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<b>Authors(s)</b>	Qazi, Hassan Wajahat, Flynn, Damian
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# Provision of Flexibility at High Wind Penetration Levels Using Modern Storage Heater Load

Hassan W. Qazi and Damian Flynn

School of Electrical, Electronic & Communications Engineering  
University College Dublin  
Dublin, Ireland

**Abstract**—Modern storage heaters can facilitate higher levels of wind generation on the system by mitigating the effects of wind variability and uncertainty. This paper presents a coordinated control strategy for modern storage heater load to reduce conventional plant ramping and cycling requirements. The control practices and mechanisms required to utilise storage heater load for reducing system net load variability have been presented. The communication update rate to the heaters has been shown to impact conformance to the control objective. Acknowledging the impracticality of individual appliance control, a clustering scheme has been proposed to reduce the overall communication requirements. Heater load shaping mechanisms have also been presented to provide real-time system ancillary services at high wind penetration levels

**Index Terms**-- Wind integration, power system flexibility, storage heaters, demand side resource, ancillary services.

## I. INTRODUCTION

The penetration of wind generation on power systems around the world is constantly increasing, with further growth expected [1]. The variability and uncertainty of wind production leads to higher ramping and startup/shutdown requirements on thermal generation [2,3], resulting in higher operational and maintenance costs for committed plant. Flexible demand has been widely acknowledged as a potential part of the solution to this problem, with its ability to provide load shifting, load following and ramping reserves without adversely influencing customer comfort [4]. Flexible load is currently being utilised to provide capacity, scheduling reserves and ancillary services in many jurisdictions such as PJM and ERCOT [5,6]. ENTSO-E has proposed the utilisation of flexible demand to provide frequency control, reactive power control and constraint management [7]. The majority of the potential demand resource is believed to be constituted of thermostatically controlled loads (TCLs), that utilise their inherent thermal inertia to defer energy consumption for a period of time [8,9]. The high penetration rates of TCLs in residential, commercial and industrial sectors, along with their cyclic nature make them suitable for the deferral of short-term power consumption. A reduction of TCL power consumption, however, introduces effects such as post-event energy payback and short-term loss of load diversity [10], which must be

recognized. Unlike TCLs, consumption deferral for storage heaters does not entail an energy payback. These appliances can provide flexibility by shifting their energy consumption within the charging window, as long as the required charging time is less than the available charging window. Advancement in the enabling technologies has enabled modern storage heaters to offer improved heat retention, on-board prediction of future energy requirements, two way communications and system frequency sensing capabilities [11]. In this work, such capabilities have been exploited for providing flexibility to the power system. Future energy requirements communicated by individual appliances to a control server, facilitates the formation of an aggregate control strategy. A communication system enables the broadcast of control commands from a central server for coordination of charging patterns of storage heaters, making it possible to modulate the shape of aggregate load profile. Autonomous operation, and the ability to measure a locally available system parameter (frequency) is utilised for the provision of system services requiring fast response times (such as contingency reserve). Storage heating has been considered as a resource to provide system flexibility [12,13]; storage heating was utilized to provide system reserves by modulating the heater core temperature over a 24 hour period. A charging profile that follows instantaneous wind penetration levels was developed. In this paper, storage heater load charging based on net load (defined as the difference between system load and wind generation) has been proposed, to mitigate thermal plant cycling and ramping requirements. A 7 hour charging window (instead of 24 hours) has been utilized, to make use of low night tariffs. Section II presents the methodology for shaping the heat load profile subject to defined optimisation constraints, while results are discussed in Section III, followed by conclusions

## II. METHODOLOGY

Both modern and conventional storage heaters typically operate on a dual electricity tariff, storing electrical energy in the form of heat during a fixed time window (charging window) at night and releasing the stored energy during the day. As the low tariff window commences, all storage heaters start charging, leading to a high initial aggregate demand on the system. As time progresses appliances satisfy their charge requirements and stop drawing power, resulting in a

continuously depleting aggregate demand, as shown in Fig. 1 (default profile). Such an aggregate demand profile offers no upward flexibility for the initial hours, and as more appliances turn off upon satisfaction of their charging requirement, the available demand resource depletes with time. This leads to a disproportionate division of possible (up/down) load flexibility along the charging horizon. In contrast to conventional storage heaters, it is possible to modify the aggregate heater demand profile of modern units. A desired heater load profile shape can be pre-determined based on, for example, wind generation and load forecasts. The aggregate heater load profile can also be reshaped such that it has the ability to provide a load increment/decrement in real time while satisfying the charging requirements of individual appliances.

