyway exceeded.

TABLE II
STATUS OF INVESTMENTS (NUMBER OF LINES)

Investment status	2030	2035	2040	2045	2050
Relevant	17	7	14	10	4
Irrelevant	2	1	0	2	2
Insufficient	0	3	3	5	4

Table II reveals the limitations of DC-OPF approach. "Irrelevant" investments reflect capital misallocation, while "Insufficient" cases from 2035 onwards confirm the inability of DC

models to anticipate thermal violations induced by reactive flows and AC losses. The proposed feedback loop rectifies these discrepancies by refining the grid expansion plan for both economic and physical viability.

3) *Voltage violations*: As illustrated in Fig. 2, overvoltages have been observed at several grid nodes. These violations are more pronounced in the southeastern region, primarily due to the capacitive charging of long and lightly loaded transmission lines.

Voltage Violation Analysis (Size – Violation Frequency)

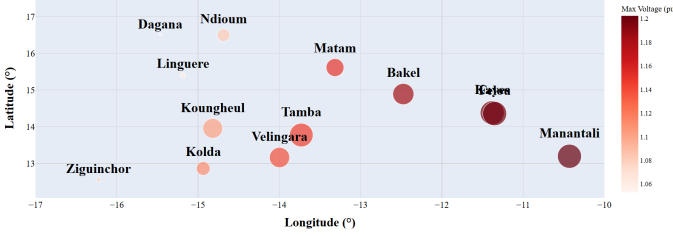


Fig. 2. Distribution of Voltage Violations across Investment Horizons

4) *Generator limits violations*: These violations are restricted to the reactive power capability limits of the IPP_Sendou and Gaz Mboro power plants. Specifically, they manifest as excessive reactive power absorption from the grid, while no active power violations have been observed. The use of a distributed slack allows the active power deficit to be better distributed across the grid, thus ensuring demand is met and transmission losses are compensated. Table III reports the statistics of these violations.

TABLE III
REACTIVE POWER VIOLATION STATISTICS OF PRODUCTION UNITS
(PERCENTAGE OF SIMULATED TIME STEPS)

Generators	2030	2035	2040	2045	2050
Gaz_Mboro	0, 0%	0, 0%	0, 0%	18, 2%	18, 8%
IPP_Sendou	69, 9%	45, 8%	9, 28%	0, 0%	0, 0%

5) *Calculation of Violation Indices*: The following metrics are defined to assess the AC feasibility of DC-OPF expansion results. The Voltage Violation Index (VVI) measures the proportion of nodes in the power grid with voltage violations.

$$VVI_{rate} = \frac{1}{N_b} \sum_{i=1}^{N_b} 1 (V_i < V_i^{\min} \text{ or } V_i > V_i^{\max}) \quad (13)$$

The Line Loading Violation Index (LLVI) evaluates the proportion of lines whose current exceeds the permissible limit.

$$LLVI_{rate} = \frac{1}{N_l} \sum_{l=1}^{N_l} 1 (I_l > I_l^{\max}) \quad (14)$$

The Generator Reactive Violation Index (GRVI) quantifies the number of generators subject to reactive power stresses.

$$GRVI = \frac{1}{N_g} \sum_{g=1}^{N_g} 1 (Q_g \leq Q_g^{\min} \text{ or } Q_g \geq Q_g^{\max}) \quad (15)$$

The AC Infeasibility Rate (ACIR) quantifies the proportion of snapshots where the DC-OPF solution fails to satisfy AC power flow requirements. The solution is considered non-feasible if at least one violation is observed in AC power flow.

$$ACIR = \frac{1}{N_t} \sum_{t=1}^{N_t} 1 \text{ if (snapshot } t \text{ infeasible)} \quad (16)$$

These indices are recorded in Table IV. The low level of

TABLE IV
VIOLATION INDICES

Year	VVI _{rate}	LLVI _{rate}	GRVI _{rate}	ACIR
2030	7.86%	0.00%	0.26%	100%
2035	4.53%	0.04%	0.17%	100%
2040	1.09%	0.95%	0.03%	90%
2045	0.75%	1.07%	0.07%	85%
2050	0.52%	1.05%	0.07%	78%

the VVI, LLVI and GRVI indices indicate that violations affect a limited subset of the total infrastructure (nodes, lines, and generators). However, results demonstrate that DC-OPF solutions are infeasible under AC evaluation for 2030 and 2035, primarily due to voltage violations. Over time, these voltage issues decrease and thermal constraints become the dominant limiting factor from 2040 onwards. Even in 2050, a significant portion of operating points remains infeasible (AIR $\approx 78\%$), highlighting the limitations of DC approximations for long-term planning.

