ENABLING SOFT OPEN POINTS TO SUPPORT LOCAL ELECTRICITY MARKETS AND INCREASE HOSTING CAPACITY OF DISTRIBUTION NETWORKS

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Abstract

Active network technologies, such as voltage regulators and capacitor banks have been used for decades to introduce flexibility in electricity networks. These technologies have been mostly used to optimize the techno-economic performance of networks; however, the extent to which they can support the sustainable development of distribution systems via markets has not been investigated. In this work, we investigate the potential of the novel technology, namely, Soft Open Point (SOP), to support Local Electricity Markets (LEMs) by alleviating network constraints and increasing social welfare by accommodating otherwise infeasible transactions. Particularly, to enable SOPs to support electricity markets and increase the hosting capacity of networks, the LEM clearing problem has been integrated into the SOP scheduling. Using realistic supply and demand of renewables and flexible load applied to the IEEE 33-bus system, our studies show that in the congested network, SOP-supported LEM can accommodate 40.7% more transactions in volume, leading to the social welfare increase of 41.9%. The results demonstrate that SOP technology possesses a substantial amount of value to support LEMs and establish sustainable development of distribution systems in terms of integration of renewables and distributed flexibility, which are the keys to efficient energy transition.

1 Introduction

With the decreasing prices for power electronics solutions, it is expected that there will be a high penetration rate of network-owned flexible inverter-based resources such as distribution static compensators, dynamic voltage restorers, battery storage systems, and Soft Open Points (SOPs). In contrast to the former technologies which solve local problems in the grid, SOP technology offers trans-locational support to the networks. Connecting two feeders at the normally open point of connection through a back-to-back converter, SOP can provide spatial arbitrage of active power and independent reactive power support of two feeders, leading to higher utilisation of electricity networks and increased hosting capacity for renewables. However, being a new technology, SOP requires novel efficient mechanisms to be integrated into the distribution system management to realise its full potential.

To establish economic signals for sustainable integration of Renewable Energy Sources (RES), distribution system operators introduce Local Electricity Markets (LEMs) to be procured from the distribution level. However, due to the particular limitations of the networks, i.e., security constraints, a significant share of market transactions can be lost because of the infrastructural limitations, while in the purely economic sense, these transactions would be beneficial for market participants (i.e., RES and network customers). Therefore, to increase network hosting capacity and economic sustainability of RES and distributed flexibility we suggest supporting the operation of LEMs with active network technologies by integrating them into the distribution system management. Particularly, in this work, we investigate the potential of SOP technology to support the operation of LEMs by optimally scheduling it with respect to the market clearing to alleviate security constraints and, as a result, release the social welfare locked by these constraints.

The concept of SOP was originally proposed by Bloemink and Green to increase the penetration of distributed generation [1]. Afterwards, SOPs were studied for such applications as feeder load balancing, voltage support, power losses reduction, three-phase balancing, and hosting capacity enhancement [2]. In [3], Deakin *et al.* assessed five SOP applications for network reinforcement deferral, reduced curtailment of RES, losses reduction, reliability improvement, and enabling flexibility services, where the latter three are found to be uneconomic. Sarantakos *et al.* [4] improve the SOP value by proposing stacked application of integrated energy storage – SOP, comprising congestion management, losses reduction, and time arbitrage. Finally, in the most recent and most relevant work by Yang *et al.* [5], the authors propose a transactive controller to manage SOPs and maintain the secure operation of distribution systems. Even though most of the works consider the operation of SOP from the techno-economic perspective, their value in supporting LEMs and facilitating sustainable development of distribution systems, including integration of RES and distributed flexibility, both vital for energy transition [6], has not been studied before.

In this work, we propose the SOP scheduling optimization problem formulation that accounts for LEM clearing and corresponding power flows to minimize network operation costs while accommodating infeasible transactions in a congested network. The framework has been applied to the IEEE 33-bus network, where LEM with realistic supply and demand has been modelled. The results demonstrate that optimal scheduling of SOPs can accommodate 40.7% more transactions at the LEM in volume, leading to a social welfare increase of 41.9%. The novelties of this work are:

- SOP-enabled distribution system management that optimally schedules SOP outputs with respect to the LEM clearing and effective power flows. The scheduling is done to optimize network costs and social welfare losses due to network security constraints.
- Quantified value of SOP technology to unlock LEMs in congested networks. Particularly, the realistic case study suggests that as much as 41.9% of the social welfare of market participants can be provided by SOPs.

