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A Study of Operation Strategy of Small Scale Heat Storage Devices in Residential Distribution Feeders

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Abstract—Passive operation of thermal energy storage devices is a well established concept in Europe; this paper looks at active operation of thermal storage devices and their role in providing demand response from residential distribution feeders. It co-simulates the power system and the thermal performance of buildings to investigate the effect of operation strategy of thermal energy storage devices on the network and thermal comfort of households. A realistic residential feeder is used to demonstrate the applicability of the presented methodology. It is shown that the operation strategy of the thermal storage devices can affect the realizable reserve from these devices, house temperature and network variables such as losses and voltage. The realizable demand response found by the presented methodology can be used for market operation to avoid underestimation and overestimation of the demand response.

Index Terms—building, distribution, flexibility, heating, low voltage, operation, optimal power flow, storage, unbalanced

NOMENCLATURE

B	Set of buses
L	Set of branches
G	Set of generators
D	Set of demands
S	Set of SETS demands
Φ	Set of phases
$V_{b,\phi}$	Voltage at bus ($b \in B$ and $\phi \in \Phi$)
$V^{\max}, V^{\min}$	Secure operation voltage limit
$I_{l,\phi}$	Current flow through branch ($l \in L$)
$I_{l,\phi}^r$	Current limit of branch
P_g, Q_g	Active and reactive power dispatch of generator ($g \in G$)
$P_g^{\max}, P_g^{\min}$	Active power dispatch limit of generator
$Q_g^{\max}, Q_g^{\min}$	Reactive power dispatch limit of generator
P_s, Q_s	Active and reactive power consumed by SETS demand ($s \in S$)
$\omega_{s,c}, \omega_{s,dc}, \omega_{s,bs}$	Charge, discharge and boost status of SETS demand
$P_c^r, P_{dc}^r, P_{bs}^r$	Rated charge, discharge and boost power of SETS device
PF_c, PF_{bs}	Power factor of the charge and boost element of SETS device
E_s	Energy stored in the SETS device

$E^{\max}$	Energy storage capacity of SETS device
η_s	Hourly efficiency of SETS device
N	Number of time steps per hour
C	Cost of electricity
$\alpha_{p,d}, \alpha_{i,d}, \alpha_{z,d}$	Percentage of constant power, current and impedance component of demand ($d \in D$)

I. INTRODUCTION

Electrification of residential heat is an attractive solution for reducing CO₂ emissions [1], however, it may cause voltage and congestion issues, among others, in the distribution network [2], [3]. Storage of electricity in the form of heat is a well-established concept in Europe. Traditionally, consumers with dual electricity tariff employed electric storage devices to reduce heating costs by charging them when the lower tariffs applied, typically at night time. Consequently, a passive peak demand reduction was achieved. An interesting emerging approach, enabled by the smart grid concept, is the active control of smart electric thermal storage (SETS) devices by aggregators [4]. This approach aims to use the synergy between electricity and heat to provide demand response from participating customers for various purposes such as load shifting, frequency control and congestion management [5] while their comfort is not compromised.

The effect of electrification of heat on distribution networks has been investigated extensively [1]–[3], [6]–[12]. An approach reported in the literature, is the decomposing of the heat demand from the distribution network model. Accordingly, demand profile for buildings is first produced using detailed building models or through historical data. Then this is used to find the optimal operation of heating devices such as heat pumps and combined heat and power units to meet the heat and electricity demand. Finally, the effect of the decisions is monitored by solving a power flow [2], [3], [6]–[8]. In [1], [9] a linearized AC optimal power flow is used instead to design and operate the distribution network using various heating technologies. These approaches don't consider the potential of using the thermal performance characteristics of buildings as they treat heat demand as a parameter rather than a variable. This is addressed in [10] by including an electric analogue representation of buildings in the single phase optimal power flow. However, this is not sufficient for studying a 3-phase unbalanced network. In [11] and [12] the detailed building model and 3-phase load flow are combined. This platform

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enables investigating the effect of electrification of heat on distribution networks. Although the previous works are useful for design and identification of the bottlenecks of the distribution network but they cannot fully use the potential demand response from active control of heating technologies while respecting both distribution network constraints and thermal comfort of households.

