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OPTIMIZATION OF MULTI-ENERGY SYSTEMS IN DISTRIBUTION NETWORKS FOR ENHANCED VOLTAGE MANAGEMENT

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Abstract

The growing integration of renewable energy sources presents challenges and opportunities for modern power systems. Multi-energy systems (MESs) offer a promising framework for addressing these complexities by coordinating energy vectors such as electricity, heat, and gas. These systems enhance sustainability by reducing greenhouse gas emissions while leveraging existing infrastructures like district heating and renewable energy sources. However, as distribution networks evolve, steady-state voltage level management becomes increasingly important due to fluctuating loads and renewable generation. This study proposes an optimization framework to enhance voltage management in distribution networks by coordinated MES operation. The model integrates electric, thermal, and gas systems with advanced control strategies and energy storage solutions to mitigate voltage deviations. By addressing key metrics—voltage control, operational efficiency, and cost—the approach ensures adaptive and secure network operation while managing the dynamic nature of distributed energy resources (DERs). Real-time optimization techniques are employed to enable predictive voltage control and decision-making. The methodology is validated using real-world data from a Finnish distribution network. Simulation results demonstrate that the proposed MES-based flexibility provision improves voltage management, reduces operational costs, and enhances overall energy efficiency.

1 Introduction

The global energy landscape is undergoing a deep transformation as traditional energy resources dwindle, concerns over climate change intensify, and global industrial and economic expansion drives increasing energy demands [1]. This shift underscores the urgent need for innovative and sustainable energy solutions to ensure long-term security and environmental resilience. These challenges have highlighted the urgent need for sustainable and carbon-neutral energy solutions to ensure long-term energy security and environmental preservation. A significant driver of this transition is the growing adoption of renewable energy sources (RES) such as wind and solar, which have been instrumental in reducing reliance on fossil fuels and mitigating greenhouse gas emissions [2].

The European Green Deal exemplifies this transformation, setting a bold objective for the European Union to become the world's first climate-neutral continent by 2050. Achieving this ambitious goal necessitates the widespread integration of decentralized distributed energy resources (DERs), which can sustainably meet future energy demands where DERs can enhance system reliability and flexibility. Concepts like microgrids, which support decentralized energy production and consumption, have further advanced the operational efficiency of DERs. Building upon these developments, MESs provide a comprehensive framework for integrating electricity, heat, and gas energy carriers into a unified, efficient network. MES optimizes energy utilization, enhances adaptability, and strengthens the reliability of distributed energy networks by dynamically coordinating generation, storage, and distribution [3].

The critical role of MES in addressing renewable energy integration challenges has been explored extensively in the literature. For instance, the authors in [4] employed a sophisticated simulation framework to analyse MES operations and their impact on distribution networks. The study highlighted the importance of strategic MES deployment, demonstrating how systems like photovoltaic installations and combined heat and power units influence grid performance and improve operational resilience. Similarly, Ref. [5] introduced a voltage control-oriented energy management system for networked MES, focusing on enhancing voltage management by integrating the control of electrical and thermal demands. This approach leveraged household flexibility to maintain voltage constraints with minimal cost increases.

Moreover, Ref. [6] developed an optimal voltage control strategy for regional distribution networks incorporating MES. By evaluating the adjustable capabilities of energy conversion devices, this model minimized voltage fluctuations and ensured efficient power restoration for critical loads. Authors in [7] proposed a two-stage volt-pressure optimization approach for integrated energy systems, utilizing Power-to-Gas (P2G) technology to manage renewable variability. Further advancements were presented in [8], where a "multi-energy node" extended traditional power node models to encompass diverse energy types. This comprehensive framework facilitated the analysis of MES dynamics and constraints, exemplifying its practical applications.

Despite the significant progress made in MES research, several challenges remain. Most existing studies focus on specific aspects of MES, such as voltage control or energy flexibility, without providing a global solution that integrates diverse energy vectors under real-world operational constraints [9]. Additionally, while methodologies like P2G and sensitivity matrix-based control offer promising results, their application often overlooks the combined effects of sector coupling, DERs, and advanced optimization techniques in enhancing grid stability, leaving a gap in achieving comprehensive voltage control and operational efficiency.