2 Methodology

To support LEMs and increase network hosting capacity, it is proposed to schedule SOPs with respect to market clearing and resulting power flows. Therefore, in the following subsections we first formulate the market clearing problem (1), followed by the optimal SOP scheduling problem (2).

2.1 Market clearing

To establish the maximum available social welfare at the LEM, a pool-based market model is considered. The optimization problem that maximizes the social welfare of the pool of bids and offers is formulated as follows:

$$\max\left(\sum_{g\in G} B_g^{\mathrm{C}}\Pi_g - \sum_{h\in H} O_h^{\mathrm{C}}\Pi_h\right) \tag{1a}$$

$$\sum_{g\in G} B_g^{\mathrm{C}} = \sum_{h\in H} O_h^{\mathrm{C}} : \lambda, \tag{1b}$$

where G and H are sets of LEM bids and offers indexed by g and h, respectively. Optimization problem variables, distinguished by italic font, include cleared bids $B_g^{\mathrm{C}} \in \mathbb{R}_{[0,\overline{\mathrm{B}}_g]}$ and offers $O_h^{\mathrm{C}} \in \mathbb{R}_{[0,\overline{\mathrm{O}}_h]}$, where $\overline{\mathrm{B}}_g$ and $\overline{\mathrm{O}}_h$ are submitted bids and offers, and Π_g and Π_h are corresponding prices. $\lambda \in \mathbb{R}_{\geq 0}$ is the dual variable of the trading balance constraint, representing the market-clearing price. The solution of the optimization problem is denoted with the asterisks after variables (e.g., $B_g^{\mathrm{C}^*}$), which are used within the optimal SOP scheduling problem (2), formulated in the next subsection.

2.2 Optimal SOP scheduling

To optimally schedule SOP outputs concerning network operation costs (i.e., network and SOP energy losses) and LEM social welfare, the following objective function is formulated:

$$\min\Bigg[\overbrace{\left(\sum_{ij\in Br} L_{ij}\mathrm{R}_{ij} + \sum_{ft\in S} P_{ft}^{\mathrm{SL}}\right)\mathrm{C}^{\mathrm{En}}}^{\text{Cost of network and SOP losses}} + \overbrace{\sum_{g\in G} B_g^{\mathrm{I}}\left(\Pi_g - \lambda^*\right) + \sum_{h\in H} O_h^{\mathrm{I}}\left(\lambda^* - \Pi_h\right)}^{\text{LEM social welfare losses}}\Bigg], \tag{2a}$$

where Br is a set of network branches and S is a set of SOPs within a network, indexed by ij and ft, respectively, both indicating "from" and "to" buses. Optimization problem variables, distinguished by italic font, include squared branch currents $L_{ij} \in \mathbb{R}_{[0,\bar{\mathrm{I}}_{ij}^2]}$, SOP losses $P_{ft}^{\mathrm{SL}} \in \mathbb{R}_{\geq 0}$, and infeasible bids $B_g^{\mathrm{I}} \in \mathbb{R}_{[0,B_g^{\mathrm{C}^*}]}$ and offers $O_h^{\mathrm{I}} \in \mathbb{R}_{[0,O_h^{\mathrm{C}^*}]}$, where $\bar{\mathrm{I}}_{ij}$ is a branch ampacity limit. Other fixed parameters within the objective function include branch resistance R_{ij} and unit cost of energy losses C^{En}.

