# Line Management in the Energy Packet Grid

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## ABSTRACT

This article introduces the innovative concept of Line Management (LM) in Energy Packet Grids (EP grids), an approach that aims to address the challenges posed by the increasing deployment of renewable energy technologies in the power grid driven by power electronics. The traditional power grid, originally designed with a top-down architecture, faces new complexities due to the distributed, bottom-up, and intermittent nature of renewable energy generation. The article explores the concept of the Energy Packet Grid, which segments the power grid into EP cells and manages power flows in discrete packets. Central to this system is the Line Manager, a software component critical to managing the transport capacity of transmission lines by orchestrating the transfer of energy packets. The paper outlines the architecture and functional aspects of the Line Manager, emphasizing its role in ensuring a stable operation of future power grids. It also discusses various methodologies for grid state calculations, including current, power, and mixed-mode transfers. The effectiveness of different calculation methods is evaluated, highlighting the importance of accurate and timely decision-making in grid management. Overall, the results contribute to ongoing research in congestion management and present a detailed description of the Line Manager concept and implementation in the context of EP grids.

## CCS CONCEPTS

• **Hardware** → **Power networks**; **Smart grid**; • **Applied computing** → *Physical sciences and engineering*.

## KEYWORDS

Line Management, Energy Packet Grid, Congestion Management, Grid State Calculation, Energy Internet

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## 1 INTRODUCTION

The increasing deployment of renewable energy technology, characterized by its $CO_2$-neutral, sustainable, and cost-effective nature, is fundamentally transforming the power grid. The rise of distributed energy resources (DER) has led to a more decentralized grid structure in terms of power generation. However, this transformation presents significant challenges. Traditional grids, designed with a top-down architecture primarily focused on the transmission system level, are now faced with the volatile and unpredictable nature

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of power supply from renewable sources [3, 11]. This volatility requires the development of flexible loads to match grid demand with the actual supply. In addition, there is a growing energy demand due to the electrification of the mobility and heating sectors [6].

One of the critical challenges in this evolving landscape is the increased probability of exceeding operational limits of electrical resources, a major concern for future grid reliability [1]. This scenario, known as grid congestion, can lead to power outages and significantly impact the grid's performance. In this context, congestion management becomes a vital area of research and practice, aimed at ensuring the economical, secure, and stable operation of power grids [13, 16, 18].

Congestion management methods typically fall into two categories: market-based or technical approaches. Market-based methods use price signals or contracts instead of direct orders to influence the behavior of flexible demand. The methods include: day-ahead dynamic tariffs, distribution capacity market, intra-day shadow price and flexibility service market [9]. In contrast, technical approaches propose traditional optimization methods for grid congestion management, suggesting algorithms to improve performance, reduce system losses, and increase system stability by controlling power flows [2].

For the application of technical management methods in the distribution grid, especially low voltage grids, it is an additional challenge to estimate the grid state of a system with low penetration of measurement and monitoring devices. There are many emerging approaches for state estimation using both conventional and machine learning methods, [5] presents recent research efforts and identifies the integration of demand response methods and optimal power management as underexplored fields in this research area. At the same time, recent research on congestion management methods seldomly address the availability of measurement data in the presented approaches. Tomar et al. [22] give an overview of technical and market based, or in their phrasing direct and indirect methods, and structure the technical methods based on the chosen control effort, separated into topology reconfiguration, reactive power control and active power control. Within their presented collection, a range of works such as [7, 8, 15] do not explicitly deal with the power flow over the transmission lines, instead focussing on the limits of other components or balancing the power based on provided voltages at the feed-in points. Of the works, that include load flow calculations into their congestion management methods, only some, e.g. [10, 25], include a system for the communication and measurement of relevant information, indicating that the structured gathering and communication of data stays a relevant, sparsely addressed topic in congestion management.

The energy packet grid proposed by the authors in [19], based on the initial foundation for understanding EP grids laid out in [4, 12, 24], addresses the aforementioned issues of future power systems by dividing the power system into cells and splitting the power flows into chunks called energy packets. In [19], the authors establish and implement a communication protocol, the Simple EP Transfer Protocol (SEPT), as an efficient method to exchange energy packets in a decentralized grid. In the subsequent contributions [20] and [21], energy transfers using the SEPT protocol are shown in hardware realizations both as single transfer, as well as a more complex power flow pattern.

This article introduces the concept of Line Management as an active controlling functionality in EP grids. With online power flow calculations, the Line Manager prevents transmission line overloading and introduces congestion management into the EP grids. In combination with the EP device management, introduced in [23], it allows the EP grid as a whole to manage both line capacity of the grid and energy capacity of single devices in a decentralized manner.

Overall, this contribution outlines the architecture, functionality, and implementation of the Line Manager, emphasizing its role in stabilizing of EP Grids. In the following Secs. 2 and 3, the EP grid and the role of Line Management within it are discussed. The implementation of grid state calculation methods for different EP transfer modes are expanded on in Secs. 4 and 5. Sec. 6 provides a detailed evaluation of the different solving methods regarding their degree of accuracy and their computation time based on exemplary topologies.