This paper presents a 3-phase unbalanced AC optimal power flow (3-OPF) that includes the building thermal performance (heat demand treated as a variable) and SETS devices models. Accordingly, it considers two energy vectors, electricity and heat, for the distribution system simulation. To reach different targets, various strategies may be adopted by an aggregator for controlling SETS devices. By using the 3-OPF, this paper investigates the effects of 3 operation strategies of SETS devices (cost minimization, loss minimization and reserve maximization) on both the residential feeder and the thermal performance of buildings. Further, it introduces a methodology for assessing the realizable demand response from SETS devices across a residential feeder, subject to not only network constraints (such as voltage and ampacity) but also thermal comfort of households. The results can be later employed in unit commitment to avoid overestimation and underestimation of the demand response from SETS devices.

The rest of the paper is structured as follows: section II describes the 3-OPF and SETS and building models. A case study is carried out and the results are discussed in section III. Finally, section IV summarizes and concludes this paper.

II. 3-PHASE OPTIMAL POWER FLOW

Optimal Power Flow (OPF) is a potent framework for power system planning and operation. Both single phase [13] and 3-phase AC OPF [14] have been proposed to study various aspects of transmission and distribution networks [15], [16]. While single phase OPF is often sufficient for studies carried out on balanced networks, studying LV distribution feeders entails 3-phase unbalanced models. A 3-phase AC OPF is employed in this paper to replicate the operation of unbalanced distribution feeders. The 4 conductor current flow approach [14] is used to formulate the 3-OPF problem. With this approach, the power generated, transferred or consumed by the equipment at each bus and phase in the network is converted to current components. The following constraints are employed.

$$\sum_{g=1}^G \text{Re}\{I_g^t\}_{b,\phi} = \sum_{d=1}^D \text{Re}\{I_d^t\}_{b,\phi} + \sum_{l=1|_{\phi=\rho}}^L \text{Re}\{I_{l,\rho}^t\}_b \quad (1)$$

$$\sum_{g=1}^G \text{Im}\{I_g^t\}_{b,\phi} = \sum_{d=1}^D \text{Im}\{I_d^t\}_{b,\phi} + \sum_{l=1|_{\phi=\rho}}^L \text{Im}\{I_{l,\rho}^t\}_b \quad (2)$$

$$P_g^{\min} \leq P_g^t \leq P_g^{\max} \quad (3)$$

$$Q_g^{\min} \leq Q_g^t \leq Q_g^{\max} \quad (4)$$

$$|I_{l,\phi}^t| \leq I_{l,\phi}^r \quad (5)$$

$$V^{\min} \leq |V_{b,\phi}^t| \leq V^{\max} \quad (6)$$

Equation (1) and (2) are current balance equations and require the real and imaginary current components entering and exiting each bus, b , at each phase, ϕ , to be equal (further details on the current balance equations and power to current conversion can be found in [14], [17]). The generator active and reactive power limits are constrained by (3) and (4). Equation (5) and (6) represent the branch limits and normal operation voltage range, respectively.

A. SETS Model

Electric heat storage devices store electricity in the form of heat. At charging time, the elements in these devices draw power from the electric grid and heat the storage material, usually internal bricks. When discharging, cold air is forced into the device by an internal fan and heated while passing through the insulated heat storage chamber. Optionally, boost elements may be provided in some heat storage devices to enable extra heating at times when the heat output from the device is not sufficient or simply the stored energy is depleted. Furthermore, the storage device may introduce heat losses due to non-ideal insulation of the storage chamber. A detailed thermal model of SETS devices incorporates differential equations defining the dynamics of heat transfer between the elements, storage material and air, however, an approximation of the operation of these devices is sufficient for the purpose of this paper, i.e. study the operation strategy of SETS devices across a distribution feeder. Equation (7)-(10) describe the heat storage devices.

