Ambient Temperature Impact on the Aggregated Demand Response Flexibility in Microgrids

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***Abstract*—Demand flexibility is the capacity of demand-side loads to change their consumption at any instant. It makes electricity more affordable by helping customers to use less power when prices are high. On the other hand, demand flexibility can also help to increase the reliability of the power grid when is highly stressed, by reducing demand for power or for integrating renewable generation. Thermostatic controlled loads (TCLs) are one of the most promising options among demand response (DR) solutions however, conventional methods for controlling single TCLs are not easily extensible to aggregated TCLs since it may cause them to synchronize. In addition, the ambient temperature may significantly influence the power flexibility offered by the TCLs. In this paper, a metric of flexibility is applied along with a modified control algorithm to de-synchronize the TCLs with the aim of fairly comparing the different control approaches applied to aggregated TCLs. Furthermore, a sensitivity analysis, considering variations of temperature in several periods of time, is performed over the TCLs power flexibility. The results were validated in Simulink/MATLAB using real demand and generation data from UK national system and simultaneously, temperature data for the same region and time frame.**

***Index Terms*—thermostatically controlled loads, demand response, flexibility, synchronization.**

I. Introduction

Flexibility is the ability of the power system to change their consumption or injection at a certain instant while keeping the demand supply. Usually this action is provided by conventional generators, such as fuel based, due to their inertia because of their rotating mass. Those generators can provide a spinning reserve, to act when there is an unusual behaviour in the system, such as an external disturbance or a sudden change in the demand. However, this is becoming harder to achieve with the continuous increase of the demand, and furthermore, considering that renewable energy based generators are being added to the power system and their stochastic behaviour should be somehow compensated. As a solution, thermostatic controlled loads can serve as a good load (source) to be controlled for offering demand side response [1] and increase the grid flexibility to compensate sudden changes [2] and variations of supplied energy, such as renewable energy from wind turbines or solar panels. Demand response in microgrids is being widely study, [3]–[7] aiming to offer voltage and frequency support to the microgrid but simultaneously providing sufficient comfort to the customer. Based on optimization problems or decision making the controllers are designed to achieve the highest and fastest performance in order to manage properly the microgrid.

It is worth to notice that when several houses in a building are offering the demand response service (with the same control instruction) the TCLs will tend to synchronize their behaviour and their energy consumption behaves in an oscillatory fashion. There are several techniques to avoid this issue. In [8] for instance, the authors developed a stochastic approach to set the temperature limits to change in function of frequency deviations, and in this sense to avoid the TCLs being synchronized [9]. Some others apply a static change in the temperature limits of each TCL, a technique which has proven to be simple and easy to implement [10].

On the other hand, the aggregator, for instance, should know the availability of the demand in order to provide ancillary services such as frequency support [11]. Therefore, the control approaches must aim not only to provide comfort to the end user, by controlling the heat exchange in their houses, but also in offering a reliable service to the grid. Additionally, the ambient temperature may affect the demand response performance of the TCLs (such as heaters), since its controller is comparing the outside temperature to keep comfortable levels of indoor temperature. This means that, when the outside temperature is high, the heaters would not be available, since they will be off, and therefore it will not be possible to provide any support to the grid. On the opposite, when the outside temperature is low the TCLs must prioritize the room temperature but the frequency support will be overshadowed in the cold periods of time. To conclude, it is imperative to establish a relationship between flexibility of the DR and the ambient temperature, since developing efficient control approaches may not be enough to determine its power flexibility.

The main contribution of this work is a comparison of several control methods to evaluate the flexibility and temperature correlation, by testing different periods of time along the year 2019. Such approach is interesting for predicting the demand flexibility according to the forecast of the weather. This is particularly useful for the aggregator to manage the DR accordingly. Furthermore, a de-synchronization technique

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is used so to avoid the so-called synchronization of the TCLs and a sensibility analysis on the confidence level of the DR regarding temperature variations is exposed.