## 2 ENERGY PACKET GRID

The EP grid as a methodology for managing electric grids outlined in this publication is founded on the detailed concept initially proposed by anonymous et al. [19]. This involves partitioning the electric grid into smaller subnetworks called EP cells. These are separate and self organized grids. Each EP cell can have different electrical parameters like current type, voltage level, frequency etc. Participants in the EP grid access the grid with an EP device. These power electronic devices have multiple energy interfaces and communication interfaces. With the different energy interfaces the devices are connected to different grids. E.g. an EP device in a household will use one energy interface to participate in the EP grid and another interface to build up the grid for the household itself. Similar to routers in the internet EP devices can also connect multiple EP cells. An overview of the resulting grid architecture is shown in fig. 1.

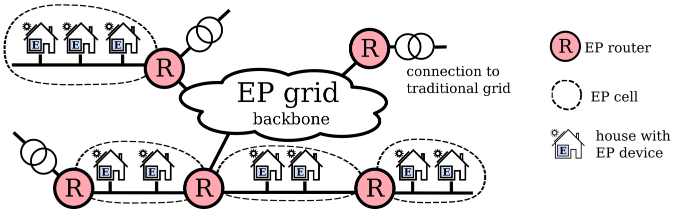

**Figure 1: Example EP-Grid consisting of several EP cells [19].**

Each EP device has one of the two roles: current controller or voltage controller. From an electric point of view depending on this role the EP device either acts as a voltage source or as a current source. An EP device in the voltage controller role is required at least once in every EP grid to provide the grid-forming voltage. Within the EP grid the EP devices exchange energy packets (EP). An EP is a timed power flow between two pre-negotiated EP devices in which a certain amount of energy is exchanged. Depending on the transfer mode the two EP devices are either controlled by power setpoints or by current setpoints. Fig. 2 shows an trapezoidal EP where $y(t)$ either stands for current or power. The packet starts with a ramp up phase where the setpoint increases to its desired value. This is followed by a constant phase where the setpoint does not change. At the end there is a ramp down phase during which the setpoint decreases back to zero.

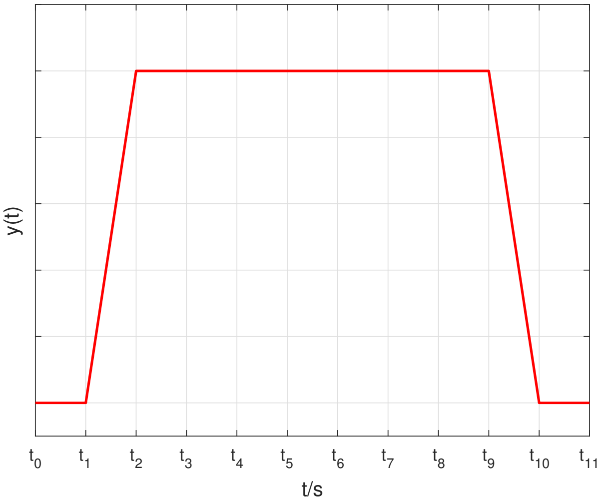

**Figure 2: Exemplary EP with trapezoidal shape.**

Within the same EP cell, two EP devices negotiate the transfer mode and the parameters of an EP with the simple EP transfer protocol (SEPT) [19]. Therefore the communication interfaces of the EP devices are used to send and receive SEPT messages. SEPT is also used to signalize the start of the EP transfer.

## 3 LINE MANAGER

The Line Manager is a software component[1], which is involved in each packet negotiation via the Simple EP Transfer Protocol (SEPT). Its task is to allow or deny requested EP transfers based on their influence on the EP cell, e.g., when line capacity is exceeded or a voltage boundary is reached. This is a major task because the resulting flow distribution in grids transmission lines follows physical principles and in most cases will not correspond exactly to the power flows defined by the EPs. Consider two EP transfers sharing some transmission line segment but with opposite flow direction. In this case, there will be physical power flows from the senders of the EP transfers to each others receiver (shortest path) and only the difference of the power flows will be transferred over the shared transmission line segment. Furthermore, depending on the transfer mode, there can exist additional power flows from or to voltage controllers, compensating for the power losses of the transmission lines. Thus, the Line Manager has to calculate the state of the grid, meaning the physical distribution of the EP transfers, to decide about the acceptance of a requested EP transfer. Calculating the grid state requires knowledge about the grids topology, the impedance of the line segments, and all ongoing EP transfers. Typically, the topology of the grid is known. The line segment impedance is derivable by the cable type and length.

Since each transfer is orchestrated and there is no other activity in the grid, the Line Manager knows the occurrence of state transitions in the grid. As a consequence, there is no need for a continuous simulation of the grid. To fulfill its task, the Line Manager can identify relevant time points and only calculate the grid state at these time points.

The Line Manager's task, therefore, can be divided into two subtasks:

- identifying relevant time points
- grid state calculation

In the following, these two tasks are analytically illustrated, and potential methodologies for their realization are discussed.

## 4 IDENTIFYING RELEVANT TIME POINTS

Whenever a setpoint of an EP device changes, a grid state change is initiated in the EP cell. These state changes are particularly significant during the ramp phases of an EP, where the setpoint changes continuously. Despite the potential complexity introduced by these continuous changes, the process is inherently monotonic when isolated to a single EP transfer. This monotonic nature simplifies the LM's task to a significant degree, allowing for a massive reduction in the number of time points that must be considered to avoid limit violations.