$$P_s^t = (P_c^r \omega_{s,c}^t + P_{bs}^r \omega_{s,bs}^t) |V_{b_s, \phi_s}|^2 \quad (7)$$

$$Q_s^t = \left(\frac{\text{PF}_c P_c^r \omega_{s,c}^t \sqrt{\frac{1}{\text{PF}_c^2} - 1}}{|\text{PF}_c|} + \frac{\text{PF}_{bs} P_{bs}^r \omega_{s,bs}^t \sqrt{\frac{1}{\text{PF}_{bs}^2} - 1}}{|PF_{bs}|} \right) |V_{b_s, \phi_s}|^2 \quad (8)$$

$$E_s^{t+1} N = E_s^t (N - 1 + \eta_s) + P_c^r \omega_{s,c}^t |V_{b_s, \phi_s}|^2 - P_{dc}^r \omega_{s,dc}^t \quad (9)$$

$$0 \leq E_s^t \leq E^{\max} \quad (10)$$

Equation (7) and (8) represent the active and reactive power consumed by the SETS device at each time step. The energy stored in the device is defined by (9), and its capacity is constrained per (10). It should be noted that, in this formulation, the energy stored in the device in the first time step is assumed to be an input parameter. The voltage element, $|V_{b_s, \phi_s}|^2$, in the above equations indicates that the boost and charge elements of the SETS device are constant impedance load [18].

B. Building Model

The energy dissipated by SETS devices is supplied to the indoor environment as a convective heat power input. In this paper, the thermal performance of semi-detached houses and mid-floor flats, representative of the Irish dwelling stock, are modeled using lumped parameter building models (RC thermal networks). Initially, detailed building energy archetype models of semi-detached houses and mid-floor flats, developed in the

EnergyPlus simulation environment, were used to generate synthetic data [19]. Then, a calibration algorithm was used to calibrate the RC thermal network parameters [20] of the electric-analogue building archetype models; this yields a linear approximation of the thermal dynamics of the buildings [21]

$$X^{t+1} = AX^t + BU^t + B_{\text{heat}}Q_{\text{heat}}^t \quad (11)$$

where X is the vector of state variables (i.e. temperature at the nodes of the RC model). The vectors U and Q_{heat} are the disturbance (e.g. weather) parameters and input heat gains at each node for time step t , respectively. The matrices $[A]_{n \times n}$, $[B]_{n \times m}$ and $[B_{\text{heat}}]_{n \times n}$ are state, disturbance and heat input coefficient matrices, respectively, where n is the number of nodes and m is the number of disturbance parameters. The heat provided by SETS devices is incorporated in items of Q_{heat} for the corresponding nodes of the house per (12). The temperature comfort range $[X^{\min}, X^{\max}]$, defined by (13), enforce the thermal comfort requirements of household h .

$$Q_{\text{heat}}^t N = (1 - \eta_s)E_s^t + P_{\text{dc}}^r \omega_{s,\text{dc}}^t + P_{\text{bs}}^r \omega_{s,\text{bs}}^t |V_{b_s, \phi_s}|^2 \quad (12)$$

$$X_h^{\min, t} \leq X_h^t \leq X_h^{\max, t} \quad (13)$$

The advantage of this approach is that it considers the latency of temperature as a result of energy input and uses it towards the SETS devices operation strategy target.

C. Reserve

The aggregated realizable reserve at the top of the feeder can be modeled by an additional set of variables that present the system steady state after an aggregated reserve (denominated with the superscript ru) is employed (after ramp down of the SETS load) at each time step. Accordingly, (1), (2), (5)-(8), (10), (11) and (13) are applied for the post-reserve operating condition using the respective set of variables. It should be noted that $P_g^t = P_g^{ru, t}$ and $Q_g^t = Q_g^{ru, t}$. Furthermore, (14) and (15) represent the effect of ramp down decision of the SETS devices on the stored energy in the subsequent time step and the heat they inject at the corresponding house nodes.

