Decentral Load Control for Grid Stabilization

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***Abstract*—Renewable energies lead to a decentralization of power generation but also to a destabilization of the power grid, as photovoltaic or wind turbine systems provide nearly zero inertia that is essential for a stable power grid. Leveraging consumer devices to support already present grid control systems counter the growing grid instability. These devices may adapt their power consumption continuously, rather than erratic on-off switching, to provide a grid-friendly stabilization effect. Simulations with a grid model of Continental Europe and multiple consumer load control schemes with different consumer-impact levels were performed to analyze stabilization effect and user tolerability. The results show effective stabilization by the tested consumer load control schemes during a reference incident, allowing them to be used for various devices and device groups. Additional, the simulations proved the scalability of the proposed control algorithms.**

***Index Terms*—decentralized grid stabilization, consumer load control, autonomous power adaptation, grid friendly behaviour, grid model**

I. Introduction

The electric power grid is for sure one of the largest constructs by human kind but only seldom consciously noticed. One reason for this is the nearly all time availability. In Europe, 19 countries form a large scale and consequently stable grid called "synchronous grid of Continental Europe". Distributed in the countries are power plants generating the electric power for the consumer. With the power grid as a distribution network rather than a reservoir, the power plants permanently have to regulate their supplied power. A strict regulation is important to keep the power grid in a stable state that defines as the ratio of power fed into the grid to power taken from the grid. Reaching a stable state with input equals output results in a stable grid frequency. With regard to the network function of power delivery and the network size, consumed power varies. This changes the previously mentioned ratio so that the producers have to regulate their output. This is the conventional, state-of-the-art approach. The following chapters present an approach to integrate consumers into the process of stabilizing the power grid. This will probably be necessary, since the trend continues to remove conventional power plants with high regulation potential from the power grid to incorporate renewable energy resources which tend to introduce fluctuations to the power supply and lack stabilization properties. [1]–[3]

This paper is organized as follows. Section II gives a brief overview on the effect of renewable energy systems on the power grid stability. Section III introduces related publications regarding the impact of decentral consumer power control. Section IV and V describe the simulation models, test scenario and examined control algorithms. Section VI and VII analyze the simulation results and their applicability to consumers. Section VIII presents the conclusion.

II. Factors of power grid stability

A. Grid stability and grid frequency

Generators in conventional power plants mainly form the connection between grid stability and grid frequency. They supply voltage with a frequency depending on their own rotational frequency. A varying energy withdrawal de- or increases the generator frequency and consequently the grid frequency. Inertia dampens these grid frequency variations. This instantaneous compensation is a stabilizing effect called *momentary reserve*. [4]

B. Impact of renewable energy

Conventional power plants have well-known negative effects on the environment, leading to the promotion and requirement of renewable energy production. Typically, this consists for example of wind turbines or photovoltaic systems, which can already provide a high amount of necessary power. In 2017, Germany generated around 36 % of the electric power with renewable energy plants [3]. However, they lack the capabilities generators of conventional power plants possess: momentary reserve and primary / secondary controllability [4]. Renewable energy systems currently have nearly no inertia that can be used for momentary reserve because of their operational principle and kind of grid integration without energy buffering. Therefore, with an increasing number of renewable energy systems coupled to the power grid, reducing the ability for stabilization, it seems reasonable to integrate consumers into grid regulation for a decentralized stabilization [5].

C. Advantages of decentralized grid stabilization

Consumers are responsible for power consumption and fluctuation. Whenever possible, devices should operate grid friendly within set boundaries. There are already international laws, which force grid friendliness. These obligates devices using a Switched Mode Power Supply (SMPS) with a rating of 75W or higher to integrate a Power Factor Correction (PFC) circuit for the reduction of harmonic frequencies resulting from the principle of operation of a SMPS [6]. This paper extends the approach of grid friendly behaviour to an active power adaptation of devices based on a continuous grid monitoring. This leads to the distribution of grid stabilization. It increases the general robustness in the case of (regional) blackouts and especially in the edges of the power grid with reduced numbers of nearby power plants. It may also reduce the load on the tie lines between different grid regions and the necessity to export or import additional power.

III. Related work

Decentralized stabilization of the power grid promises an effective way of general grid stabilization which is made possible by the sheer amount of power grid connected devices. On condition, they act grid friendly, which means modulation of their power consumption dependent on the power grid state. To counteract possible side effects, if devices start changing their power consumption beside their usual function, there are already studies investigating possible regulation methods. The following examples with focus on power grid stability give an overview on the state of the art.

Lu and Hammerstrom have investigated the idea of load regulation based on grid frequency in [7]. They proposed controlled on-off switching of certain devices with additional delay between switching events to avoid oscillations. In simulations, they investigated and discussed the effect of frequency set point, triggering delay, and reset delay as load control parameters on the grid stability. Considering that not every device is able to act the same, parametrization enables algorithm adaptation for different devices. An additional random delay effect was proposed, so not all devices switch their power state at the same time, further reducing oscillations.