#### A. Reduction of net load variance

The Wind variability and uncertainty manifests itself in terms of net load variance. With the communications and control capabilities of modern storage heater load, it is possible to schedule individual appliance charging such that the aggregate heater load profile can contribute to smoothing the net load. Improved heat retention capabilities of modern storage heaters make it possible to balance the heater charging requirement over a window of 3-4 days, thus enabling heaters to be overcharged on days with abundant wind production (low net load). This overcharge can be utilised on a non-windy day (higher net load), leading to a smaller charge being drawn by the heaters. Modern storage heaters can predict their future charging requirements based on appliance operational history, which are communicated to a central server before the start of the charging window. Based on the storage heater charging requirements, 3 day system load and wind forecasts, an optimization problem can be defined such that the heater load at each dispatching interval  $t$  is calculated such that the aggregate heater load profile follows a reflection of the system net load over a 3 day period.

$$\min \sum_{t=1}^{3 \times t_H} (1 - a - b)^2 \quad (1)$$

$a = p_t^{tot} / p_{max}^{tot}$ , represents the heater load at any dispatch interval  $t$  as a fraction of maximum heater load,  $p_t^{tot}$  being the control variable

$b = \frac{NL_t - NL_{min}}{NL_{max} - NL_{min}}$ , represents the expected system net load at a time  $t$  as a fraction of expected maximum values of system net load over a 3 day period.

$t_H$  is the time horizon (7 hours) for one day and  $p_{max}^{tot}$  indicates the maximum possible power draw from all appliances. The total power consumption from all appliances  $p_t^{tot}$  at dispatch interval  $t$  and charge accumulated by an individual appliance  $C_{d,i}^{ap}$ , on a certain day,  $d$  are represented by (2)

$$p_t^{tot} = \sum_{i=1}^N a_{i,t} \times p_i^{rat}, \quad C_{d,i}^{ap} = \sum_{t=1}^{t_H} a_{i,t} \times p_i^{rat} \quad (2)$$

$p_i^{rat}$  is the power rating of an individual appliance  $i$  and  $a_{i,t}$  is a binary variable that indicates the on/off status of individual

appliances. The residual charge (excess charge stored on one day, carried to the next day),  $R_d^{ap}$  is calculated by (3), while  $ER_{d-1}^{ap,or}$  is the original charge requirement on day  $d$ .  $ER_d^{ap,new}$ , the effective charge requirement for an appliance on day  $d$  is given by (4),  $\eta$  is the fraction of overcharge from the previous day appearing as residual charge on the next day

$$R_d^{ap} = C_{d-1}^{ap} - ER_{d-1}^{ap,or} - R_{d-1}^{ap} \quad (3)$$

$$ER_d^{ap,new} = ER_d^{ap,or} - \eta \times R_{d-1}^{ap,or} \quad (4)$$

User comfort is ensured by combining the constraints that the charge drawn on a certain day must be at least equal to the effective charging requirement. Individual appliances can't store beyond their maximum storage capacities. These constraints are given by (5).

$$C_d^{ap} \geq ER_d^{ap,new}, \quad C_d^{ap} \geq C_d^{ap,max} \quad (5)$$

Optimisation of the charging schedule generates an on/off sequence for individual appliances at each time interval. The aggregate charging pattern for a certain day is combined with the original net load to reduce the predicted net load variance

#### B. Uniform distribution of resource

The default, aggregate heater load profile shown in Fig. 1, represents a continuously depleting demand resource, with an unequal distribution of upward/downward flexibility along the charging horizon. In order produce a more equal distribution of flexibility, the original heater demand profile must be altered such that it is possible to increase/decrease heater demand in response to system requirements. This can be achieved by scheduling the charging cycles of individual appliances such that the aggregate heater profile can be maintained at the same level (between maximum and minimum) for the entire charging window as shown in Fig. 1. This optimisation of appliance charging schedule is performed on a daily basis and does not involve balancing the available heater storage capacity over a number of days, and is given by

$$\min \sum_{t=1}^{t_H} |p_t^{tot} - p_{av}|, \quad p_{av} = \frac{\sum_{t=1}^{t_H} p_t^{tot}}{t_H}$$

where  $p_{av}$  is the average aggregate power draw across all time intervals, while equations (2), and (5) remain valid.