### 4.1 Simplifying Time Point Analysis through monotony criterion

The key finding in dealing with changes in grid state is that the constant phase phase of an EP device's operation is of highest importance. During this phase, the EP device reaches its maximum setpoint following a monotonic ramping process. Remarkably, at the end of an EP transfer, the grid returns to its initial state as the setpoint decreases to zero during the ramp down phase, eliminating the need for additional limit checks at the end of the transfer. This understanding allows the LM to streamline the decision making process by focusing solely on whether a grid limit is exceeded during the constant phase.

### 4.2 Monotonic transition processes

The complexity of the LM decision increases with the introduction of overlapping EP transfers. Through the visualization of overlapping trapezoidal EPs, cf. Fig. 3, it becomes evident that even in scenarios with overlapping ramp phases, the identification of relevant time points can be managed with the same logic as before. It can be seen that the grid state becomes steady at $t_1, t_6, t_9, t_{10}, t_{11}$. In between there are transition processes introduced by the ramp phases of the EPs. Because there is no overlap of the ramp phases, each of the transition processes is monotonic. As before this implies that for the Line Manager only the time points at steady state are relevant to decide whether any grid limit is exceeded.

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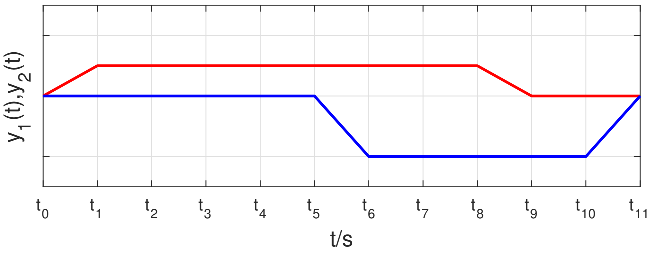
[1] The source code is published under https://github.com/KIT-IAI/Line-Management-EPGrid



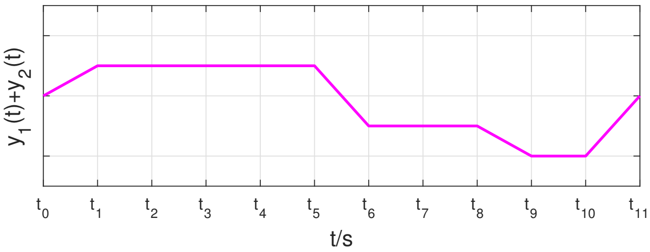
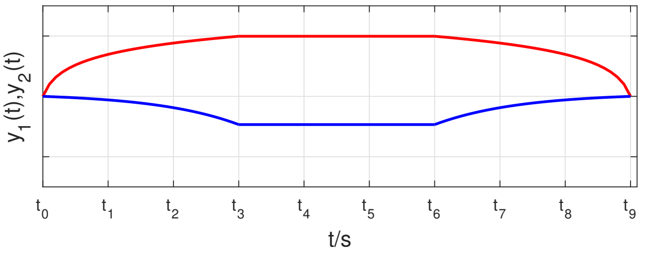


**Figure 3: Example of overlapping trapezoidal EPs.**

### 4.3 Non-monotonic transition processes

More complex scenarios arise when two EP transfers have an overlap in their ramp phases, see Fig. 4. This applies in particular to EPs with non-linear ramp phases. In such cases, the potential for non-monotonic changes in the grid state requires a detailed analysis with high time resolution. This ensures that all potential extremum in the grid state that could lead to a limit violation are detected and treated. However, for EPs of trapezoidal shape – as envisioned by the concept – the analysis can be simplified by focusing only on the start and end points of the ramp phases.



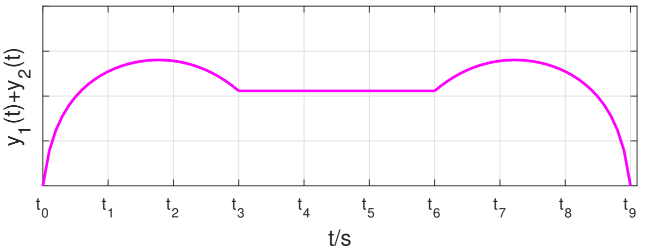


**Figure 4: Example of two EPs with overlapping ramp phases.**

### 4.4 Takeaways for a Line Manager

In summary, three conclusions for identifying relevant time points can be drawn:

1. The LM must always consider the start of the constant phase of an EP because at this point the EP itself reaches its maximum setpoint.
2. Within the duration of a requested EP all previously tagged relevant time points have to be recalculated and evaluated.
3. For overlapping ramp phases the LM has to calculate each time point during the overlapping period of the ramp phases. With only trapezoidal shapes, this can be reduced to calculating the grid state at the start and the end of the ramp phases during the overlapping period.

## 5 GRID STATE CALCULATION

A basic grid model is used to illustrate the calculations and formulas for grid condition analysis. The primary focus of this article is on DC grids, but the formulas presented are also applicable to AC grids, provided there are no unbalanced loads. Fig. 5 shows the circuit model of a simplified grid, featuring three EP devices. EP devices in the EP grid can be modeled as voltage sources or current sources depending on their role which is either voltage controller or the current controller. The transmission line segments in between are modeled as resistors. Since the line inductance of cables used in residential areas is usually relatively small compared to the resistance, the inductance can be neglected for a first approximation. The resulting current transitions caused by the relatively low inductance are therefore of short duration and can also be neglected in the context of the line manager. The resistances $R_{Sx}$ model the common segments of the low-voltage cable. The resistances $R_x$ model the resistance of the individual connection cables that connect the individual households to the common cable.