In [8], Molina-García et al. presented a demand response control algorithm that is comparable to primary control, linearly regulating the power consumption of consumers. Their proposal depends not only on the frequency deviation but also on its temporal behaviour. Different devices and respectively device groups used distinct control regions to include various device profiles. The load regulation results in the decision if a device gets shutoff, using effectively load shedding for load reduction. The authors simulated their approach in a power grid model consisting of the primary control, neglecting self-regulating effect, and secondary control.

Simulations in a North American grid model were done in [9]. They proposed intelligent, autonomously acting loads acting with a linear load modulation like primary control. As in [7] and [10], they investigated the impact of their proposal on a load incident, which is used for testing purposes since it highly affects the system stability. The authors compared the results of their grid model including the logic to the default simulation model without intelligent loads and were able to show that it is possible to reduce frequency hops and oscillations. Similar to previously mentioned works ([7], [10]), their load regulation consisted of controlled load shedding of cooling and heating devices, basically.

The authors of [5] investigated the risk of a raid of malicious consumer electronics on the European power grid. A botnet consisting of various IT and smart home devices represents the network attack. Synchronized as swarm over the internet, these devices modulate their power consumption, inserting malicious control power. Because of their fast reaction time, the botnet can perform on the resonance frequency of the power grid. This could lead, under certain conditions, to load shedding in designated areas. The authors also show that with a decreasing number of conventional power plants due to the rise of renewable energy systems, the power grid tends towards a less inert state. The simulation results show the potentially significant impact of frequency-aware devices on the power grid.

This paper features the design and parametrization of an automatic control mechanism for consumer devices. This control should operate continuously and autonomously within devices altering their power consumption slightly, without the need for user interaction and preferably without perception. Target is the collaboration with the already present automatic grid control systems. The control verification uses a grid model that represents the synchronous grid of Continental Europe.

IV. Power Grid Simulation

A. Grid Model

A MATLAB Simulink model re-implemented from [4] represents the basis for all simulations. It is optimized and parameterized to meet the official specifications from [2], [11] and real world conditions from [1]. The power grid modelled by Equation 1 establishes a closed loop system with the automatic grid control instances. These instances handle grid frequency fluctuations and unexpected events like the European grid separation in November 2006 [4], [12]. Figure 1 shows a schematic of the power grid model including the control instances. The grid model parametrization allows different representations, e.g. small grids like the independent power grid of United Kingdom or large grids like the synchronous grid of Continental Europe. Representation of the latter assumes the same frequency in the whole power grid, all control participants acting the same and neglecting of tie lines. We do not consider the base load and daytime conditional load variations, because of their accommodation with the daily schedule, which defines the working point of power plants. Additional control mechanisms (e.g. tertiary control, load shedding) were deliberately ignored because they are both manually controlled and subject to extreme situations. With these design decisions, integrating just the automatic control systems to compensate power deviations models a suitable power grid. The parameters for the grid model are given in Table I. To a certain degree they allow the reliable verification of additional control systems. For more detailed information to the power grid model it is suggested to check [4].

The grid model also contains the following control algorithms:

- *Primary control:* It consists of a P-controller which responds directly and proportionally to a frequency deviation using Equation 2. Equation 4 limits the rate of change of the P-controller. Primary control is used to stabilize a frequency deviation which is predominantly realized via conventional power plants and therefore, with generators using the characteristic in Equation 5 [2], [11], [13].

- *Secondary control:* This control instance consists of a PI-controller with a delayed response that leads the frequency back to the norm frequency f_{norm} of 50 Hz if a frequency deviation consists for a prolonged time. The PI-controller computes the output based on Equation 3. The input represents the current impact of the *primary control* on the power grid. A rate limiter restricts the effect of the *secondary control*, see Equation 4. Limiting the integrator of the PI-controller to the maximum secondary power P_{sec} uses the "clamping" anti-windup method, to enable a fast controller response in the case of saturation [11] [2]. As the *secondary control* also uses turbines for electric power generation, it also uses Equation 5 as characteristic transfer function. The *secondary control* reaction time is designed to be lower than the *primary control* so that it only responds to frequency deviations, that do not automatically resolve by themselves.
- *Grid self-regulating effect (SRE):* It is inherently available due to loads with frequency dependent properties like grid-coupled motors. Ref. [11] defines it as percentage grid load change per grid frequency change with dimension in $\frac{\%}{Hz}$ units. It acts like a P-control with the frequency deviation Δf as input and already comparable with a passive consumer regulation effect for grid stabilization.