To address these gaps, this paper presents an optimization framework that enhances voltage management in distribution networks by coordinated operation of the MES. The proposed model incorporates electric, and gas systems, leveraging advanced strategies and energy storage solutions to mitigate voltage deviations and to improve grid resiliency. The methodology is validated using real-world data from a Finnish distribution network.

2 Methodology

The MES considered in this study meets both electrical and heating demands by utilizing DERs and energy exchanges with the distribution network. The MES, taken from [10], integrates various components, including a combined heat and power (CHP) unit, an electric heat pump (EHP), a chiller boiler, a furnace, and an electric energy system (EES). Fig. 1 illustrates the structure of the MES and its connection to the distribution network, highlighting the flow of energy between the different components. In this section, we present the mathematical model used for optimizing the operation scheduling of this system.

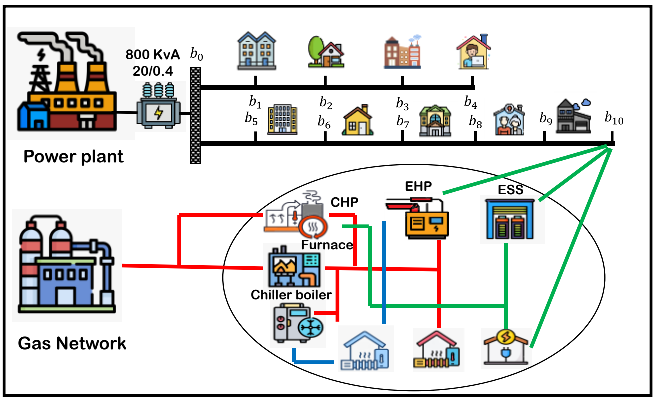


Fig. 1. The schematic of the MES connected to the distribution network.

$$P^{2Net}_{n=POC} + A - P^{D}_{n} - \sum_{\acute{n}}\left(P^{DW}_{n,\acute{n}} - P^{UP}_{n,\acute{n}} + R_{n,\acute{n}}SI_{n,\acute{n}}\right) + \sum_{\acute{n}}\left(P^{DW}_{\acute{n},n} - P^{UP}_{\acute{n},n}\right) = 0 \tag{1}$$

In the presented model, Eq. (1) functions as the active power balance constraint. It ensures equilibrium in the active power within the local distribution network. This equation ensures that the total power entering or exiting the network is perfectly balanced. It considers several key factors: A , the maximum power that can be imported into the network; P^{D}_{n}, representing the power demand from local users; and the sum of active power transactions across the distribution lines. These transactions are detailed by the expression $\sum_{\acute{n}}\left(P^{DW}_{n,\acute{n}} - P^{UP}_{n,\acute{n}} + R_{n,\acute{n}}SI_{n,\acute{n}}\right) + \sum_{\acute{n}}\left(P^{DW}_{\acute{n},n} - P^{UP}_{\acute{n},n}\right)$. Here, $P^{DW}_{n,\acute{n}}+$ represents the downstream active power flow from node n to node n'. Similarly, $P^{UP}_{n,\acute{n}}$ represents the active power flowing from node n to node n' in an upstream direction.

$$Q^{2Net}_{n=POC} + B - Q^{D}_{n} - \sum_{\acute{n}}\left(Q^{DW}_{n,\acute{n}} - Q^{UP}_{n,\acute{n}} + X_{n,\acute{n}}SI_{n,\acute{n}}\right) + \sum_{\acute{n}}\left(Q^{DW}_{\acute{n},n} - Q^{UP}_{\acute{n},n}\right) = 0 \tag{2}$$

Eq. (2) manages the reactive power in the electrical network, similar to Eq. (1).