For simplicity, but without loss of generality for symmetric three-phase systems, in this example the forward and return conductor resistances are combined and modeled in the feed line from the source to the sink. This approach results in varying potentials at the model's junction points, in contrast to a scenario where all resistances are modeled separately. Nonetheless, this simplification does not impact the overall voltage and current in each branch, nor does it affect the voltage and current of each source. While the potentials at the nodes are altered, the resultant potential differences remain unchanged.

In order to make a decision regarding the approval of a proposed EP transfer, the Line Manager must evaluate two key electrical parameters: the current flowing through each segment of the transmission line and the voltage drop occurring across each source. The presented model is suitable in this context. Furthermore the model has reduced complexity and needs less node potentials which results in smaller computation effort.

In the following the grid state calculation based on the shown model is explained. The parts are subdivided into the three different EP transfer modes: current-, power- and mixed-mode.

### 5.1 Current-mode

In the current-mode operation, each current controller is assigned a current setpoint for packet transfer. Determining the grid state

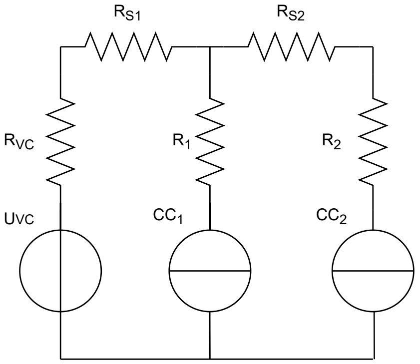


**Figure 5: Example EP grid circuit diagram.**

in this context is a fundamental task, typically addressed through nodal analysis. This involves transforming the model’s voltage source into an equivalent current source, as depicted in Fig. 6. Eq. (1) shows the resulting equation system with the admittance matrix $A$, the node potential vector $\vec{x}$ and the current vector $\vec{b}$, which holds the current setpoint of each controller. Note that node potential $v_2$ mathematically would not be needed in the equation system, but it unifies the representation of every EP device in the equation system and avoids adding any exceptions for the last EP device in a grid.

Computing the grid state in this mode requires solving the linear equation system. The admittance matrix remains constant as long as the grid topology does not change, allowing for efficiencies such as computing the lower-upper (LU) decomposition of the admittance matrix just once. Subsequent grid state calculations can then use this decomposition, significantly accelerating computation. The direct solution of electrical equations in this mode ensures accuracy in the results.

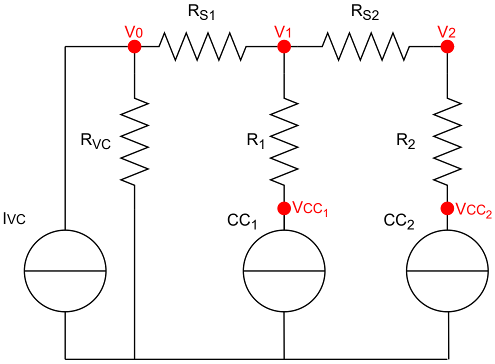


**Figure 6: Circuit diagram with equivalent current source**

$$A\vec{x} = \vec{b} \tag{1}$$

$$A = \begin{bmatrix} G_{VC}+G_{S1} & -G_{S1} & 0 & 0 & 0 \\ -G_{S1} & G_{S1}+G_1+G_{S2} & -G_{S2} & -G_1 & 0 \\ 0 & -G_{S2} & G_{S2}+G_2 & 0 & -G_2 \\ 0 & -G_1 & 0 & G_1 & 0 \\ 0 & 0 & -G_2 & 0 & G_2 \end{bmatrix}$$

$$\vec{x} = \begin{bmatrix} V_0 \\ V_1 \\ V_2 \\ V_{CC_1} \\ V_{CC_2} \end{bmatrix}, \vec{b} = \begin{bmatrix} U_{VC}/R_{VC} \\ 0 \\ 0 \\ I_{CC_1} \\ I_{CC_2} \end{bmatrix}$$

## 5.2 Power-mode

In the power-mode operation, each current controller is assigned a power setpoint for packet transfer. Therefore grid state calculation needs a power setpoint based equation system. This can be achieved by replacing the controller currents $I_{CC_x}$ of the current mode equation system based on the power equation $I_{CC_x} = P_{CC_x}/V_{CC_x}$. This results in equation system eq. (2) with current vector $\vec{b}_P$. This system is still based on nodal analysis and vector $\vec{b}_P$ is still a current vector but the definition is based on power setpoints now.

$$A\vec{x} = \vec{b}_P \tag{2}$$

$$\vec{b}_P = \begin{bmatrix} U_{VC}/R_{VC} \\ 0 \\ 0 \\ P_{CC_1}/V_{CC_1} \\ P_{CC_2}/V_{CC_2} \end{bmatrix}$$

Given the denominators $V_{CC_x}$, the power-based equations are quadratic in nature. For an EP grid with $N$ current controllers and accordingly $N$ power setpoints, the solution set for the equation system encompasses $2^N$ elements. This makes solving the equation system computationally intensive. For the Line Manager with its time constraints this motivates the need of a solving method with some kind of linearization to reduce the necessary computation time. Subsequently, three methods are discussed: current working point (COP), Newton’s method and Fast Linear Power Flow (FLPF).