$$\Delta f(s) = \frac{f_{norm}}{2 * H * S_B * s} \tag{1}$$

$$c_P(\Delta f) = \begin{cases} C_{npfc}\Delta f & \text{, if } |c_P| < P_{prim} \\ P_{prim} & \text{, if } c_P > P_{prim} \\ -P_{prim} & \text{, if } c_P < -P_{prim} \end{cases} \tag{2}$$

$$c_{PI}(\Delta f) = \begin{cases} -C_p(C_{npfc}\Delta f) \\ \quad -\frac{1}{T}\int(C_{npfc}\Delta f)dt & \text{, if } |c_P| < P_{sec} \\ P_{sec} & \text{, if } c_P > P_{sec} \\ -P_{sec} & \text{, if } c_P < -P_{sec} \end{cases} \tag{3}$$

$$\Delta P(c) = \begin{cases} \frac{P}{T} & \text{, if } \Delta c \geq \frac{P}{T} \\ \Delta c & \text{, otherwise} \end{cases} \tag{4}$$

$$G(s) = \frac{1}{T_{td} * s + 1} \tag{5}$$

where (cf. [4], [13])

Δf = deviation from the norm frequency f_{norm}
$c_P(\Delta f)$ = P-controller output of primary control
$c_{PI}(\Delta f)$ = PI-controller output of secondary control
$\Delta P(c)$ = rate limited power change
G = turbine response
f_{norm} = norm frequency of the power grid
s = Laplace variable
P = control power of prim. or sec. control
T = control response time of prim. or sec. control
Δc = controller output deviation

Additionally, the parameters from Table I.

TABLE I
GRID MODEL PARAMETERS

Parameter	Variable	Value	Unit	Source
Base Power	S_B	$232 * 10^9$	W	[1]
Self Regulating Effect	D	1	$\frac{\%}{Hz}$	[11]
Rotational Inertia	H	6	s	[4]
Turbine Delay	T_{td}	5	s	[4]
Primary Control				
Power	P_{prim}	$3000 * 10^6$	W	[2]
Response Time	T_{prim}	30	s	[11]
Network Power - Frequency Characteristic	C_{npfc}	$19.5 * 10^9$	$\frac{W}{Hz}$	[11]
Secondary Control				
Power	P_{sec}	$16 * 10^9$	W	[11]
Response Time	T_{sec}	125	W	[11]
P-value	C_p	-0.25	s	[11]
I-value	C_i	$-1/T_{sec}$	Hz	[11]

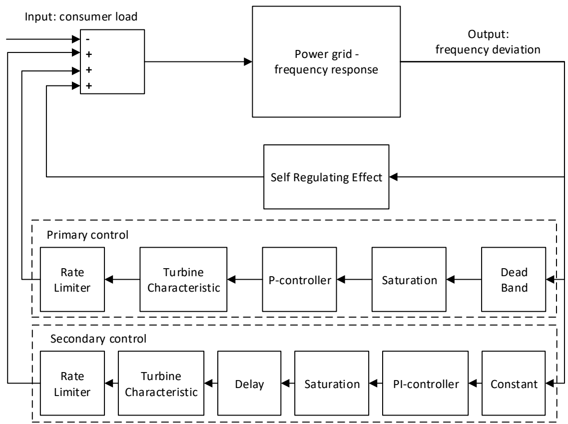

Fig. 1. Schematic of the power grid model (based on [4])

B. Simulation Model

As shown in Figure 2, the complete Simulink model consists of four elements:

- *Grid load,* simulates the power consumption of the consumer with an incident happening $50s$ after simulation start. These incidents are either positive or negative load changes that need compensation by control schemes preferably without oscillations and overshooting. Defined in [2], [11], [14], some incidents are:

- $600 * 10^6 W$ (smallest marked incident)
- $1000 * 10^6 W$ (observation incident)
- $3000 * 10^6 W$ (reference incident)

The grid frequency does not only change during larger incidents but instead keeps fluctuating permanently. Therefore, some load noise is added that is represented by a Gaussian-distributed random signal with a variance of 1, mean of 0, sample time of $0.02s$ and a additional gain factor of $15 * 10^8 W$. This empirically determined value leads to a simulated frequency deviation that is comparable to real world frequency deviations.

- *Consumer load control*, added to the grid load it represents the decentral regulated percentage of the base load. Basically, it is specified by Equation 6 and comparable to the *self-regulating effect*. Integrating an identical system without consumer load control enables a comparison of the model examined.
- *Grid model*, as described in section IV-A, consists of control mechanisms and system response functions forming a closed loop system, see Figure 1. Its target is to minimize the frequency deviation. For additional details see [4].
- *Observer/ data saving*, resp. feedback of the grid model for analysis and input for the examined load control schemes.

$$\Delta P = P_{CLC}(\Delta f) * ASRE * S_B \tag{6}$$

where:

ΔP	=	consumer grid load deviation
$P_{CLC}(\Delta f)$	=	frequency to power factor function of chosen consumer load control
$ASRE$	=	Active Self Regulating Effect
S_B	=	base load of the power grid

TABLE II
SIMULATION MODEL PARAMETERS

Parameter	Value
Simulation time	$400s$
Incident time	$50s$
Incident value	$3000 * 10^6 W$
Gaussian load variance	1
Gaussian load mean	0
Gaussian load gain	$15 * 10^8 W$
Gaussian load sample time	$0.02s$
Norm frequency	$50Hz$
Controllable base load portion	1%
Shutoff base load portion	0.1%