$$SV_{n} - SV_{\acute{n}} + Z^{2}_{n,\acute{n}}SI_{n,\acute{n}} - 2R_{n,\acute{n}}\left(P^{DW}_{n,\acute{n}} - P^{UP}_{n,\acute{n}}\right) - 2X_{n,\acute{n}}\left(Q^{DW}_{n,\acute{n}} - Q^{UP}_{n,\acute{n}}\right) = 0 \tag{3}$$

Eq. (3) outlines how the power flowing through the lines correlates with the voltages at different nodes. Within this constraint, SV_{n} acts as a substitute variable representing the voltage squared at node n. Additionally, $SI_{n,\acute{n}}$ serves as a substitute variable for the squared current that flows between nodes n and n' in.

$$V^{2}_{Min} \le SV_{n} \le V^{2}_{Max} \tag{4}$$

$$I^{2}_{Min,n,\acute{n}} \le SI_{n,\acute{n}} \le I^{2}_{Max,n,\acute{n}} \tag{5}$$

Constraints (4) and (5) ensure that the squared voltages and squared currents remain within specified limits. These constraints limit the squared voltages SV_{n} and squared currents $SI_{n,\acute{n}}$ to their minimum values V^{2}_{Min} and $I^{2}_{Min,n,\acute{n}}$, and their maximum values V^{2}_{Max} and $I^{2}_{Max,n,\acute{n}}$, respectively.

$$P_{Min} \le P^{2Net}_{n=POC} \le P_{Max} \tag{6}$$

$$Q_{Min} \le Q^{2Net}_{n=POC} \le Q_{Max} \tag{7}$$

Likewise, constraints (6) and (7) set limits on the active and reactive power that can be input or output from the local distribution network, considering the capacity of the transformer.

$$P^{DW}_{n,\acute{n}} + P^{UP}_{n,\acute{n}} \le V_{Rated}\overline{I_{n,\acute{n}}} \tag{8}$$

$$Q^{DW}_{n,\acute{n}} + Q^{UP}_{n,\acute{n}} \le V_{Rated}\overline{I_{n,\acute{n}}} \tag{9}$$

Constraints (8) and (9) are designed to prevent congestion in the power lines, where V_{Rated} refers to the rated voltage.

$$V_{Rated}^{2}\overline{SI_{n,\acute{n}}} = \sum_{i}(2i-1)\Delta S_{n,\acute{n}}\Delta P_{n,\acute{n},\iota} + \sum_{i}(2i-1)\Delta S_{n,\acute{n}}\Delta Q_{n,\acute{n},\iota} \tag{10}$$

$$P_{n,\acute{n}}^{DW} + P_{n,\acute{n}}^{UP} \leq \sum_{i}\Delta P_{n,\acute{n},\iota} \tag{11}$$

$$Q_{n,\acute{n}}^{DW} + Q_{n,\acute{n}}^{UP} \leq \sum_{i}\Delta Q_{n,\acute{n},\iota} \tag{12}$$

$$0 \leq \Delta P_{n,\acute{n},\iota} \leq \Delta S_{n,\acute{n}} \tag{13}$$

$$0 \leq \Delta Q_{n,\acute{n},\iota} \leq \Delta S_{n,\acute{n}} \tag{14}$$

$$\Delta S_{n,\acute{n}} = \frac{V_{Rated}\overline{I_{n,\acute{n}}}}{N^{i}} \tag{15}$$

$$P_{n,\acute{n}}^{DW}, P_{n,\acute{n}}^{UP}, Q_{n,\acute{n}}^{DW}, Q_{n,\acute{n}}^{UP}, A, \Delta P_{n,\acute{n},\iota}, \Delta Q_{n,\acute{n},\iota} \geq 0 \tag{16}$$

Constraints (10) to (16) relate to the application of the piecewise linearization technique on the power flow equations. In these constraints, i is the index that identifies the specific partition used in the linearization process, and N^{i} represents the total number of partitions. The term $\Delta Sn,n'$ defines the maximum apparent power that can be transferred between nodes n and n' within this linearized framework. The variables $\Delta P_{n,\acute{n},\iota}$ and $\Delta Q_{n,\acute{n},\iota}$ denote the discretized active and reactive power amounts for each partition i, detailing the power flows between nodes n and n'.