$$E_s^{ru, t+1} N = E_s^t (N - 1 + \eta_s) + P_{\text{c}}^r \omega_{s,\text{c}}^{ru, t} - P_{\text{dc}}^r \omega_{s,\text{dc}}^{ru, t} \quad (14)$$

$$Q_{\text{heat}}^{ru, t} N = (1 - \eta_s)E_s^t + P_{\text{dc}}^r \omega_{s,\text{dc}}^{ru, t} + P_{\text{bs}}^r \omega_{s,\text{bs}}^{ru, t} \quad (15)$$

The aggregated total reserve is reflected by introducing a virtual generator at the point of interest in the network (e.g. top of the distribution feeder) which can only absorb/inject active and reactive power ($P_{\text{flex}}^{ru, t}$ and $Q_{\text{flex}}^{ru, t}$) in the post-reserve operating condition to compensate for the change of power flow at the point of interest. This is equivalent to a generator ramping up at the point of interest ($P_{\text{flex}}^{ru, t}$ is defined to be less than or equal to zero).

D. Objective Function

Three objective functions are defined to enable comparison between different operation strategies of SETS devices.

- Reserve Maximization: It maximizes the total reserve energy realizable from controlling the SETS devices within the distribution feeder over a defined time period, T .

$$\text{Max} \sum_{t=1}^T -P_{\text{flex}}^{ru, t} \frac{1}{N} \quad (16)$$

- Loss Minimization: It minimizes the total energy loss across the distribution feeder over T .

$$\text{Min} \sum_{t=1}^T \left(\sum_{g=1}^G P_g^t - \sum_{s=1}^S P_s^t - \sum_{d=1}^D (\alpha_{p,d}^t + \alpha_{i,d}^t V_{b_d, \phi_d}^t + \alpha_{z,d}^t V_{b_d, \phi_d}^t)^2 P_d^t \right) \frac{1}{N} \quad (17)$$

- Cost Minimization: It minimizes the total cost of operation of SETS devices, i.e. cost of heating across the distribution feeder over T .

$$\text{Min} \sum_{t=1}^T \sum_{s=1}^S P_s^t C_t \frac{1}{N} \quad (18)$$

E. Problem Formulation

Three separate optimization problems are formulated based on the presented equations.

- Reserve Maximization
 - Objective Function: (16)
 - Constraints: (1)-(13), and (1), (2), (5)-(8), (10), (11) and (13)-(15) for post reserve operating condition as well as $P_g^t = P_g^{ru, t}$ and $Q_g^t = Q_g^{ru, t}$
 - Decision variables: P_g , Q_g , P_{flex}^{ru} , Q_{flex}^{ru} , ω_{c} , ω_{dc} , ω_{bs} , ω_{c}^{ru} , ω_{dc}^{ru} and ω_{bs}^{ru}
- Loss Minimization
 - Objective Function: (17)
 - Constraints: (1)-(13)
 - Decision variables: P_g , Q_g , ω_{c} , ω_{dc} and ω_{bs}
- Cost Minimization
 - Objective Function: (18)
 - Constraints: (1)-(13)
 - Decision variables: P_g , Q_g , ω_{c} , ω_{dc} and ω_{bs}

To manage the scale of the problem and enable a smart charge control in which the charge interval may span over the day before the demand occurs, one day-ahead approach is taken. With this approach, the optimization problem is initially solved for 2 consecutive days. The result for the first day is stored, and the next optimization problem is solved for the next 2 days until the time horizon of interest is fully covered. The initial condition for SETS devices and houses temperatures are fixed to the values found for the last time step in the previous day. A more robust technique is the rolling optimization approach [16]. It enables capturing uncertain

parameters such as demand and PV generation. However, for the purpose of this paper the day-ahead approach is sufficient. It should be noted that 3-OPF is a non-convex non-linear problem and, in general, its complexity may increase with the increase in the number of buses. However, it may not be possible to define a specific number of buses as a hard bound for 3-OPF feasibility.

III. CASE STUDY

A. Test Network

The residential feeder shown in Fig. 1 was used to demonstrate the application of the proposed methodology. This network is based on a LV distribution feeder in a suburban area in Dublin, Ireland [22]. It consists of 74 single phase consumers connected through 2.16 km single phase and 432 m 3-phase cable. A 400 kVA transformer connects the feeder to the external grid. The lumped load at bus 2 represents another feeder branch supplied through the same transformer, and the resulting voltage drop at bus 2 (further details about the network can be found in [22]).