V. FREQUENCY-BASED CONSUMER CONTROL ALGORITHMS

The development of an additional control mechanism needs careful design as proven by [5]. Due to the complexity and importance of the power grid integrating consumer devices into power grid stabilization needs careful investigation. Therefore, potential grid control method tests often use incidents as they demand the action of multiple control systems and show possible implications. For the simulations, only 1% of the

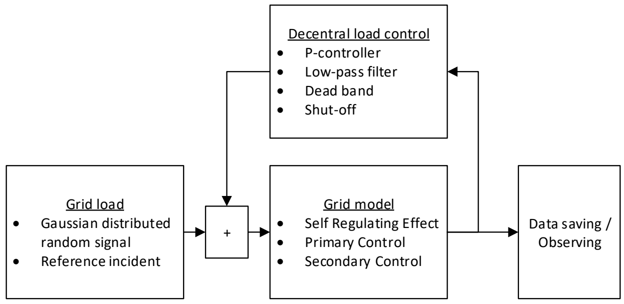

Fig. 2. Schematic of the complete simulation model in MATLAB Simulink

base load, specified as Active Self Regulating Effect ($ASRE$), is regulated. From the $ASRE$, only $\pm 10\%$ are adaptable, implying an effective power modulation of 0.1% of the base load. The remaining control scheme parameters are presented in table III and were partly determined heuristically. Below follows a brief description of different consumer control algorithms investigated. The visualization of the control algorithms in Figure 3 presents the calculation of the *power factor* P_{CLC}. This factor indicates the power adaptation of the consumer devices as percent of their current power consumption.

A. P-control

The consumer load control for grid stabilization proposed by [9] is a single P-controller with a gain value of 1.

B. Low-pass filter

For the continuous power adaptation, a steady control course steady course is preferred. Due to the usually existent frequency fluctuation, a single P-controller injects noise into the power adaptation based on the present frequency noise. Depending on the device, this could have certain disadvantages, for example flickering of lights. Therefore, introducing a low-pass filter placed before the P-controller dampens relative high frequencies and smooths the course. The choice of a smoothing method deliberately did not apply to an I-controller. The idea of a minimum impact on the consumer makes a low-pass filter essential to return the controller output to normal operation with an input frequency deviation of zero. This is not necessarily the case for the I-controller, that holds their current output if the input gets zero. As the P-controller gain value of 1 described in [9] yields beneficial results, this value was also chosen for this paper.

C. Low-pass filter and dead band

In addition to the low-pass, this consumer load control integrates a dead band. This was adapted by the primary control but with the intention that only larger frequency deviations lead to power adaptation while small frequency fluctuation does not alter the power consumption. Outside the dead band boundaries this control uses the P-controller above.

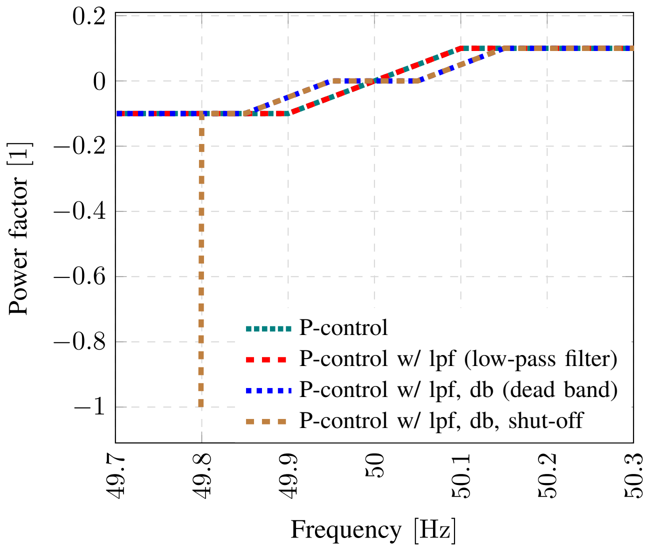

Fig. 3. Frequency-to-power-function of the consumer load controls

D. Low-pass filter, dead band and shutoff

As already mentioned in previous works, devices could also switch off if necessary. The shutoff respectively the start up function implementation needs careful design with a hysteresis. For this, different frequency deviation values were specified for shutoff and start up of devices. Switching off a high number of devices takes a high load from the power grid, leading to a smaller maximum frequency deviation but possible oscillations. Considering this, only 0.1% instead of 1% of the base load determine the regulated proportion for consumer load control, because of the significant impact of removing nearly instantaneous 1% of the load from the grid. Furthermore, all shut-off devices turn linearly over $500s$ back on. Otherwise, oscillations are likely to occur, because the load previously taken off the grid would promptly return.