### 5.2.1 *Current operating point (COP).*

Especially with the serial resistance being quite low it is possible to roughly estimate the voltage of every current controller. This operating point voltage $V_{CC_x}\big|_{OP}$ can either be set to the grids nominal voltage or to the current controllers voltage in the previous grid state if already calculated. Based on this operating point voltages the current operating point of each current controller can be calculated. The resulting operating point current vector $\vec{b}_P\big|_{OP}$ is shown in Eq. (3).

$$\vec{b}_P\big|_{OP} = \begin{bmatrix} U_{VC}/R_{VC} \\ 0 \\ 0 \\ P_{CC_1}/V_{CC_1}\big|_{OP} \\ P_{CC_2}/V_{CC_2}\big|_{OP} \end{bmatrix} = \begin{bmatrix} U_{VC}/R_{VC} \\ 0 \\ 0 \\ I_{CC_1}\big|_{OP} \\ I_{CC_2}\big|_{OP} \end{bmatrix} \tag{3}$$

Using the operating point currents the equation system is linear again and can can be solved. After solving the equation system the calculated voltages can be set as new operating point voltages to successively approximate the solution. Like in current-mode solving the admittance matrix stays the same for unchanged topology allowing faster computation based on matrix decomposition.

### 5.2.2 *Newton’s method.*

Alternatively, the Newton’s method can be used for an iterative approximation of the power based equation systems solution. Eq. (4) and (5) show the general formulas of Newton's method.

$$f'(x_i) \cdot \Delta x_{i+1} = -f(x_i) \tag{4}$$

$$x_{i+1} = x_i + \Delta x_{i+1} \tag{5}$$

For grid state calculation the function $f(x)$ is defined in Eq. (6), which is just another representation of the already shown power-mode equation system, cf. Eq. (2). Note that in this form the mentioned quadratic behavior of the terms can be seen directly. There are linear functions defined by the potentials $V_x$ in the grid and quadratic functions defined by the current source potentials $V_{CC_x}$.

$$f(x) = \begin{pmatrix} (G_{VC}+G_{S1})V_0 - G_{S1}V_1 - U_{VC}/R_{VC} \\ -G_{S1}V_0 + (G_{S1}+G_1+G_{S2})V_1 - G_{S2}V_2 - G_1V_{CC_1} \\ -G_{S2}V_1 + (G_{S2}+G_2)V_2 - G_2V_{CC_2} \\ G_1V_{CC_1}^2 - G_1V_{CC_1}V_1 - P_{CC_1} \\ G_2V_{CC_2}^2 - G_2V_{CC_2}V_2 - P_{CC_2} \end{pmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

Newton's method requires the derivative $f'(x)$ of the function which is a Jacobian matrix. Looking at the linear functions of Eq. (6) it can be seen that the partial derivations of these functions result in the prefactors of the individual voltages, which are defined in the admittance matrix $A$. So the row of the Jacobian matrix for potentials $V_x$ are identical to the corresponding rows of the admittance matrix itself. For the quadratic functions this changes. The generalized representation of the quadratic functions is shown in Eq. (7). It can be seen, that except derivation by $V_{CC_x}$ and $V_x$ all other partial derivations are zero. Derivation by $V_{CC_x}$ leads to Eq. (8) and derivation by $V_x$ leads to Eq. (9). The resulting jacobian matrix for $f'(x)$ of the example model is shown in Eq. (10). With the generalized definition of the entries of the Jacobian matrix the line Manager can directly calculate each entry of the matrix or copy them from the admittance matrix and does not need to calculate any deviation.

$$G_xV_{CC_x}^2 - G_xV_{CC_x}V_x - P_{CC_x} \tag{7}$$

$$\frac{\mathrm{d}}{\mathrm{d}V_{CC_x}} G_xV_{CC_x}^2 - G_xV_{CC_x}V_x - P_{CC_x} = 2G_xV_{CC_x} - G_xV_x \tag{8}$$

$$\frac{\mathrm{d}}{\mathrm{d}V_x} G_xV_{CC_x}^2 - G_xV_{CC_x}V_x - P_{CC_x} = -G_xV_{CC_x} \tag{9}$$

$$J_f(x) = \begin{bmatrix} G_{VC}+G_{S1} & -G_{S1} & 0 & 0 & 0 \\ -G_{S1} & G_{S1}+G_1+G_{S2} & -G_{S2} & -G_1 & 0 \\ 0 & -G_{S2} & G_{S2}+G_2 & 0 & -G_2 \\ 0 & -G_1V_{CC_1} & 0 & 2G_1V_{CC_1}-G_1V1 & 0 \\ 0 & 0 & -G_2V_{CC_2} & 0 & 2G_2V_{CC_2}-G_2V_2 \end{bmatrix} \tag{10}$$

Newton's method needs to solve a linear equation system with the Jacobian matrix holding the linear equations for each iteration. Because the Jacobian matrix changes with every iteration this does not allow matrix decomposition for improved computation time.