Fig. 1. Test network [22]

Nine standard load profiles of the Irish electricity market were obtained from [23] and randomly assigned to the loads across the feeder. Further, 30 consumers were chosen arbitrarily to install SETS devices; these are marked with black dots above/below the load in Fig. 1. The SETS devices were assumed to be available for control by an aggregator. Consumers with SETS devices and connected to buses 4 and 9 were modeled as mid-floor flats [19]. The rest of the consumers with SETS devices were modeled as semi-detached houses [19]. The corresponding A and B matrices were derived with the technique presented in [20]. Six clusters of house occupancy profiles were derived from [24] and randomly assigned to the houses according to the percentage of houses represented by each cluster. Accordingly, $[X_h^{\min}, X_h^{\max}]$ at the controlled nodes of all houses were set to $[20, 25]$, $[13, 23]$ and $[-\infty, \infty]$ (in Celsius degrees) when the occupants are awake, asleep and away, respectively. The non-controlled nodes were left unbounded. It should be noted that other temperature limits may also be assigned based on the requirements of the households. Two different SETS devices were used, one for each type of house. Table I lists the specifications of these devices [25]. Apart from the SETS devices which were modeled as constant impedance, the rest of the loads in the feeder were considered as 50% constant power and 50% constant impedance. The voltage limit across the feeder was set to $[0.9, 1.1]$ pu and the

total load allowed for each customer at every time step was limited to 12.5 kVA. The electricity tariff employed was 0.18 and 0.09 €/kWh for 8am-11pm and 11pm-8am, respectively. Simulation was carried out for one winter week, and with hourly resolution, i.e. $N = 1$. It was assumed that the results found for each time step persist for one hour.

TABLE I
SPECIFICATIONS OF SETS DEVICES

Specification	Mid-floor flat	Semi-detached house
P_c^r	1.56 kW	2.76 kW
P_{dc}^r	0.7 kW	1.25 kW
P_{bs}^r	0.63 kW	1.13 kW
PF_c	1	1
PF_{bs}	1	1
$E^{\max}$	10.9 kWh	19.3 kWh
η	0.975	0.975
Devices per house	2	2

B. Results and Discussion

The 3-OPF explained in Section II was employed to find the charging pattern of SETS devices in the test network for three different objective functions, i.e. maximization of total reserve energy realized by the SETS devices, minimization of total energy losses in the feeder and minimization of the cost of operation of SETS devices. For cost and loss minimization cases, fixing the charge and discharge and boost profiles found, the reserve maximization was run additionally, in order to find the maximum realizable reserve when these operation strategies are employed.

Table II lists, the total reserve energy, total lost energy and cost of operation of the SETS devices for the studied cases. It is noted that maximizing the total reserve energy from SETS devices results in approximately three times higher cost of operation compared to the cost minimization case. This is due to the fact that the SETS devices are charged for longer periods regardless of the electricity price. Further, comparing cost minimization and energy loss minimization cases, it can be seen that 3% reduction in losses, resulted in 24% increase in the operation cost of SETS devices. Accordingly, controlling the SETS devices for minimization of feeder losses isn't in favor of the customers as it may increase the heating costs.

TABLE II
COMPARISON OF TOTAL RESERVE ENERGY, TOTAL NETWORK ENERGY LOSS AND TOTAL OPERATION COST OF THERMAL STORAGE DEVICES

Objective Function	Reserve Energy (MWh)	Energy Loss (MWh)	Cost (€)
Max Reserve	21.26	7.92	2885
Min Loss	7.72	6.79	1188
Min Cost	8.61	6.99	960

Figure 2 shows feeder losses for the three studied cases. Although for several hours, power losses throughout the feeder is lowest when cost minimization is used as the objective

function, the overall energy losses (area below the trend) is smallest for the loss minimization case. This indicates that operating SETS devices to achieve the least power loss at one snapshot may lead to higher losses at other snapshots. Further, the higher loss for reserve maximization case is due to longer charge periods of SETS devices.