### III. RESULTS & DISCUSSION

In order to investigate the effects of storage heater load modulation, the Irish power system has been considered as a test case. It is a small (11.7 GW installed conventional generation by 2020), synchronously isolated system with limited DC interconnection (1000 MW to GB) and high installed wind capacity (4.9 GW). The modern storage heater load has been assumed to consist of four representative appliance types (1.5, 2, 2.5 & 3 kW). An appliance penetration rate of 3% (50,000 units) in Irish households has been assumed to represent charging load diversity. 500 individual heaters have been simulated and scaled up to the system level, with an appliance charging window of 7 hours (00:00-07:00). Reshaping the aggregate storage heater load profile based on 3 day system demand and wind generation

forecast, following the procedure outlined in Section II-A can lead to a reduction in system net load variance as demonstrated in our previous work [14]. Since the wind and system load forecasts, are regularly updated, this dictates that the reshaped storage heater load profile should also be updated based on new information.

#### A. Correction of forecast errors

Generally, the accuracy of wind and system load forecasts improves if they are performed closer to real time; which implies that for a 3 day forecast, day 1 is likely to be most accurately forecasted. In order to counter forecast inaccuracies for subsequent days, a rolling optimisation has been performed based on updated system load and wind generation forecasts. The heating load charging pattern is optimised for a 3 day block (days 1, 2 & 3) but only the charging schedule for the first day is implemented. The charging schedule for day 2 is obtained by optimizing the heater load with a more recent three day system load and wind generation forecast (days 2, 3 & 4). This procedure results in the broadcast of a charging schedule obtained with the most accurate forecast. (A charging profile which is not updated based on changes in system load and wind generation forecasts has been termed here as ‘fixed’)

Representative Wind and load forecasts for the Irish power system have been obtained from the transmission system operator. Fig. 2 shows the original and modified system net load for a week period. The modified net load has been created by combining the results of rolling optimisation of the heater load profile with the original net load profile. Pre-calculated dispatches for individual heaters are communicated before the start of the charging horizon. The dispatches contain the target heater state (on/off) for each time period of the charging horizon (hourly dispatches). Modified net load is smoother and significantly (up to 100 MW on day 5) increases the minimum net load, which may result in base load units not being switched off. Fig. 3 shows the required and actual aggregate charge across a week period, where days 3 & 4 are weekend days with a higher heating requirement. It can be observed that on days with lower net load (generally due to higher wind generation), the actual charge drawn is higher. Although the charged required on day 5 and 6 is almost the same, the actual charge drawn is higher on day 5 owing to lower net load. The availability of this excess residual charge on day 6 leads to a reduced charge being drawn.

#### B. Intra hour load variance

An hourly dispatch of the heater load implies that the resulting profile has been pre-programmed to change in accordance with the expected change in net load at each hour, such that it contributes to a minimization of the net load variance. This (hourly dispatch) arrangement implies that expected sub-hourly fluctuations in net load are not catered for. Communication of a half-hourly pre-programmed dispatch sequence can further reduce the net load variance. To this end, half-hourly dispatch commands have been generated, utilising wind and net load forecasts with a 30 minute resolution. Fig. 4 shows the improvement in net load profile on day 6 of the considered week. It can be seen that by