5.2.3 *Fast linear Power Flow (FLPF) [26].* In contrast to the two other methods FLPF is not an iterative method. It always requires solving of two linear equation systems. One for calculating a linearized solution and one for an error correction of the solution. FLPF uses the already shown power equations, cf. Eq. 2, but expresses the voltages as deviation from the nominal grid voltage, cf. Eq. 11. This splits up the voltage into several terms which allows neglecting the high order part for linearization purpose. The resulting linear equation system is shown in Eq. 12. In difference to the power equations the voltage vector $\vec{x}$ is replaced by the voltage deviation vector $\tilde{x}$.

$$\vec{x} = \vec{V} + \tilde{x} = \vec{V} + \begin{bmatrix} \Delta V_0 \\ \Delta V_1 \\ \Delta V_2 \\ \Delta V_{CC_1} \\ \Delta V_{CC_2} \end{bmatrix} \tag{11}$$

$$A\tilde{x}_0 = \frac{1}{V^2}\vec{b}_p \tag{12}$$

The error $o^2(\Delta\tilde{x}_0)$ of the linearized solution is calculated by Eq. 13. Eq. 14 shows the second linear equation system which is solved to gain the more precise solution $\Delta\tilde{x}_1$.

$$\sigma^2(\tilde{x}_0) = \vec{b}_p - A\tilde{x}_0 \tag{13}$$

$$A\tilde{x}_1 = \vec{b}_p - \sigma^2(\tilde{x}_0) \tag{14}$$

Both systems of linear equations utilize the admittance matrix, enhancing computational efficiency through matrix decomposition. Moreover, computing the grid state for the same grid should consistently take the same amount of time, as it involves solving two linear and comparable equation systems. This is in contrast to iterative methods, where the computation time varies based on the number of iterations required.

## 5.3 Mixed-mode

In mixed-mode operation, one current controller is assigned a current setpoint $I_{CC_x}$, while the other operates with a power setpoint $P_{CC_y}$. This necessitates the use of solving methods capable of handling both current and power setpoints. Among the methods discussed, only COP and Newton's method meet these criteria. The subsequent section details how these two solving methods can be adapted to incorporate current setpoints.

5.3.1 *COP.* Using this method, the initial step is the calculation of the current operating point derived from power setpoints, followed by a transition to current-based equations. This process straightforwardly allows the integration of additional current setpoints. Eq. 15 shows how the current setpoints can be added to the solution vector $\vec{b}_P\big|_{OP}$.

$$\vec{b}_P\big|_{OP} = \begin{bmatrix} U_{VC}/R_{VC} \\ 0 \\ 0 \\ P_{CC_1}/V_{CC_1}\big|_{OP} + I_{CC_1} \\ P_{CC_2}/V_{CC_2}\big|_{OP} + I_{CC_2} \end{bmatrix} \tag{15}$$

It can also be seen, that with COP an EP device can have a current

**Table 1: Comparison of the different solving methods.**

| | Nodal | Newton | COP | FLPF |
|---|---|---|---|---|
| **Constant matrix for decomposition** | ✓ | × | ✓ | ✓ |
| **Linear equation systems to solve per iteration** | 1 | 1 | 1 | 2 |
| **Iterative method** | × | ✓ | ✓ | × |
| **Current mode** | ✓ | ✓ | ✓ | × |
| **Power mode** | × | ✓ | ✓ | ✓ |
| **Mixed mode** | × | ✓ | ✓ | × |
| **Different transfer modes on EP device level** | × | × | ✓ | × |

setpoint and a power setpoint at the same time, which allows simultaneous EP transfers of different transfer modes on single device level.

*5.3.2 Newton's method.* The equation system $f(x)$ of Newton's method contains quadratic functions defined by power setpoints and linear functions defined by currents of the grid. It is possible to select a power setpoint based function or a current setpoint based function for each current controller. Eq. 16 shows the equation system where the power setpoint of current controller $CC_2$ is changed to a current setpoint. This allows using Newton's method for calculating the grid state for mixed mode EP transfers. The previously described rules for calculating the jacobian matrix stay the same. But, as it can bee seen, it is impossible to define a current setpoint and a power setpoint for a single EP device at the same time.

$$f(x) = \begin{pmatrix} (G_{VC}+G_{S1})V_0-G_{S1}V_1-U_{VC}/R_{VC} \\ -G_{S1}V_0+(G_{S1}+G_1+G_{S2})V_1-G_{S2}V_2-G_1V_{CC_1} \\ -G_{S2}V_1+(G_{S2}+G_2)V_2-G_2V_{CC_2} \\ G_1V_{CC_1}^2-G_1V_{CC_1}V_1 \\ G_2V_{CC_2}-G_2V_2 \end{pmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ P_{CC_1} \\ I_{CC_2} \end{bmatrix} \tag{16}$$

## 5.4 Comparative analysis of solving methods

Comparing the solving methods using Tab. 1, it becomes clear that there are two specific methods, Nodal and FLPF, designed to compute the grid state exclusively in either current mode transfers or power mode transfers. Since these methods are non-iterative, they are expected to maintain a relatively constant computation time for each network state calculation. In scenarios where multiple transfer modes coexist, the Newton or COP method must be used. The COP method is generally the better choice because both methods require solving a system of equations at each iteration, but COP offers the advantage of matrix decomposition to reduce computational complexity. In addition, it is capable of handling different transmission modes simultaneously at the individual EP device level.