Next, to realistically model SOPs within the scheduling problem, the following set of constraints is considered for each SOP within a network ($\forall\ ft \in S$):

$$P_{ft}^{\mathrm{SF}^2} + Q_{ft}^{\mathrm{SF}^2} \leq S_{ft}^{\mathrm{SF}^2} \tag{2b}$$

$$P_{ft}^{\mathrm{ST}^2} + Q_{ft}^{\mathrm{ST}^2} \leq S_{ft}^{\mathrm{ST}^2} \tag{2c}$$

$$P_{ft}^{\mathrm{SF}} = -P_{ft}^{\mathrm{ST}} + P_{ft}^{\mathrm{SL}} \tag{2d}$$

$$P_{ft}^{\mathrm{SL}} \geq \frac{\mathrm{R}^{\mathrm{Eq}}}{\mathrm{V}^{\mathrm{DC}^2}}\left(S_{ft}^{\mathrm{SF}} + S_{ft}^{\mathrm{ST}}\right)^2 + \frac{\Delta\mathrm{V}^{\mathrm{D}}}{\mathrm{V}^{\mathrm{DC}}}\left(S_{ft}^{\mathrm{SF}} + S_{ft}^{\mathrm{ST}}\right) + \mathrm{P}^{\mathrm{NRG}} \tag{2e}$$

where the optimization problem variables include SOP active $P_{ft}^{\mathrm{SF}} \in \mathbb{R}$, reactive $Q_{ft}^{\mathrm{SF}} \in \mathbb{R}$, and apparent $S_{ft}^{\mathrm{SF}} \in \mathbb{R}_{[0,\bar{\mathrm{S}}_{ft}]}$ power outputs at "from" buses and active $P_{ft}^{\mathrm{ST}} \in \mathbb{R}$, reactive $Q_{ft}^{\mathrm{ST}} \in \mathbb{R}$, and apparent $S_{ft}^{\mathrm{ST}} \in \mathbb{R}_{[0,\bar{\mathrm{S}}_{ft}]}$ power outputs at "to" buses, where $\bar{\mathrm{S}}_{ft}$ is the SOP installed capacity. Fixed parameters include equivalent SOP resistance R^{Eq}, DC link voltage V^{DC}, voltage drop of power diodes $\Delta\mathrm{V}^{\mathrm{D}}$, and SOP energization power $\mathrm{P}^{\mathrm{NRG}}$.

Finally, to model power flows with respect to the actual bids and offers delivered and SOP dispatch, *DistFlow* formulation [7] is adapted. While the current and voltage constraints are used as is, active and reactive power balance constraints have been modified as follows:

$$P_{ij} = \sum_{k:j\to k} P_{jk} + L_{ij}\mathrm{R}_{ij} + \mathrm{P}_j^{\mathrm{FD}} + \sum_{t:j\to t} P_{jt}^{\mathrm{SF}} + \sum_{f:f\to j} P_{fj}^{\mathrm{ST}} + \left(\sum_{g\in G|j}\left(B_g^{\mathrm{C}^*} - B_g^{\mathrm{I}}\right) - \sum_{h\in H|j}\left(O_h^{\mathrm{C}^*} - O_h^{\mathrm{I}}\right)\right) \tag{2f}$$

$$Q_{ij} = \sum_{k:j\to k} Q_{jk} + L_{ij}\mathrm{X}_{ij} + \mathrm{Q}_j^{\mathrm{FD}} + \sum_{t:j\to t} Q_{jt}^{\mathrm{SF}} + \sum_{f:f\to j} Q_{fj}^{\mathrm{ST}} + \mathrm{tg}\varphi\left(\sum_{g\in G|j}\left(B_g^{C^*} - B_g^{I}\right) - \sum_{h\in H|j}\left(O_h^{C^*} - O_h^{I}\right)\right) \quad (2g)$$

where additional variables include active $P_{ij} \in \mathbb{R}$ and reactive $Q_{ij} \in \mathbb{R}$ power flows. Fixed parameters include active $\mathrm{P}_j^{\mathrm{FD}}$ and reactive $\mathrm{Q}_j^{\mathrm{FD}}$ firm demand, branch reactance X_{ij}, and $\mathrm{tg}\varphi$, representing the reactive to active power ratio.

3 Numerical study

This section describes the case study and demonstrates the results of the proposed framework for SOP supported electricity markets by considering a particular snapshot of a distribution system in time.