TABLE III
CONSUMER LOAD CONTROL PARAMETERS

Parameter	Value
Maximum power deviation	$\pm 10\%$
P-controller gain (proposed by [9])	1
low-pass frequency (first order butterworth)	$2\pi 0.005Hz$
dead band	$\pm 50mHz$
shutoff frequency	$-250mHz$
start up frequency	$-100mHz$
start up time	$500s$

VI. Simulation Results

In Figure 4 a frequency drop related to the incident (see tab. II) is observable. The graph "Reference" serves as reference for comparison with the results of the consumer load control models. Maximum frequency deviation of the reference model is $\Delta f_{max} = -0.431Hz$ but a reduction of the maximum frequency deviation during the incident would have advantages, e.g. better (partial) blackout prevention. The consumer load control graph, displayed in Figure 6, shows the output of the respective consumer load controls. A negative output at the moment the frequency starts falling heavily indicates a correct behaviour of every control scheme as the power consumption is reduced. This reduces the amount of power deviation that needs regulation by the control algorithms. Within the simulations, the P-controller with or without low-pass filtering reaches the best effect of stabilization. The maximum frequency deviation due to the reference incident is around $-0.38Hz$, which is an improvement of around 11% compared to the reference model. Slight damping of normal frequency fluctuations are observable in Figure 4 between $0-50s$. This is also the case in the same time range of Figure 6: With the continually adapting power deviation, devices using these approaches continuously change their power consumption. However, the control with additional low-pass provides the same stabilizing effect for large incidents as a single P-controller but reduces power factor course fluctuation. This is more suitable for decentral load control since the impact on the user is generally smaller. The reduction of frequency deviation is still around 11%. The noise reduction ability reduces significantly but is still recognizable. Integrating a dead band into the control allows devices to operate unaffected under normal grid condition but enables stabilization support for larger incidents nearly as effective as the P-controller. The dead band effectively removes the frequency noise damping as expected. A combination of low-pass, dead band and shutoff function needs a proper modelling to prevent oscillations. Reducing the $ASRE$ to 0.1% prevents implications like large oscillation peaks which could e.g. damage generators. This control scheme offers the weakest performance (around 9.5%), which is potentially reasoned by the delayed shutoff function which starts shortly after an already happened frequency deviation to prevent device shutoff during normal operation and the following reactivation of the shut-off devices.

Scalability of consumer load control is shown with an increase of $ASRE$ to 2%. Choosing the same test scenario facilitates the comparison of the stabilization effect. Figure 5 shows the frequency response to the incident. Table V gives the the simulation results for the scalability test. Generally, the maximum frequency deviation reduces further compared to the results with $ASRE = 1\frac{\%}{Hz}$. Therefore it increasingly improves the grid stabilization. Using the single P-controller of [9] enhances the impact compensation by around 22%, regarding to the result without additional load control, with a maximum frequency deviation of $-0.33Hz$. Using the filtered P-control, the improvement is still around 21%. Both control schemes reach nearly the double effect with a doubling of the $ASRE$. Integrating a dead band with and without shut off clearly has a diminishing return. The simulation with the shut off control even results in an overshoot followed by light oscillations. With more devices that turn off during an incident, overshooting and oscillation further increases.