This paper is organized as follows: Section II provides the microgid configuration used in the study cases, section III describes the control techniques commonly used for demand response. The demand response flexibility is described in IV and Section V presents the results based on the sensitivity analysis of the flexibility in response to the ambient temperature behavior. Finally, in Section VI, conclusions are drawn and the future work is outlined.

II. Microgrid configuration

The microgrid system model consists of various distributed generators such as PVs, micro turbines and wind turbines interconnected with residential loads. The load can be divided into two types, non-controllable loads, which demand a fixed power consumption, and the TCLs for supporting the frequency through the control of their thermal characteristics.

The microgrid scheme is implemented based on a test microgrid, adapted from [12], which is shown in Fig.1. The microgrid can work in both islanded and grid-connected modes. In order to evaluate the effectiveness of the control approaches in the microgrid, the main grid has been replaced with a synchronous generator powered by a diesel engine. This has been developed in Simulink to observe the behaviour of the control methods applied to the aggregated TCLs and therefore offering frequency support as a service for increasing reliability [4]. Furthermore, the model includes a supplementary control loop [13], which is also known as secondary control and the speed droop controller to regulate the output power (AGC) [14].

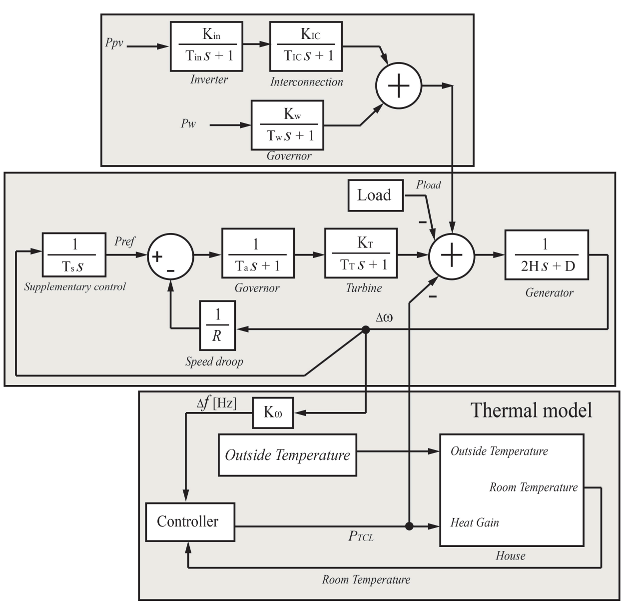

Fig. 1. Frequency response model for the ac microgrid system

A. Aggregated TCLs model

Several residential houses with a heating system represent the named aggregated thermostatically controlled loads. This means, a group of houses with an electrical heater and its controller, which interrelates the heating exchange between the outdoor temperature and the room temperature that is constantly adjusted by the heater [15]. The model that relates the power consumption and the room temperature is described in Eq. 1, in which P_{heater} is the heater power consumption (of each domestic house), T_{room} and T_{out} are the room (or house) and outdoor temperature. R_{eq} is the room equivalent thermal resistance [15]. The conduction losses term includes conduction through the surface of the house. Similarly, C is the heat capacity of the house which includes different components such as air flow, walls and floor. For this application, the aggregated TCLs are considered as homogeneous loads.

$$\frac{dT_{room}}{dt} = \frac{1}{C}\left[P_{heater} - \frac{1}{R_{eq}}(T_{room} - T_{out})\right] \qquad (1)$$

III. Demand response control

A. Modified ON/OFF Control

The conventional ON/OFF control method switches the TCL ON when the temperature reaches the lower bound or OFF if the upper bound is reached, to keep the room temperature within comfortable limits. The modified ON/OFF control applied in [15], considers the room temperature to control the heater, but additionally the frequency of the grid is also considered when taking the decision of switching the TCL ON or OFF. Nevertheless, the heater is switched ON or OFF regardless of the frequency deviations, if the temperature exceeds its limits, as the conventional ON/OFF algorithm operation.