V. AC POWER FLOW AFTER CORRECTION

A. Network investment

Table V demonstrates that the retroactive approach leads to either a reduction in investment requirements (e.g., in 2030 and 2045) or upward adjustments (e.g., in 2035 and 2050), depending on the planning horizon. These variations reflect a consideration of the physical realities of the power grid. In 2040, the impact is neutral, as the identified reinforcement needs were already taken into account in previous years. Thus, beyond the respect of operational constraints, the proposed approach makes it possible to achieve a more robust, technically feasible, and better-optimized power grid expansion plan.

TABLE V
INVESTMENT IN THE POWER GRID (KM OF LINES)

Year	2030	2035	2040	2045	2050
Before correction	420	417	527	449	307
After correction	392	445	527	351	383
Cost variation	-2.6%	2.6%	0.0%	-24.2%	2.1%

B. Investment in shunts

1) *Compensation Requirements for Reactive Regulation*: The iterative AC-PF/DC-OPF loop modified the initial generator violations, the evolution of which is summarized in

TABLE VI
Q VIOLATION RATE BREAKDOWN

Generators	2030	2045	2050
Gaz_Mboro	0%	6, 81%	0, 36%
IPP_Sendou	23%	0%	0%
C_CCGT_BelAir_2045	0%	15, 2%	0%
C_CCGT_CapDesBiches_2050	0%	0%	5, 25%

Table VI. A total absence of violations for the 2035 and 2040 horizons is observed. This demonstrates the effectiveness of the stabilization process, which reinforces the AC feasibility of solutions from the DC-OPF model. The expansion plan optimization led the power plants IPP_Sendou in 2030 and Gaz Mboro in 2050 to reverse their reactive power regime, transitioning from absorption to production. This structural shift resulted from the removal of redundant underground line investments. Table VII presents compensation needs.

TABLE VII
REACTIVE COMPENSATION REQUIREMENTS (MVAR) FOR Q VIOLATIONS

Generators	2030	2045	2050
Gaz_Mboro	0	50.30	-11.76
IPP_Sendou	-18.22	0	0
C_CCGT_BelAir_2045	0	29.77	0
C_CCGT_CapDesBiches_2050	0	0	27.99

2) *Required reactive compensation for voltage regulation:* The needs are presented in Table VIII, No investment is required for 2050, during which no voltage violations are observed.

TABLE VIII
REACTIVE COMPENSATION REQUIREMENTS (MVAR) FOR V VIOLATIONS

Year	2030	2035	2040	2045
Total shunt	168.32	135.56	117.61	76.37

VI. CONCLUSION

This work presents a robust methodology to assess the feasibility of DC-OPF solutions within an AC power flow framework. Beyond the simple observation of differences between models, this study proposes a methodology to adapt optimization solutions for technical feasibility in real-world operations. This approach is particularly critical for grid management in developing power systems where automated control infrastructure is limited, rendering the management of reactive power flows especially sensitive to planning inaccuracies. The simulations reveal critical levels of infeasibility when transitioning to the AC framework, quantified specifically through the ACIR index. Systematic re-evaluation of the development plans indicates a tendency to overestimate structural requirements: several grid investments identified by the DC-OPF proved to be useless or premature. Consequently, this analysis enables

the optimization of the investment schedule, ensuring that every grid expansion addresses a verified technical requirement under steady-state operating conditions. On the other hand, it highlights investment needs that are not captured by the DC-OPF solution. This enables the establishment of a feedback loop that supports the iterative adjustment of the expansion plan, thereby ensuring compliance with physical constraints. In addition, the integration of reactive power flows in this method gives a complete picture of technical feasibility. This not only helps to stabilize the voltage profile and prevent generation units from operating beyond their permissible reactive power limits, but also enables an estimate of the reactive power compensation requirements. This work establishes the foundation for a multi-scale planning framework capable of leveraging physical constraints as drivers for optimization. A future perspective involves formulating Gas-to-Power flexibility within the specific context of Senegal's energy transition.

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