The primary goal of this paper is to minimize the overall operational costs of the system. These costs are directly affected by the amount of electricity E_t and gas G_t procured from the upstream network, with their respective prices represented by λ_t^{El} and λ_t^{Ga}. By optimizing energy consumption and procurement strategies, the study aims to achieve cost-efficiency while ensuring reliable system operation.

$$MinObj = \sum_{t}\lambda_t^{El}E_t + \lambda_t^{Ga}G_t \tag{17}$$

The system fulfils its electrical demand by utilizing three key sources: the energy released from the battery during discharge E_t^{Dch}, the electrical power provided by the transformer $\eta^{ElE}E_t^{2}$, and the electricity produced by the CHP unit $\eta^{GaE}G_t^{1}$. This is shown in Eq. (18).

$$\eta^{ElE}E_t^{2} + E_t^{Dch} + \eta^{GaE}G_t^{1} = D_t^{E} \tag{18}$$

The electricity purchased from the upstream grid is distributed to support various key operations within the system. A portion of this electricity is used to charge the ESS, i.e., E_t^{1}. Another share is directed to the input side of the transformer, enabling the delivery of electricity throughout the network. Additionally, it provides the energy needed to run the heat pump EHP E_t^{3}, ensuring it can meet heating or cooling demands as required as stated below.

$$E_t = E_t^{1} + E_t^{2} + E_t^{3} \tag{19}$$

$$E_t^{1} = E_t^{Ch} \tag{20}$$

ESS has the capability to store electrical energy and subsequently discharge it. The functional operations of the ESS, including how it charges and discharges electricity, are detailed through specific mathematical formulations as follows from (21) – (26):

$$SOC_t = SOC_{t-1} + \left(E_t^{Ch}\eta^{Ch} - \frac{E_t^{Dch}}{\eta^{Dch}}\right)\Delta t \tag{21}$$

$$\underline{E^{Ch}}\gamma_t^{Ch} \leq E_t^{Ch} \leq \overline{E^{Ch}}\gamma_t^{Ch} \tag{22}$$

$$\underline{E^{Dch}}\gamma_t^{Dch} \leq E_t^{Ch} \leq \overline{E^{Dch}}\gamma_t^{Dch} \tag{23}$$

$$\underline{SOC} \leq SOC_t \leq \overline{SOC} \tag{24}$$

$$\gamma_t^{Ch} + \gamma_t^{Dch} \leq 1 \tag{25}$$

$$\gamma_t^{Ch}, \gamma_t^{Dch} \in \{0,1\} \tag{26}$$

SOC_t represents the state of charge in the ESS. It indicates the current energy level within the system. The terms E_t^{Ch} and E_t^{Dch} correspond to the amount of electricity charged into and discharged from the ESS, respectively. Additionally, binary variables $\gamma_t^{Ch}$and γ_t^{Dch} are used to indicate whether the ESS is in charging mode or discharging mode at any given time t. The natural gas purchased from the upstream network is consumed by both the furnace and the CHP unit as shown in (27).

$$G_t = G_t^{1} + G_t^{2} \tag{27}$$

The heating demand is met by the furnace and CHP, with additional support from the EHP for electric-based heating.

$$\eta^{GaH}G_t^{1} + H_t^{1} + H_t^{EHP} = D_t^{H} \tag{28}$$

A portion of the furnace's output is directed to the chiller boiler, while the remaining part is used to meet the heating demand.

$$\eta_F^{GaH}G_t^{2} = H_t^{1} + H_t^{2} \tag{29}$$

The cooling demand is met through the combined operation of the EHP and the chiller boiler.