B. Droop-based Control

The droop based control combines the previous control (modified ON/OFF) and a droop-based control, which affects the power of the TCL proportionally to the grid frequency deviations. If the grid frequency decreases, the heater power consumption is increased and vice versa. Therefore, this control works as an ON/OFF control when the grid frequency exceeds its determined limits, and while the heater is in ON mode (when the heater needs to warm up the room). Simultaneously, the droop control algorithm controls the power consumption of the electrical heater regarding grid frequency deviations.

C. Variable Temperature Limits for Aggregated TCLs

The modified ON/OFF control is a very simple control approach, however when it is applied to a several TCLs, they will tend to synchronize [8], [10]. On the other hand, although in previous studies the droop-type control approach shows the lowest frequency deviations in comparison with other controllers exposed in [15], the same phenomena occurs to aggregated TCLs, its behavior exhibits a tendency to synchronize causing high peaks in frequency and power. This highlights that conventional controllers for single TCLs must be modified when applied to aggregated loads in order to offer a better support of frequency and power from the demand side. Therefore, to avoid the mentioned synchronization of the aggregated TCLs, a random adjustment on the temperature limits (upper and lower bound) at even intervals of time (e.g. every hour) is applied to the previous control methods exposed in this section. Furthermore, this can be applied as a decentralized method with low computational effort, since the temperature limit set points are parameters but varying in time. Equations 2 and 3 describe a random uniform distribution for the maximum and minimum temperature limits of each room temperature, where n indicates the n^{th} TCL. And additionally, the random uniform distribution is a variable within zero and one, 4.

$$T_{n,max}(t) = T_{max_u} - \phi \Delta T \quad (2)$$

$$T_{n,min}(t) = T_{min_l} - \phi \Delta T \quad (3)$$

$$\phi \approx u(0,1) \quad (4)$$

where ΔT is the bandgap for the temperature limits:

$$\Delta T = T_{min_u} - T_{min_l} = T_{max_u} - T_{max_l} \quad (5)$$

IV. Demand response flexibility

For quantifying the frequency support given by the demand response, we use the metric of power flexibility, which is defined as "the availability of the power reduction/increase of the aggregated TCLs". This index expresses the reliability of the DR method for supporting the grid frequency. Two variables represent either the power reduction or the increase of consumption. Therefore, $P_{neg,n}(t)$ is defined as the possible power reduction of the n^{th} TCL:

$$P_{neg,n}(t) = flex_{neg,n}(t) \cdot P_n(t) \quad (6)$$

where $P_{neg,n}(t)$ is a function of time, $P_n(t)$ is the consumed power of the n^{th} TCL and $flex_{neg,n}$ is a binary variable, which expresses if the TCL can be turned off or not. In this sense the former can be zero, if the TCL cannot be turned off or one if it can be turned off. Similarly, the ability to increase the TCL power consumption is defined as $P_{pos,n(t)}$as follows:

$$P_{pos,n}(t) = flex_{pos,n}(t) \cdot [P_{max} - P_n(t)] \quad (7)$$

where P_{max} is the maximum power that the TCL can consume and $flex_{pos,n}$ is a binary variable which indicates if it is possible or not to increase the power consumption. When the room temperature is within limits, both $flex_{neg,n}$ and $flex_{pos,n}$ will be equal to one. On the other hand, when the room temperature is between the upper limit, the load is fully charged, this means $flex_{neg,n} = 1$ and $flex_{pos,n} = 0$, in other words, the load will lower down its consumption. Likewise, when the room temperature is touching the lower limit, the load consumption is at its minimum, this means $flex_{neg,n} = 0$ and $flex_{pos,n} = 1$, the load will increase its demand. For the aggregated load, the total available power reduction (P_{neg}) and power increase (P_{pos}) are the sum of all TCLs 8 - 9:

$$P_{pos}(t) = \sum_{n=1}^{N} P_{pos,n}(t) \quad (8)$$

$$P_{neg}(t) = \sum_{n=1}^{N} P_{neg,n}(t) \quad (9)$$

Furthermore, the power flexibility will be represented as the minimum of P_{neg} and P_{pos}. This means that P_{flex} is the minimum power that is ready to be dropped or increased considering the comfort of the residential user temperature in their home.