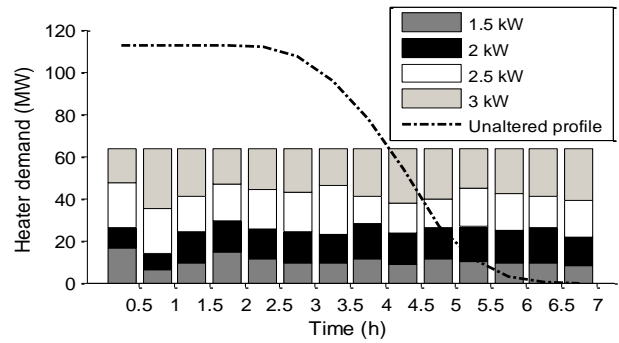


Fig. 1. Unaltered & modified heater load profile

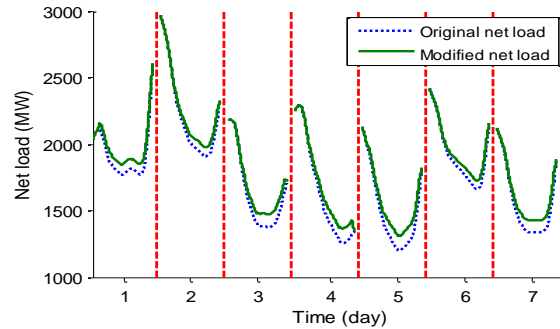


Fig. 2. Original & modified net load (rolling optimisation-7 hours/day)

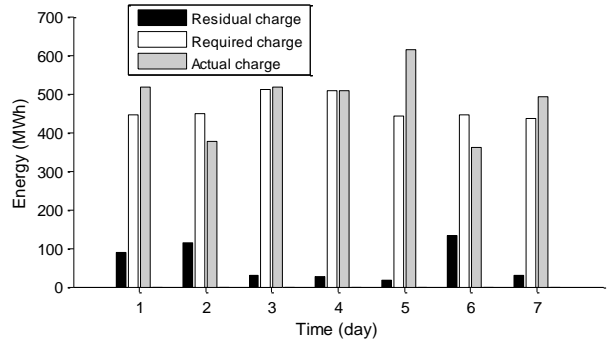


Fig. 3. State of charge per day (rolling optimisation)

using hourly dispatches with a non-rolling optimisation, the system net load profile variance has been reduced, however sharp reductions in net load can still be seen (between hour 1 & 2). Comparison of the modified net load (fixed-hourly), with the modified net load in which half-hourly dispatching has been utilized (rolling-sub-hourly) results in a still smoother net load profile.

In order to quantify the reduction in net load variance, the mean of 5 minute rolling net load variance for each day has been calculated, which allows for the quantification of small fluctuations in net load. Fig. 7 shows the percentage reduction in variance in comparison with the original net load. The heater charging profile based on sub-hourly rolling dispatches (half hour) results in a daily net load reduction of 10 to 23% as compared to 4 to 21% for hourly rolling dispatches (for the considered week). It should be recognized, however, that a sub-hourly dispatch (half hour) mechanism, as compared to hourly dispatch, doubles the volume of information to be sent, which may not always be practical.

#### C. Reduction in communication requirements

Individually controlling each heater becomes more impractical with an increasing number of controllable appliances. The volume of data transfer from appliances to a central server to determine future energy requirements, can be