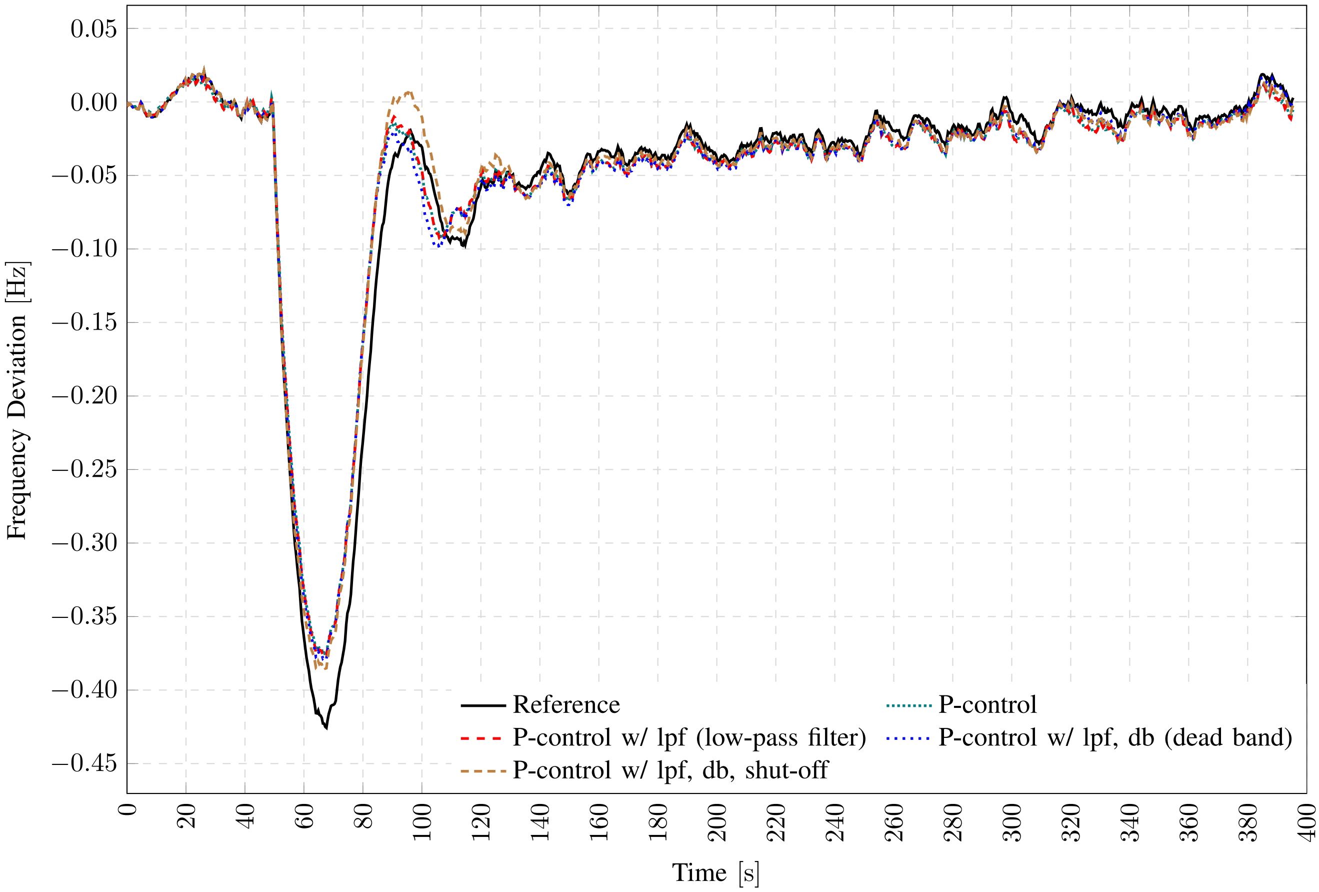

Fig. 4. Frequency response to a positive reference incident and 1% ASRE

TABLE IV
CONSUMER LOAD CONTROL SIMULATION RESULTS FOR $ASRE = 1\%$

Control scheme	Max. $\Delta f[Hz]$	Improvement [%]
Reference model	-0.431	-
P-controller w/o low-pass	-0.383	11.67%
P-controller w/ low-pass	-0.382	11.33%
W/ low-pass, dead band	-0.384	10.95%
W/ low-pass, dead band, shutoff	-0.390	9.463%

TABLE V
CONSUMER LOAD CONTROL SIMULATION RESULTS FOR $ASRE = 2\%$

Control scheme	Max. $\Delta f[Hz]$	Improvement [%]
Reference model	-0.431	-
P-controller w/o low-pass	-0.33	22.31%
P-controller w/ low-pass	-0.334	21.41%
W/ low-pass, dead band	-0.339	20.35%
W/ low-pass, dead band, shutoff	-0.353	16.97%

VII. SIMULATION EVALUATION

We simulated multiple load control algorithms with the grid model presented. To reduce the consumer impact but still allow grid friendliness, a consumer load control with inertia is the favoured behaviour. The integration of a low-pass generally achieved that goal as it dampens potential grid frequency fluctuations or other high frequency changes. This allows effective network stabilization without significant consumer impairment.

Integrating the dead band or shutoff option leads to a slight setback regarding to grid stabilization. A major advantage is that all methods are usable for different device categories. Unlike other proposals, which only take the on/off switching of heating and cooling devices into account, load adaptation by using power altering considers all electronic devices. By integrating a decentral load control, devices like computer continue to operate as usual, although the computing power reduces for a short period if necessary in favour of power reduction. The charging current of batteries de- or increases for some time in certain bounds without malfunctioning. Washing machines could reduce their rotational speed or the heating power. Other devices, like lamps, could help in stabilizing during larger incidents by using the presented decentral load control with low-pass and dead band. Some light intensity deviation is preferred compared to a potential blackout. Nevertheless, during normal activity the lights should not flicker because it would be annoying and potentially sickening. Of course, leaving out safety or medical devices is essential since they need to operate without interfering. A high amount of all electric devices could support stabilizing the power grid within