3.1 Case study

3.1.1 Network configuration and parameters: the case study uses the original IEEE 33-bus distribution system, which network parameters can be found in [8]. Original demand, considered in the methodology as firm demand was increased by 40%, which corresponds to the GB electrification forecast by 2035 [9]. Unit cost of energy losses $\mathrm{C}^{\mathrm{En}} = 10$ p/kWh. Each of the five tie lines of the original network has been equipped with a SOP.

3.1.2 Soft open point characteristics: installed capacity of each SOP is 200 kVA. Other SOP parameters include equivalent resistance $\mathrm{R}^{\mathrm{Eq}} = 0.1\ \Omega$, DC-link voltage $\mathrm{V}^{\mathrm{DC}} = 700$ V, voltage drop of power diodes $\Delta\mathrm{V}^{\mathrm{D}} = 0.7$ V, and constant energization power $\mathrm{P}^{\mathrm{NRG}} = 1$ kW.

3.1.3 Bids and offers: supply and demand at the LEM were derived using flexible energy consumption and generation modelling developed in [10]. The particular bids and offers considered are provided in Table 1. Each bid and offer is characterized by its location (bus number), energy amount in kWh, and corresponding unit price in p/kWh.

Table 1 LEM bids and offers

	Bids			Offers	
Bus №	Energy, kWh	Price, p/kWh	Bus №	Energy, kWh	Price, p/kWh
12	100	9	3	100	8
13	100	17	19	100	7
14	200	6.5	20	400	0
15	100	16	21	200	3
16	100	8.5	22	100	4.5
17	100	15.5	23	400	1.5
29	200	7.5	24	200	4
30	300	14	25	100	5.5
31	250	12			
32	50	5.5			
33	100	9.5			

3.2 Results

To demonstrate technical performance of SOPs, the case study has been separately solved and compared for three scenarios: 1) case study network with firm demand only and passive network (i.e., without LEM and SOP); 2) case study network with flexible demand procured via LEM and passive network (i.e., LEM without SOP support); and 3) SOP supported LEM. Fig. 1 demonstrates how the voltage is distributed across the network for each scenario. As Fig. 1 suggests, the introduction of LEM stimulates more energy consumption, which leads to significant voltage fluctuations and compromises the security of supply. However, when SOPs are optimally scheduled with respect to the market clearing and resulting power flows, the voltage profile of the network can be maintained within the statutory limits, which in our case are 0.94 and 1.1 pu.

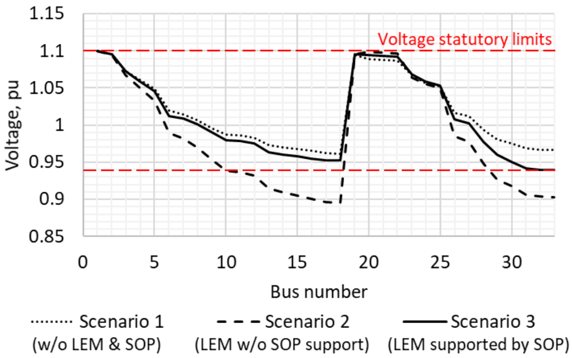

Fig. 1 Network voltage values for three scenarios

Next, Fig. 2 depicts the results of scenario 3 in terms of the LEM clearing (i.e., ascending offers and descending bids, represented with blue and orange step curves, respectively). Ideally, if the market is resolved agnostic of infrastructural limitations, all transactions to the left of the intersection of two curves would be accepted and delivered and the whole area between them would constitute the social welfare of market participants. However, due to network limitations, bids and offers represented with solid curves that originate from buses 22, 24, 25, 29, and 30 have not been delivered in full due to infeasibility with respect to security constraints. The resulting social welfare, in this case, corresponds to the area between the delivered transactions, represented with dotted curves, where the solid filled area represents the original social welfare of the LEM without SOP support (determined in scenario 2) and the cross-hatched area represents the social welfare of transactions accommodated by SOPs (determined in scenario 3). While the amount of the original social welfare constitutes only 44.4% of the total welfare available (or 60.3 £ out of 135.8 £), the social welfare of the SOP-supported LEM clearing reaches 86.3% (or 117.2 £). Therefore, the amount of social welfare accommodated by SOP corresponds to 41.9% (or 56.9 £) of the available social welfare at the LEM. Because of SOP support, the amount of transactions in volume increased from 480 kWh to 1,050 kWh or by 40.7% of the economic transactions, which total amount is 1,400 kWh.