$$P_{flex}(t) = min\,[P_{pos}(t), P_{neg}(t)] \quad (10)$$

This gives an indicator of the flexibility that the demand can offer to the grid at any instant of time. By using P_{flex} it is possible to compare different control methods on aggregated TCLs, sine by choosing the control with better flexibility characteristics, will offer a more reliable grid service.

V. Results

In order to establish a relationship among the ambient temperature and the flexibility of the TCLs, a sensibility analysis over the outside temperature behaviour is exposed in this section. Additionally a comparison of the performance of modified ON/OFF and droop controllers is performed using the microgrid shown in Fig.1.

In this model the primary control is the droop control (1/R) and secondary frequency control is added by an additional integral control loop [5]. The parameters were selected according to [6] and are presented in Table I. For all the control methodologies, a random variation of the heaters temperature limits is applied with the purpose of avoiding the so called synchronization of the TCLs.

Moreover, the results are based on real data from the UK considering the installed capacity of wind and PV pannels (onshore 23%, offshore 29.2% and PV 27.7% of the total installed capacity the renewable energy in 2019), the historical demand data from UK National Grid [16] and the ambient temperature in Nottingham [17]. These are depicted in Fig. 2, in which the time line was considered for 5 consecutive days, with the purpose of having a wider perspective of the phenomena. The implementation was performed using MATLAB/Simulink. The power consumption of 50 TLCs is expressed as an equivalent load corresponding to 30% of the total power consumption in the system.

In the following subsections different periods of the year were selected to be evaluated regarding temperature variations, in this sense subsection V-A will expose the period among 01-05 Feb 2019 in which the average temperature is around $3°C$, meaning the coldest days along the year. On the other hand, the warmest day is also considered, this period is presented in subsection V-B, in which the days 25-30 Jul 2019 are evaluated and average temperature is around $18°C$.

Finally, a sensitivity analysis is performed considering several periods of the year, in order to assess the impact of the ambient temperature in the flexibility of the DR accordingly, this is shown in subsection V-C

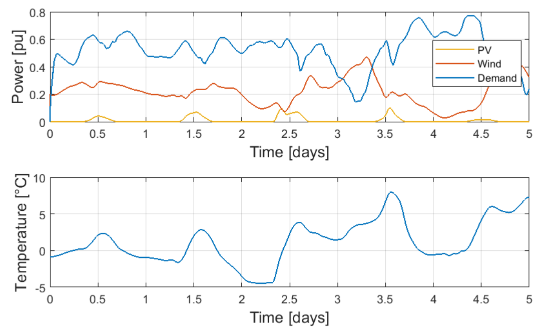

Fig. 2. (Top) Demand, wind and PV generation from UK historical data. (Bottom) Ambient temperature, Nottingham 01-05 Feb 2019

TABLE I
PARAMETERS OF THE MICROGRID MODEL

$K_T(pu)$	0.1	$T_T(s)$	0.3	$R(pu)$	0.5
$K\omega(pu)$	$1/2\pi$	$T_s(s)$	100	$D(pu)$	1
$T_a(s)$	0.2	$H(s)$	6.5	$K_w(pu)$	1
$K_{in}(pu)$	1	$T_{in}(s)$	0.04	$T_w(s)$	1.5
$K_{IC}(pu)$	1	$T_{IC}(s)$	0.04		

A. Case I: The Coldest Period

In order to validate that the temperature impact on the demand response flexibility, instead of evaluating the controllers behaviour over the TCLs, we focused on testing different periods of time over the same year and location, using real data from [17]. The extreme cases are interesting, therefore in this subsection the days 01 to 05 of February 2019, among this period the lowest temperature ($-4.47°C$) was recorded. This is also shown in Fig. 2. Keep in mind that a cold day provides the desirable conditions so the heaters can apply their functionalities, to warm up the house, as it should be. However, this is not the case for the warm periods of time.