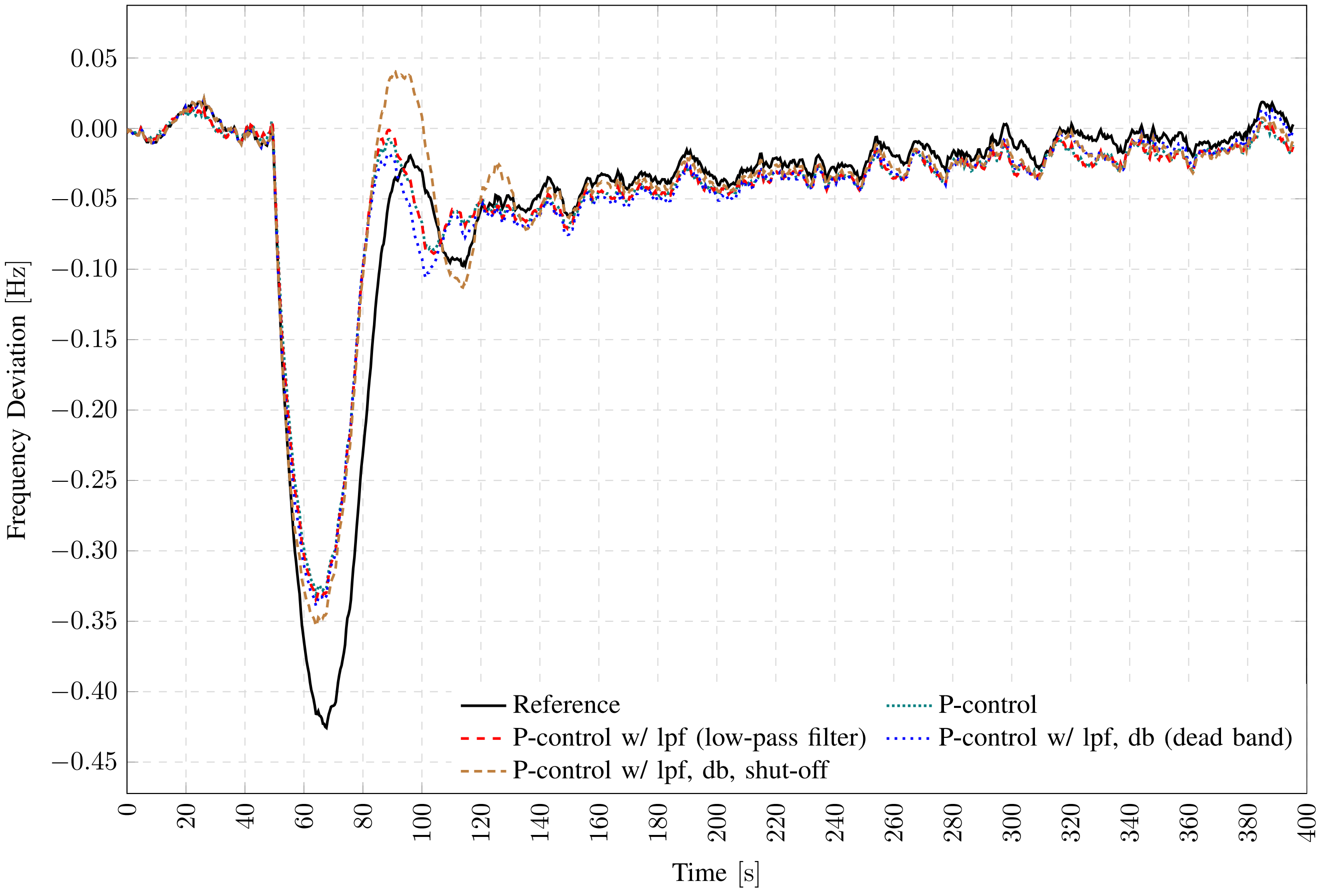

Fig. 5. Frequency response to a positive reference incident and 2% ASRE

their individual boundaries and still keep their functionality. An increasing number of devices that support decentral load control will also greatly enhance the stabilizing effect proven by the scalability of the continuous load control schemes in the previous section.

VIII. Conclusion

The development of a decentral load control algorithm for continuous power adaptation included the joint implementation of a suitable grid model with three automatic control algorithms (*self regulating effect*, *primary control*, and *secondary control*) and a parametrization to represent the synchronous grid of Continental Europe power grid. This specific task needed some adjustments on the power grid model but allowed simulations with a sufficient precision and performance while preserving the possibility for extension. Results show that a P-controller with low-pass filter offers the best trade-off between consumer impact, grid stabilization, and scalability. This consumer load control algorithm provides the same stabilization effect during an incident as the on without low-pass filter. Considering the idea of equipping electronic devices with a power control mechanism concludes that not all devices can or should act the same because of their task. For example, lights might be safety related so that the deviation of the light intensity could easily distract or annoy people. The integration of electric cars into grid stabilization offers further options beside power adaptation for example charge delaying and energy buffering that is subject of future work. Just considering these examples, it seems necessary to divide devices into classes. These classes should specify their support ability so that an algorithm can be used, which suits the nature of a specific device without heavily interfering the consumer. All MATLAB Simulink models and parameters used are available at [15].

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References

[1] Eurostat, “Supply of electricity - monthly data,” European Statistical Office, Tech. Rep., 2018, europe (19 countries), 08 September 2018.

[2] ENTSO-E, “Appendix 1 - Load-Frequency Control and Performance,” European Network of Transmission System Operators for Electricity, Tech. Rep., 2004.