$$\eta^{HC}H_t^{2} + C_t^{EHP} = D_t^{C} \tag{30}$$

An EHP efficiently regulates indoor climates by utilizing electricity to generate either heat or cooling, depending on the selected operational mode, Eqs. (31)-(35). In its heating configuration, the EHP transforms electrical power into thermal energy to meet the heating requirements, represented by H_t^{EHP}. Alternatively, in its cooling configuration, it extracts heat to lower indoor temperatures, satisfying the cooling requirements denoted by C_t^{EHP}. The Coefficient of Performance Ψ is a metric that measures the efficiency of an EHP. It specified the ratio of heat or cooling output to the electrical energy input. The heat pump is designed to adjust its output to either heat or cool within the specified minimum and maximum limits of its operational capacity. It's crucial to note that the heat pump cannot operate in heating and cooling modes simultaneously.

$$C_t^{EHP} + H_t^{EHP} = E_t^3\Psi \quad (31)$$

$$\underline{H}_t\zeta_t^H \le H_t^{EHP} \le \overline{H}_t\zeta_t^H \quad (32)$$

$$\underline{C}_t\zeta_t^C \le C_t^{EHP} \le \overline{C}_t\zeta_t^C \quad (33)$$

$$\zeta_t^H + \zeta_t^C \le 1 \quad (34)$$

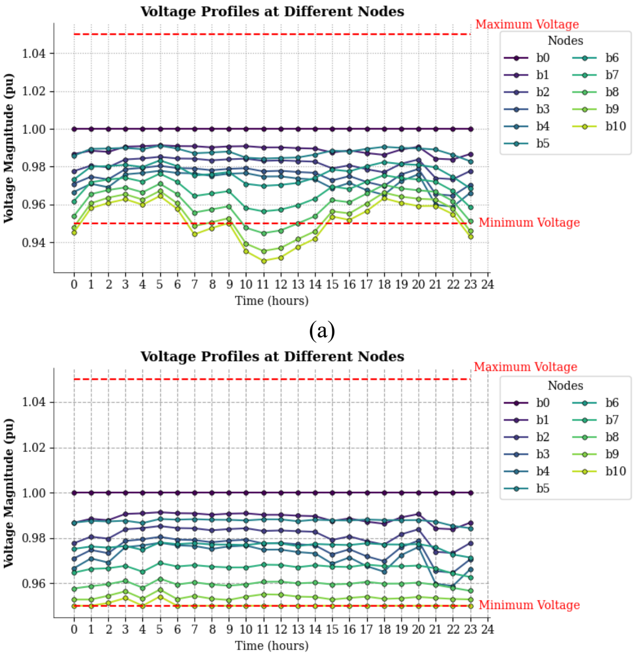
$$\zeta_t^H, \zeta_t^C \in \{0,1\} \quad (35)$$

3 Results

In this study, a modified IEEE 10-bus power distribution system with an MES that integrates electrical, heating, and combined demands is used to demonstrate the effectiveness of the proposed model. Figure 1 illustrates the structure of the case study, showcasing the MES's interaction with the distribution network and its internal components. The simulation results, obtained using Python software on a personal computer, provide insights into the performance of the MES under various scenarios. These results reveal how the MES balances energy supply and demand, optimizes costs, and ensures system reliability, offering valuable perspectives on the benefits of MESs.

Fig. 2 compares the voltage profiles of a distribution network under two scenarios: (a) without an MES connection and (b) with an MES connected through a single node. In the first scenario, the voltage magnitudes at nodes 8, 9, and 10 fall below the minimum allowable limit (0.95 pu) during the hours of 7:00 to 14:00, indicating under-voltage issues caused by high load conditions. Other nodes also experience fluctuations, though most remain within the acceptable range. By contrast, in the second scenario, connecting the MES effectively resolves these issues, as the voltage levels of all nodes remain consistently within the specified range (0.95 pu to 1.05 pu) throughout the 24-hour period. This demonstrates the MES's ability to control voltages, mitigate under-voltage conditions, and enhance the overall reliability and quality of the distribution network.