# 6 EVALUATION

For the evaluation the two main properties of computation time and accuracy have to be considered. A low computation time is needed to fulfill the time constraints of the Line Manager. A high accuracy is needed to make the right decision and not exceed any grid limits. For accuracy comparison of different solving methods the widespread circuit simulation tool ngspice [14] was integrated in the Line Manager to generate a reference. Note that this only allows evaluation of accuracy of the solving methods and not of the underlying grid model. As grid topologies for evaluation, models from [17] are used. They propose European grid models for different areas based on publicly available data. For the Line Management use case the low voltage models for rural (1-LV-rural1–0-no_sw), semiurban (1-LV-semiurb4–0-no_sw), and urban area (1-LV-urban6–0-no_sw) are selected. The implementation uses 4 cores and has a time resolution of 100 ms. For each grid model a randomized set of 40 trapezodial EPs in power mode is generated. The Line Manager gets the request of the EPs one after each other and has to decide about the acceptance for each of them while considering already accepted EPs. Every random EP starts during the first 20 seconds of simulation time, has a power between 1-30 kW, transfers energy of 0.1-1 kWh and has ramps of 1-50 kW/s. The termination criterion of the iterating methods COP and Newtons's method is set to $||\Delta\vec{x}||_2 < 1e^{-10}$ where $\Delta\vec{x}$ is the deviation of the voltage vector between two iterations.

Figs. 7-9 show the accuracy and the computation time of different solving methods in the three grid models. For this experiments the Line Manager runs with deactivated time point reduction. This means that the grid state is calculated whenever any of the setpoints change, even if the according time point is not identified as relevant for the Line Manager decision, cf. Sec. 4. Thus, the Line Manager in that case is like a simulator calculating the new state whenever the input data changes but not explicitly for each discrete time step. This allows a comparison of the solving methods accuracy over the entire time period, instead of only comparing the accuracy for relevant time points. It also has the effect that more grid states are calculated for each request, which makes it easier to differentiate the required computation time of the different solving methods. The deactivated time point reduction in the plots is indicated by the extension "_SIM" at the end of each methods name. As metric for accuracy the L2-norm of the voltage difference with the ngspice result is used. The computation time plots show the individual computation time for each of the 40 requests.

For each of the three models it can be seen that the results of FLPF have a higher deviation from the ngspice result than the other methods under the selected termination criterion. COP and the Newton's method have similar accuracy, which is to be expected if both methods converge to the same solution under the same termination criterion. FLPF and COP tend to have a similar computation time and provide the fastest results. Newton's method and Spice have significantly longer computation time. In the results computation time fluctuates between individual requests and has the trend to rise with the later requests. Due to deactivated time point reduction this can not be a result of increasing number of relevant time points caused by more and more overlapping EP transfers. Instead this is another issue, where the increasing number of overlapping transfers add more non zero power setpoints to the equation system, leading to a higher computational effort which increases the required computation time.