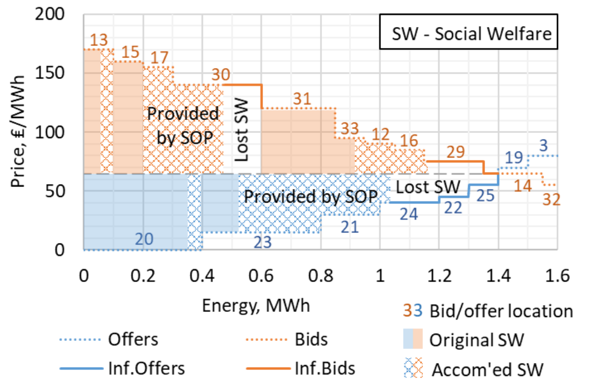

Fig. 2 LEM clearing (scenario 3): original social welfare – without SOP support (solid filled areas), accommodated social welfare – provided by SOP (cross-hatched areas)

Finally, to demonstrate the economic performance of the proposed SOP-enabled electricity market framework (i.e., SOP value), the three scenarios above are compared in terms of the network operation costs (i.e., network and SOP energy losses) and social welfare loss. Fig. 3 depicts the breakdown of these characteristics for three scenarios, where the blue bars illustrate the cost of network losses, the green bars represent the cost of SOP losses, and the orange bars illustrate the loss of social welfare due to transaction infeasibility. For the particular case study without LEM and SOP (scenario 1), network losses are 42.5 £ and the loss of social welfare comprises 135.8 £, which is the total market welfare available. When LEM was introduced without SOP support (scenario 2), the network losses increased to 55.7 £ and the LEM social welfare loss reduced to 75.5 £, holding 55.6% of the total social welfare available. Lastly, when SOP is optimally scheduled with respect to LEM clearing and resulting power flows (scenario 3), more transactions are delivered, leading to the LEM social welfare loss of 18.6 £ (or 13.7% of the total available). As a consequence of additional transactions being delivered, network losses slightly increased to 56 £. And SOP losses comprised 6.3 £. Overall, optimal scheduling of SOPs allowed to increase the LEM social welfare by 56.9 £ (or 41.9%) at an increase of energy losses of 6.6 £.

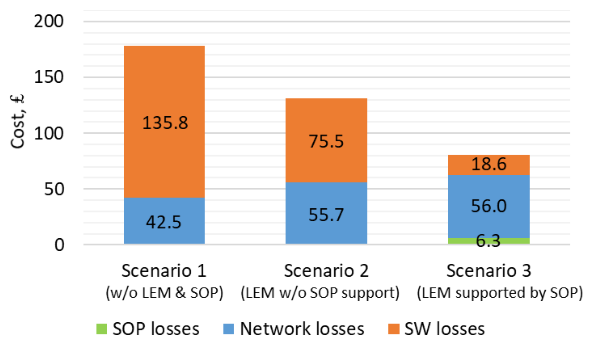

Fig. 3 Economic characteristics of the three scenarios

According to the results, the introduction of the LEM can lead to network overload and a significant amount of transactions being rejected because of network security constraints. On the other hand, SOP technology can accommodate most of these transactions, providing the corresponding social welfare to the market participants and facilitating sustainable development of distribution systems (i.e., integration of renewables and distributed flexibility).

4 Conclusion

This work demonstrated that novel active network technologies, such as SOP can be effectively used to support the operation of LEMs by alleviating infrastructural limitations posed by distribution networks and facilitating the integration and sustainability of renewables and distributed flexibility, both of which are vital for the energy transition. Considering realistic supply and demand at the LEM, the numerical study showed that the SOP-supported electricity market can release up to 41.9% more social welfare available and accommodate 40.7% more transactions in volume. To conclude, technology-supported LEMs can be useful in developing clean, equitable, and sustainable energy systems by providing equal rights for network customers to access markets and, therefore, increasing liquidity of these markets, which will be further investigated in future work.

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