For instance, Fig. 3 shows the behaviour of the ON/OFF control method applied to 50 TCLs, the variation after the day two is due to the high drop in the temperature, when it goes down to the lowest temperature $-4.47°C$, hence the heaters keep their warming action until the temperature increases again above $0°C$, this can be compared to the temperature previously shown in Fig. 2.

Later on, Fig. 5 will show the TCLs power, considering the ON/OFF and the droop-type control applied to the TCLs over the microgrid configuration. In particular, for this period of time, there are no irregularities, the system is affected a bit different from one control to another, but in general works as it should be.

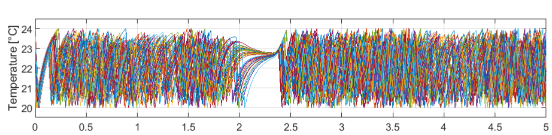

Fig. 3. Room temperature 01-05 Feb 2019

B. Case II: The Warmest Period

Similarly as the previous case, in this subsection the warmest temperature ($31.7°C$) is reached, which in turn will affect considerably the heaters, therefore the room temperature and the power flexibility offered by the demand response. To notice this effect, the temperature of the period 25-30 of July 2019 was considered. This is shown in Fig. 4, from which is noticeable that when the outside temperature is greater than $24°C$ (the heaters upper limit) there is nothing that the TCLs can do but to set their consumption to zero, this is also visible from Fig. 5 in particular during the first day.

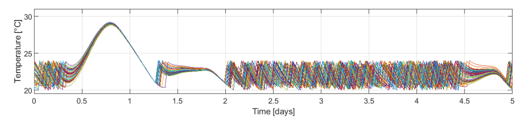

Fig. 4. Room temperature 25-30 July 2019

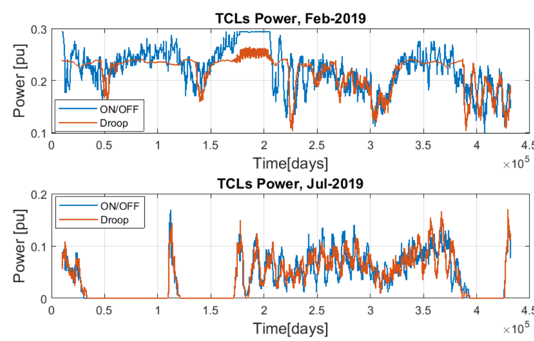

Fig. 5. TCLs power for Case I and Case II, using both control techniques

C. Sensitivity Analysis

It is worth to analyze the demand response flexibility when the temperature is varying over time. This is the aggregator point of view, since the weather prediction will help to determine how much flexibility can offer the TCLs in different periods of the year, thus, to offer a more reliable frequency support despite the applied control technique. Moreover, it can also be an option for the aggregator to help them to choose one control approach over other, depending on the weather forecast.

Hence, in this section, besides the two cases mentioned above more periods of time were tested, with the purpose of evaluating different ambient temperatures. Initially an intermediate period was tested, the average temperature over these time periods is around $1.2°C$, $9°C$ and $18°C$. Both control techniques were implemented over these time periods, and in Fig. 6 the flexibility is shown with the temperature as the sensitivity factor. From which is visible that, for higher temperatures, it is not possible to offer a confidence level higher than 90%, and with 60% confidence it can guarantee to offer at least 0.026pu, which is quite low in comparison with other periods of time that offer a better flexibility for the same confidence level (60$\%$ of probability), for instance for the coldest period with average temperature $1.2°C$ the flexibility correspond to at least 0.06pu for the ON/OFF control and 0.072 for the droop-type control. Even it increases significantly for intermediate temperatures such as periods with average temperature of $9°C$, for the same confidence level the ON/OFF approach offers at least 0.099pu and the droop-type control 0.104pu.