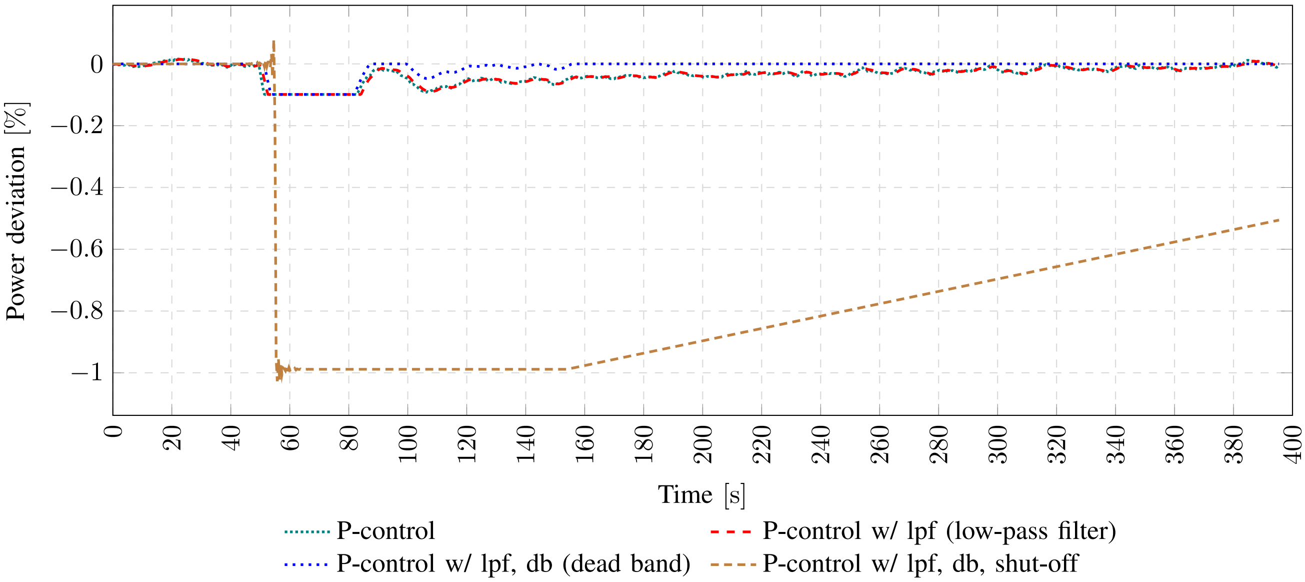

Fig. 6. Power consumption deviation of the regulated part ($ASRE = 1\%$) of the base load in response to a positive reference incident

[3] Bundesministerium für Wirtschaft und Energie, "Erneuerbare Energien in Zahlen," brochure, september 2018.

[4] A. Ulbig, T. S. Borsche, and G. Andersson, "Impact of low rotational inertia on power system stability and operation," *IFAC Proceedings Volumes*, vol. 47, no. 3, pp. 7290–7297, 2014.

[5] A. Dabrowski, J. Ullrich, and E. R. Weippl, "Grid shock: Coordinated load-changing attacks on power grids: The non-smart power grid is vulnerable to cyber attacks as well," in *Proceedings of the 33rd Annual Computer Security Applications Conference on - ACSAC 2017*, ser. ACSAC 2017. New York, NY, USA: ACM Press, 2017, pp. 303–314.

[6] U. Schlienz, *Schaltnetzteile und ihre Peripherie*, ser. Vieweg Praxiswissen. Vieweg Friedr. + Sohn Verlag, 2007.

[7] N. Lu and D. Hammerstrom, "Design considerations for frequency responsive grid friendly™ appliances," in *2005/2006 PES TD*. IEEE, May 2006, pp. 647–652.

[8] A. Molina-Garcia, F. Bouffard, and D. S. Kirschen, "Decentralized demand-side contribution to primary frequency control," *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 411–419, feb 2011.

[9] D. Trudnowski, M. Donnelly, and E. Lightner, "Power-system frequency and stability control using decentralized intelligent loads," in *2005/2006 PES TD*. IEEE, May 2006, pp. 1453–1459.

[10] K. Pandiaraj, P. Taylor, N. Jenkins, and C. Robb, "Distributed load control of autonomous renewable energy systems," *IEEE Transactions on Energy Conversion*, vol. 16, no. 1, pp. 14–19, mar 2001.

[11] ENTSO-E, "P1 - Policy 1: Load-Frequency Control and Performance," European Network of Transmission System Operators for Electricity, Tech. Rep., 2009.

[12] UCTE, "Final report, system disturbance on 4 november 2006," Union for the Co-ordination of Transmission of Electricity (UCTE), Tech. Rep., 2007.

[13] G. Andersson, "Dynamics and control of electric power systems," *Lecture notes*, pp. 227–0528, 2012.

[14] ENTSO-E, "Incidents classification scale methodology," European Network of Transmission System Operators for Electricity, Tech. Rep., 2014.

[15] F. Uster, "Netz-Stabil - Dezentrale Netzstabilisierung," https://gitlab.com/FelixUster/netz-stabil---dezentrale-netzstabilisierung, 2019.