Fig. 3 illustrates the hourly energy exchange and corresponding prices for imported and exported power between the MES and the distribution network. The MES cannot simultaneously import and export energy, and the export price is deliberately kept lower than the import price to encourage balanced energy generation within the MES. If the import price were lower, the MES operator might rely entirely on imported power rather than utilizing the DERs to meet demand.



(a)

(b)

Fig. 2. The voltage profile of the studied case system (a) test system without connected to an MES (b) test system connected to the MES through one node.

During some hours, the energy exchange is zero, indicating that the MES neither generates, imports, nor exports energy during these periods. At hour 10, despite high import prices, the MES imports significant energy due to increased consumption demand. Conversely, during evening peak periods, the MES utilizes its DERs to generate power and export it to the distribution grid, taking advantage of high energy prices. This dynamic pricing and operational strategy highlight the MES's role in maintaining energy balance and optimizing its operations based on price and demand fluctuations.

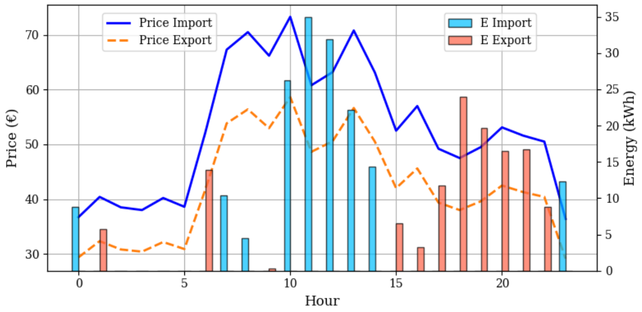


Fig. 3. The energy and its corresponding price of the imported and exported power from the MES.

Fig. 4 illustrates the charging and discharging patterns of the ESS alongside the EHP electrical consumption over the studied period. The ESS operates exclusively in either charging or discharging mode during a given period, never simultaneously performing both functions. During periods of excess energy generation from the DERs, the surplus energy is stored in the ESS, primarily during off-peak hours. This stored energy is then utilized to meet consumption demands during peak hours (17:00–22:00), when demand is highest and it is more cost-effective for the operator to draw from stored reserves. This operational strategy highlights the ESS's role in balancing supply and demand, optimizing energy costs, and ensuring efficient energy utilization during peak periods.

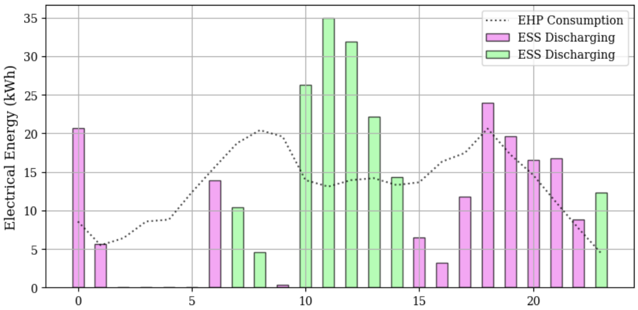


Fig. 4. The ESS charging and discharging modes and EHP electrical consumption.

4 Conclusion

An optimization framework was developed to address the challenges of integrating renewable energy sources and maintaining voltage management in electricity distribution networks. By leveraging the coordination of MES, including electric, thermal, and gas systems, the proposed approach effectively enhances grid resilience, operational efficiency, and sustainability. The integration of advanced control strategies and energy storage solutions allowed for the mitigation of voltage deviations, ensuring stable and reliable operation under fluctuating loads and renewable generation.

The simulation results, based on real-world data from a Finnish distribution network, demonstrated the effectiveness of the proposed model. Key findings include significant improvements in voltage management, operational flexibility, and cost efficiency across diverse scenarios. The results also highlight how MES optimization reduces greenhouse gas emissions by promoting better utilization of DERs and renewable energy.

The proposed framework provides valuable insights for future energy management strategies, paving the way for more efficient, flexible, and resilient energy systems that align with the goals of enhancing energy security.

5 Acknowledgements

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