This widens the perspective on demand response flexibility, since the control methods can influence its behaviour, this study shows how the ambient temperature changes can modify the flexibility even more.

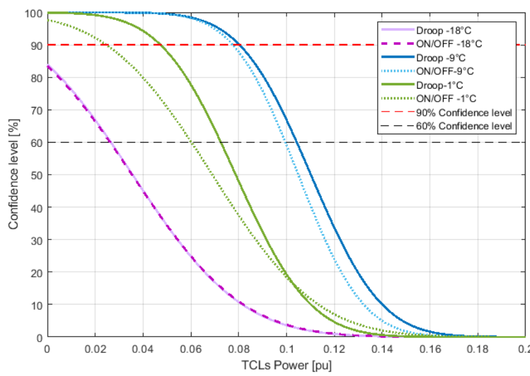

Fig. 6. TCLs flexibility over three periods of time, UK, 2019

Similar to the previous analysis, adding several time periods, considering the temperature variations, the tested periods had average temperature around $1.2°C$, $3°C$,$7°C$, $9°C$, $14°C$ and $18°C$. See Fig. 6, from which is visible that the flexibility is worse in the extreme temperatures, during the coldest and warmest days. However, when the average temperature is for instance $9°C$, meaning intermediate temperatures in which the heaters still operate, the flexibility is much higher with high confidence levels as well.

In order to help visualizing the temperature sensitivity impact on the TCLs power flexibility, observe Fig.7, in which all the periods of time are evaluated at a confidence level of 90$\%$, it can be observed that in one hand the flexibility is higher as we already mentioned when the temperature is around $9°C$ for both types of controllers, and even when the average temperature is $7°C$ both controllers offer the same flexibility, meaning that it is not a matter of developing complicated control techniques, since the ambient temperature may affect them equally in some periods of time. However, it is worth to be noticed that when the coldest periods are present, there is a noticeable difference among one control approach over the other, this is visible in all the tested periods, the droop-type control helps to improve the flexibility in comparison with the ON/OFF control method.

On the other hand, as higher the temperature, it is less the need for using heaters and that considerably affects the power flexibility offered by this type of flexible loads.

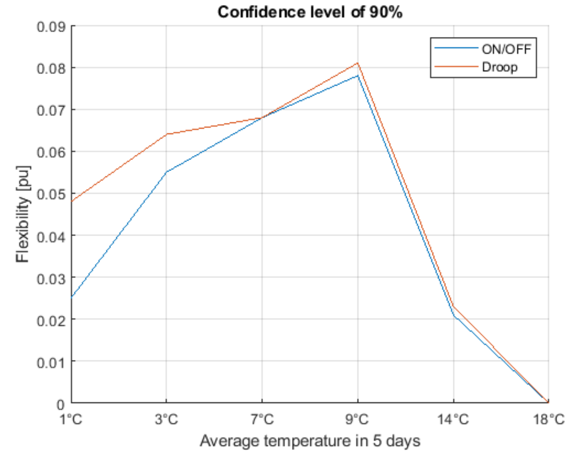

Fig. 7. Room temperature 25-30 July 2019

VI. Conclusions

The ambient temperature considerably impacts on demand response systems based on heating devices, which makes it a relevant parameter for offering ancillary services to the power grid, such as frequency support. This effect can not be ineluctable especially when choosing a desirable controller for flexible demand response.

Furthermore, from the results it is evident that in extreme weather conditions the flexibility of the TCLs is severely restricted or in some cases, such as very warm weather there is not flexibility at all, despite of the type of controller used for the TCLs. Nevertheless, the droop-type control shows a better performance, in this sense offers, $0.23pu$ more flexibility, for the coldest day in comparison with the ON/OFF approach at the same confidence level (90$\%$).

Further research will focus on comparing other type of controllers, also it is possible to consider a higher installed capacity of the TCLs (a larger percentage of participation in DR) in order improve the contribution to flexibility in microgrids.

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