Self-Regulation of Dispatchable Loads: Stabilizing Interconnected Networks with Resilient Microgrid Technology

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Self-Regulation of Dispatchable Loads: Stabilizing Interconnected Networks with Resilient Microgrid Technology

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Abstract

In this paper, the methodology of "self-regulation of dispatchable loads" is presented as a "keep it simple and stupid" (KISS) implementation for the grid integration of dispersed flexibility options in low-voltage networks. The corresponding technical specification IEC TS 62898-3-3 is explained in detail as well as the related economic assessment. In the light of the speed of expected deployments of electric vehicles and heat pumps, the authors advocate a quickly scalable approach that has already been used in the past with distributed generators: a type test as conformity assessment of standardised requirements.

1 Introduction

Self-regulation is important for the resilience of electric power systems. [1] Traditionally, frequency is automatically stabilized by frequency-adaptive consumption of certain loads, including directly coupled electric drives like pumps, etc. Similarly, voltage-adaptive ohmic loads can help to maintain voltage stability in distribution grids. However, the traditional self-regulating effect is slowly declining, as more loads are controlled by power electronics that lack the dynamic behaviour of "traditional" loads.

In the ongoing energy transition, dispatchable loads such as electric vehicles and heat-pumps (including air-conditioners) are expected to be deployed in large numbers. These devices have the potential to compensate for this decline of self-regulation in electric power systems. In contrast to critical loads which only serve the user's needs, dispatchable loads can help stabilise the grid by modifying their power profiles, while also maintaining functionality for the end user within acceptable ranges. Frequency and voltage could be easily used as information carriers in control algorithms to emulate the self-regulating effect.

Self-regulation is a simple, easy-to-implement, robust and hacker-proof method to integrate large amounts of small dispatchable loads into an electric power system. The rapid deployment of electric vehicles [2] demands a scalable approach for grid integration, which does not lead into the complexity trap. Self-regulation will offer a simpler smart charging method. The standardisation project IEC TS 62898-3-3 "Self-Regulation of Dispatchable Loads" is soon to be finished. This IEC document deals with both frequency and voltage stabilisation. Although its scope focuses on self-regulation in microgrids, the principles are also applicable to loads in interconnected distribution networks. Microgrids may serve as testing ground for the implementation in larger power systems.

2 Self-Regulation Explained

Self-regulation of loads is a phenomenon known very well by transmission system operators. [3] This effect emerged from the dynamic behaviour of speed controlled generators and electric motors. They were used to power mechanical drivetrains e.g. for pumps or air blowers. The higher the rotational speed of the drive, the more active power is needed and vice versa. This effect automatically contributes to frequency stabilisation without a supervisory control. With dispatchable loads responding to the grid frequency, no bidirectional communication channels or complex control systems are needed. Small loads can be quickly integrated in the common task of keeping the electric system stable.

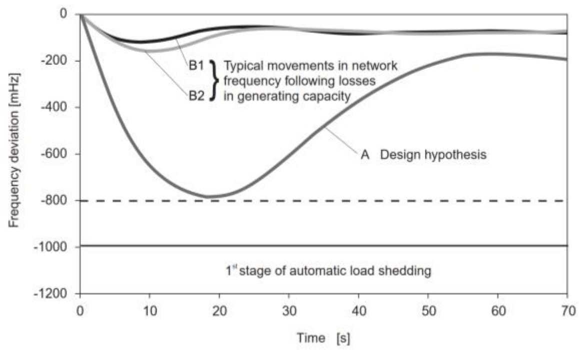

Figure 1 Frequency development after a disturbance with different levels of self-regulation B1, B2 [4]

There is also a self-regulation effect by resistive loads. The current through a resistive load increases at higher voltages. This increased current also flows through the impedance of the upstream supply network, resulting in a voltage reduction. This effect helps to stabilise the voltage.

3 Technical Aspects

3.1 Stabilisation of frequency and voltage

The self-regulation of loads can contribute to the stability of both frequency and voltage by emulating the known behavior of traditional loads. Their control schemes are provided below.

3.1.1 Frequency regulation

Frequency stabilisation by dispatchable loads is achieved through a frequency-sensitive control mode (P(f) load regulation) of the load's controller, where the dispatchable load will adjust its active power consumption level in response to a change in power frequency. The objective of this self-regulation is to contain nominal frequency without major deviations and to improve frequency quality. This approach emulates the known behaviour of a constant torque rotating electric machine directly connected to the electric power system. It avoids the P(f) = const behaviour of some loads, e.g. inverter-controlled drives, which causes degradation of the self-regulation effect.

Specifically, the P(f) control function can be formulated as follow

$$P(f) = P_{set} + \Delta P(f) \tag{1}$$

$$\Delta P(f) = k_{1c,f} \cdot (f - f_{set}) \cdot P_{set} + k_{3c,f} \cdot \frac{df}{dt} \cdot P_{set} \tag{2}$$

The response function in (2) contains two components. The k1c,f term represents frequency response with proportional droop, which emulates a constant torque. The k3c,f term is frequency response proportional to df/dt (derivative component), which delivers synthetic inertia. The respective components can be disabled by setting k1c,f or k3c,f = 0. The differential in the derivative component amplifies high frequency noise (see Fig. 2 for the Bode diagram). Therefore, a first-order low pass filter is needed for compensation and to level out the noise above a certain cut-off frequency.