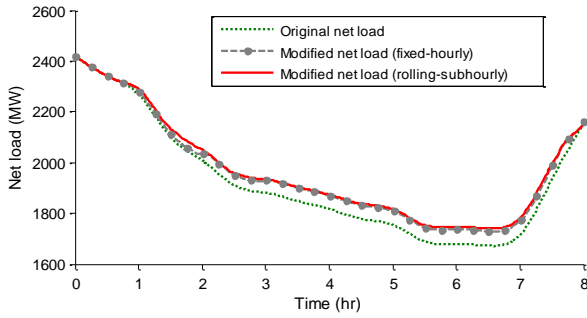


Fig. 4. Net load comparison on a sample day

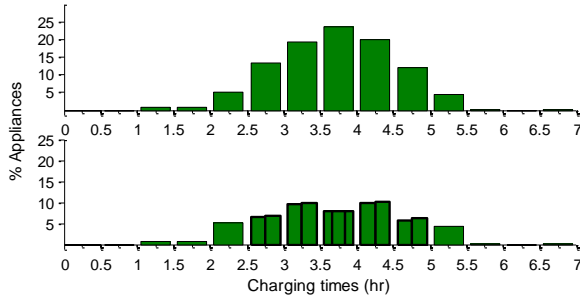


Fig. 5. (a) Initial appliance clustering, (b) appliance sub-clustering

significantly reduced by population sampling. Similarly, in order to reduce the volume of data sent from the central server to appliances (containing charging sequences), individual appliances can be clustered such that a single dispatch instruction is valid for the entire cluster. Based on the distribution of day1(3 day block) required charging times defined by population sampling and selection of half-hourly wide bins results in the creation of 14 unique bins as shown in Fig. 5(a). Individual appliances have been allocated to clusters such that their required charging times fall within the respective bins. Using appliance clustering reduces the number of unique dispatches, thereby reducing the data transfer required for appliance control.

As seen in Fig. 5(a), some clusters represent a very small fraction of appliances, while others contain the majority share. This grouping criterion may lead to more populous clusters influencing the aggregate load profile, making it uneven. A further sub-clustering of more populous clusters is therefore required which could be achieved by forming sub-bins as shown in Fig. 5(b). Each dispatch command for a certain cluster incorporates the target group identifier (required charging time interval). Upon initiation of a dispatch command, individual appliances select relevant dispatch commands, based on their required charging time. In order to control 50000 appliances, with each appliance being controlled independently, 50000 unique dispatch sequences would be broadcast. With the clustering mechanism shown in Fig. 5, the number of unique dispatch commands reduces to 17 (number of bins after sub-clustering). An increase in the number of total clusters implies an increase in the volume of communication data flow, while having a smaller number of clusters implies populous clusters dominating the aggregate load profile. The total numbers of clusters to be created should therefore be determined in view of this trade off. A reduction in number of dispatches sent implies that it becomes possible to include more information in each dispatch sequence.

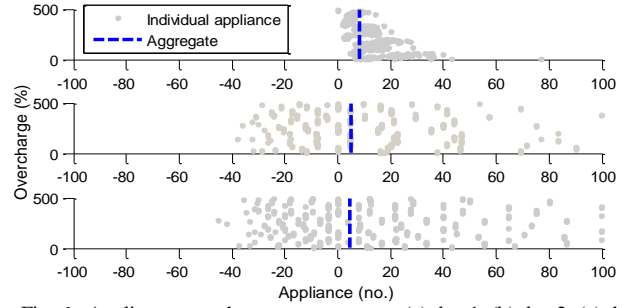


Fig. 6. Appliance overcharge percentage on (a) day 1, (b) day 2, (c) day 3

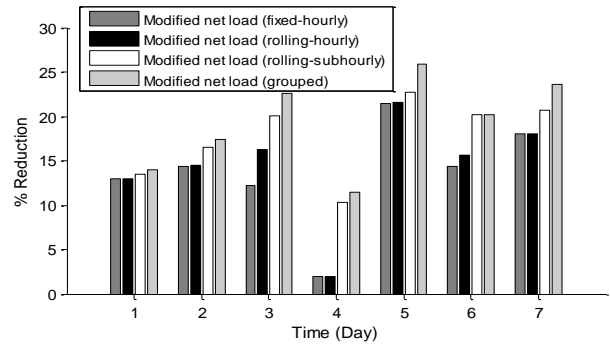


Fig. 7. Comparison of reduction in net load variance

The heater load profile can be pre-programmed to change in accordance with the expected change in net load every 10 minutes (10 minute dispatch) instead of a half-hourly dispatch. Since the appliance clustering is based on the charging times for the of a three day optimisation window, the associated clustering of appliances will likely be invalid for subsequent days, leading to over/under charging of individual appliances in a cluster if left unaltered. It is however, important to perform a 3 day optimisation to ascertain the most suitable periods for overcharging of storage heater fleet. Fig. 6 shows the percentage overcharge of a fleet of clustered appliances. It can be observed that on day 1, Fig. 6(a) that there are no undercharged appliances (all appliances meet their charging requirements), while on day 2, Fig. 6(b) and 3 Fig. 6(c) a number of appliances would be undercharged. For a clustering strategy to succeed, the rolling optimisation becomes more important, as only the charging patterns for the first day are ever implemented in a rolling optimisation, with the remainder being replaced. However, the aggregate overcharging on days 2 and 3 is positive and reflective of system net load forecasts which are subsequently updated on day 2 and 3, along with the storage heater required energy forecasts.