Fig. 2. Comparison of total network losses

The reserve available from the feeder at each hour is illustrated in Fig. 3. Despite the fluctuations in the available reserve from the feeder, it is noted that at least 84 kW is available through shedding the SETS devices load when reserve maximization was used as the objective function. However, for the other studied cases, i.e. loss and cost minimization, for several hours zero reserve is available from the SETS devices across the feeder; this corresponds to hours at which the devices are not charging and the boost element is turned off.

Fig. 3. Comparison of total reserve provided by thermal storage devices

Figure 4 shows the controlled node's temperature at two houses of different type for the studied objective functions. It can be seen that generally, higher temperature is achieved in the mid-floor flat compared to the semi-detached house. This is due to the fact that the mid-floor flat model, represents recently built blocks with high thermal efficiency, and thus less heat input from the SETS device is sufficient to heat it to higher levels (the spikes in temperature). It can also be noticed that for both houses, with reserve maximization used as the objective function, the temperature in the house is adjusted to a higher level than the other studied cases. The reason for this behavior

Fig. 4. Comparison of room temperature for two houses

is the longer charge and discharge period of SETS devices when the target is maximizing reserve. An interesting behavior witnessed in the house connected to bus 9 (phase *a*) is that in order to minimize cost, at several hours, the house is pre-warmed to a temperature higher than 25°C when tenants are away.

The change of voltage at buses where SETS devices are connected is illustrated in Fig. 5 against the change of charge status of the respective device (in every 2 consecutive time steps) in the reserve maximization case. It can be noted that voltage across the network is affected by the charge status of the SETS device. Several hours are seen for which voltage change as low as -0.033 pu occurs with the change of charge status of the SETS devices across the network. Further, several hours were identified for which the charge status of the SETS device is limited ($\omega_c < 1$) by the voltage limit, i.e. 0.9 pu (marked with red diamonds). This indicates that deployment of SETS devices may cause low voltages in the feeders (particularly at the end of the feeder) and the aggregator should consider this issue when assigning a charge profile to these devices.

IV. SUMMARY AND CONCLUSION

A 3-phase unbalanced AC optimal power flow platform was implemented. SETS devices were modeled in this platform. Approximation of the thermal performance of buildings enabled tracking the influence of the heat dissipation from the SETS devices on temperature in the houses. This potent platform can be employed to study the charging and discharging profiles of the SETS devices (and other heating solutions) as well as their effect on distribution feeder and the household thermal comfort. A test feeder based on a LV distribution

Fig. 5. Change of voltage against the change of thermal storage device charge status (hours which charge status of the SETS device is limited ($\omega_c < 1$) by the voltage limit, i.e 0.9 pu are marked with red diamonds)

feeder in a suburban area in Dublin was used to demonstrate the ability of this co-simulation platform in exploiting the synergy between heat and electricity demand. Three cases were studied, i.e. reserve maximization, loss minimization and cost minimization. It was shown that maximizing reserve from SETS devices results in longer charging times and significantly higher cost of operation of these devices compared to the minimum realizable cost. It was also seen that minimization of total energy loss in the feeder, by controlling the SETS devices, may not be cost effective due to the increased cost of operation. Thus, it is important to consider the revenue earned by reducing losses, providing reserve, etc before choosing an operation strategy for SETS devices. Furthermore, it was demonstrated that adjusting the charge and discharge profile of the SETS devices enables identifying the amount of reserve that can be realized at each time step from the feeder subject voltage and ampacity constraints, and now thermal comfort of household. The methodology presented can be utilized to approximate the realizable reserve from all SETS devices in the power system; this can be later used for unit commitment to take into account the participation of demand response in the provision of operational reserve. Accordingly, overestimation and underestimation of the available reserve from this source of demand response may be avoided. Future work will capture the effect of demand uncertainty and explore the potential benefits of using a multi-objective approach for the operation of SETS devices by employing relevant cost functions for reserve and losses.

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