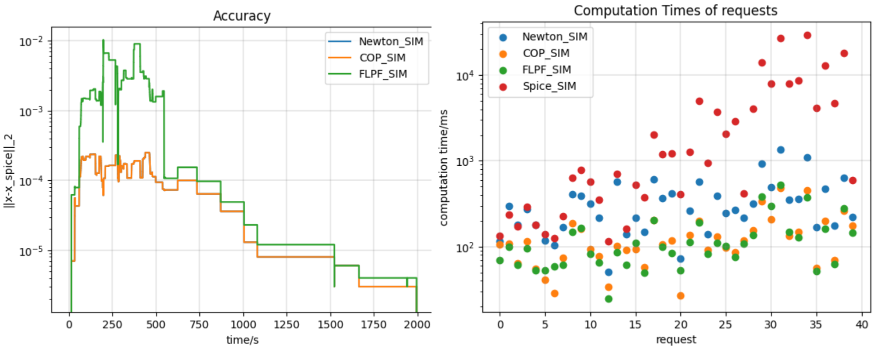


**Figure 7: Voltage deviation and computation times of different solving methods in rural grid.**

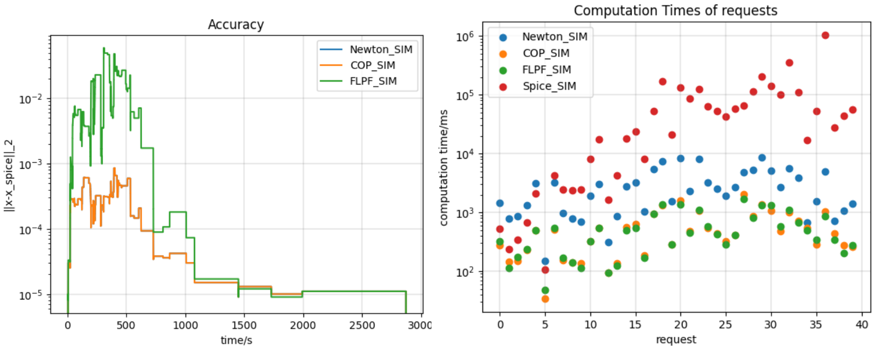


**Figure 8: Voltage deviation and computation times of different solving methods in semiurban grid.**

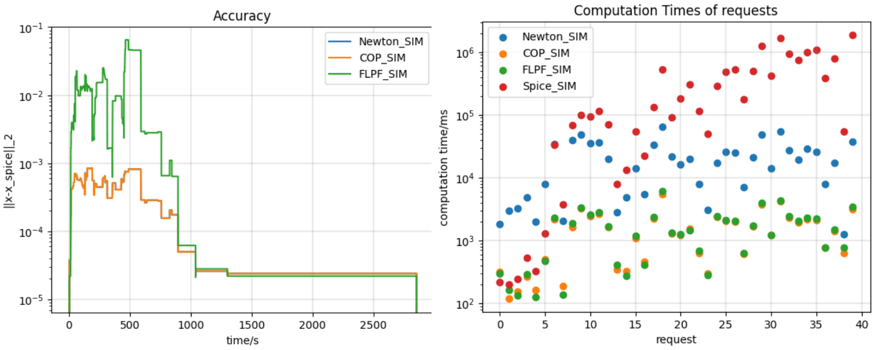


**Figure 9: Voltage deviation and computation times of different solving methods in urban grid.**

Figs. 10-12 show the computation time for the same requested EPs with time point reduction activated. It can be seen, that due to the reduction, the needed computation time in the results is reduced by at least one magnitude. The individual improvement for each requested EP of course depends on the number of overlapping transfers, and in particular, the number of overlapping ramp phases, that the request involves. Theoretically, with an increasing number of overlapping EP transfers, the set of relevant time points more and more matches the complete set of time points. This also means that the computation time will get closer to the results with deactivated time point reduction. In our results with randomized requests this is clearly not yet the case.

Overall it can be seen that COP is as precise as the Newton's method and requires similar computation time as the FLPF method which is less precise. This makes COP the best method in the context of the Line Manager. This is quite handy as it is also the only solving method allowing different transfer modes on a single EP Device level at the same time. Also note that COP as an iterative method has an adjustable trade off between accuracy and computation time by the selection of the termination criterion.

## 7 CONCLUSION

This article motivates the necessity of the Line Manager within the EP grid, focusing on its fundamental role in determining the state of the grid and making decisions to approve or reject proposed EPs

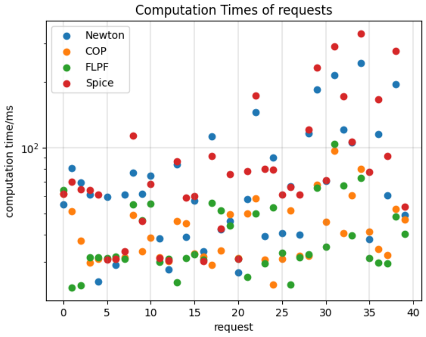


**Figure 10: Computation times of Line Management in rural grid.**

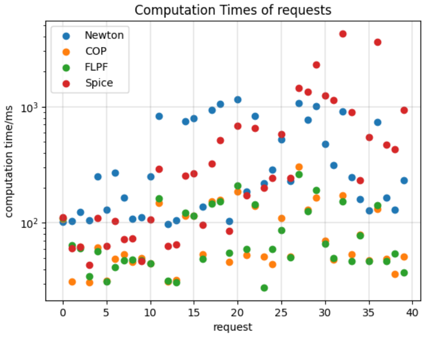


**Figure 11: Computation times of Line Management in semiurban grid.**

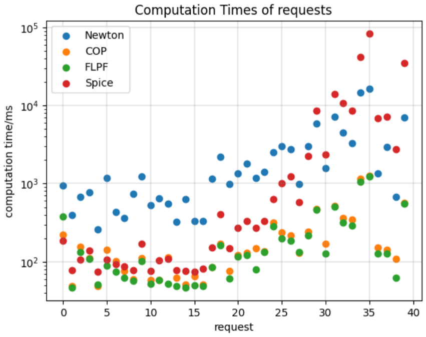


**Figure 12: Computation times of Line Management in urban grid.**

based on their impact on the grid. In addition, the contribution highlights the Line Manager's responsibilities, which include assessing transmission line capacity and adhering to grid voltage limits. Central to the Line Manager's effectiveness is the ability to make quick and accurate decisions, primarily through grid state calculations. In order to optimize the decision making process and minimize the computation time, the paper proposes a set of rules to identify critical points in time that are relevant to the Line Manager's decisions. In order to reduce the number of grid state calculations and thus the computation time, a rule set is defined to identify time points that are relevant for the Line Manager's decision. Four different methods for calculating the state of a DC network are presented and evaluated in terms of accuracy, computation time, and support for different EP transfer modes: current-, power-, and mixed-mode. The evaluation results show that in the context of the Line Manager COP is the most suitable method as it supports all EP transfer modes and is also faster than other methods with the same high accuracy. The choice of the termination criterion, which is a trade-off between accuracy and computation time, leaves room for further investigation into what level of accuracy is required for line management and how much performance can be increased without sacrificing decision quality. Further optimizations, such as a fast, less accurate computation that is recalculated with a stricter termination criterion when the network state is close to a limit, are possible.

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