Fig. 7 compares the improvement in net load variance reduction with various control mechanisms discussed. Fixed optimisation, considering 3 day optimisation period blocks, reduces the net load variance. It can be observed that the introduction of a rolling optimisation with hourly dispatches leads to a further reduction in net load variance. Since updated wind generation and system load forecasts are not recognised in fixed-hourly optimisation, an improvement in the net load variance can be seen when rolling-hourly optimisation is performed. A sub-hourly dispatch schedule leads to a further reduction (4% on average) in net load variance, as the sub-hourly variations in net load are catered for in heater load dispatches. Appliance clustering further

improves the net load variance reduction by enabling a 10 minute dispatching schedule, as well as a reduction in the communication requirements for the heaters.

#### D. Contingency reserve provision

While maintaining the storage heater load profile to reduce system net load variability, the storage heater load can also be utilized to perform system ancillary services. The Storage heater demand can be shifted to a minimum or maximum state in response to a system loss of generation or load, by making use of the on-board frequency sensor. For illustration purposes, provision of over-frequency contingency reserve by means of storage heater load, resulting from the loss of a HVDC export has been demonstrated for the Irish system. Following the procedure outlined in Section II-B, the aggregate power draw profile across a 7 hour window has been adjusted to permit an increase/decrease in power consumption (contingency reserve). It has been assumed that every heater turns on/off if the system frequency increases/decreases by more than 0.2 Hz from the nominal value (50 Hz). The Irish power system has been modeled with a single bus representation with storage heaters incorporated as flexible load. The power system model has been calibrated over a number of years with data obtained from the transmission system operator [15]. When the loss of export (250 MW) occurs and the system frequency exceeds 50.2 Hz, all appliances turn on, thus providing a sudden increase in demand and controlling the system frequency, Fig. 8. It has been assumed here that the appliances provide the reserve for a fixed period (assumed to be 10 minutes), after which they randomly recover back to their initial charging profile within a fixed time (assumed to be 10 minutes). As shown in Fig. 8(b), the charging profile has been changed (between hour 1 & 2) by means of a re-dispatch to recognize the charging pattern alteration. Flat charging profiles have been assumed for illustration purposes, but provision of an under/over-frequency reserve, while reducing system net load variance, implies that the initial dispatch sequence issued before the event becomes invalid, and a new dispatch sequence must be generated considering the state of charge of appliances, to ensure compliance to the charge requirement.

#### IV. CONCLUSIONS

Modern storage heaters with improved heat retention, the ability to predict their energy requirements, two way communications and on-board frequency sensing capabilities are shown to provide flexibility at high wind penetration levels by mitigating the effects of wind variability. Optimal charging patterns for storage heater load result in reduction of conventional plant cycling and ramping requirements. Balancing the charging requirements with available wind energy over a 3 day window results enables a better utilization of available wind energy. Rolling optimisation of heater charging profile reduces the effects of wind forecast errors. A reduction in heater load dispatch intervals improves the net load variance. To reduce communication overheads, a clustering mechanism is presented, that allows for more frequent heater load dispatch, which results in a smoother net

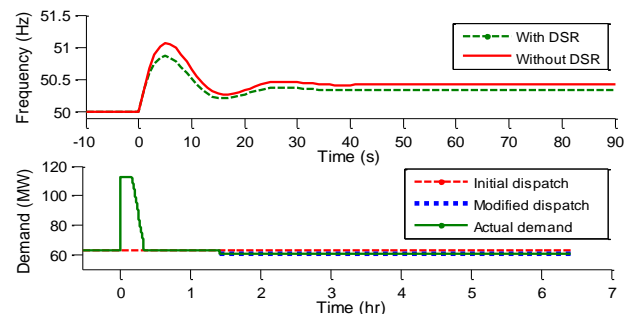


Fig. 8. Provision of over-frequency reserve

contingency reserve is demonstrated. Dispatching and coordination mechanisms that improve system performance at high wind levels are highlighted.

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