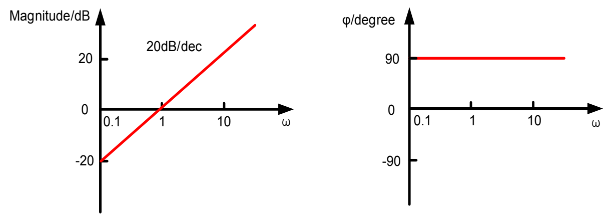

Figure 2 Bode diagram of a typical differential loop

The functional diagram of a combined frequency control function is presented in Fig. 3.

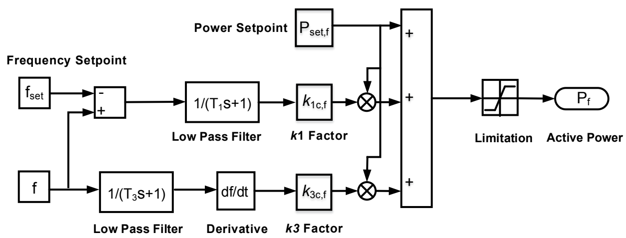

Figure 3 Block diagram of combined frequency control

3.1.2 Voltage regulation

Voltage stabilisation by dispatchable loads is achieved through a voltage-sensitive control mode (P(U) load regulation) of the load's controller, where the dispatchable load will adjust its active power consumption level in response to a change in system voltage. The objective of this self-regulation is to contain nominal voltage without major deviations and to improve voltage quality. This approach emulates the known behaviour of an ohmic resistor or a constant current source, having a constant or linearly rising current with rising voltage. It avoids the P = const behaviour of some loads as this means a negative differential resistance, which is equal to a reduction of effective short circuit power.

$$P(U) = P_{set} + \Delta P(U) \tag{3}$$

$$\begin{aligned}\Delta P(U) = {} & k_{1c,U} \cdot (U - U_{set}) \cdot P_{set} + k_{3c,U} \cdot \frac{dU}{dt} \cdot P_{set} \\ & + k_{2c,U} \cdot \left[2 \cdot U_{set} \cdot (U - U_{set}) + (U - U_{set})^2 \right] \cdot P_{set}\end{aligned} \tag{4}$$

The response function in (4) consists of three components. The k1c,U term is the proportional component emulating a constant current source. The k2c,U term emulates the behaviour of constant ohmic resistors and grows linearly with current. The k3c,U term represents voltage response proportional to dU/dt (derivative component), which emulates a capacitor. The respective components can be disabled by setting k1c,U, k2c,U or k3c,U = 0. Similar to frequency regulation, as the differential in the derivative component amplifies high frequency noise, a first order low pass filter can be used to level out the noise. The functional diagram of a combined voltage control function is shown in Fig. 4.

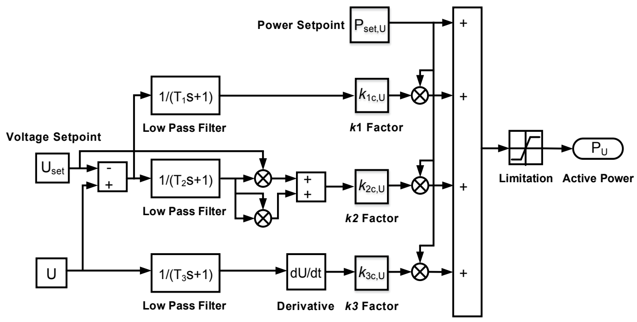

Figure 4 Block diagram of combined voltage control

3.1.3 Hybrid control for both voltage and frequency

The frequency response function (2), voltage response function (4), and the set value coming from the economic dispatch (EMS) can be added to create a hybrid control scheme:

$$P(f,U) = P_{set} + \Delta P(f) + \Delta P(U) \tag{5}$$

The related time constants for each of these sub-functions, e.g. for filtering the frequency and voltage input values can be different. The synchronisation of the sampling rates should be considered. The last available RMS value should be used at the reporting moment t for both frequency and voltage.

3.1.4 Prioritisation of the current capability

Grid-stabilising features by dispatchable units, both on the generating and consuming side of the balancing equation of the electrical energy supply system, are more and more requested, see also the discussion on grid-forming and related services. Nevertheless, the term is not properly defined. Does it refer to frequency, voltage or current, and how should the prioritisation of different targets be managed? A multi-dimensional optimisation is needed and also the final translation into financial incentives is crucial, else the end user will not be interested.

3.2 Hysteresis control of switchable loads

The control schemes introduced in 3.1 have assumed that the dispatchable loads are continuously dispatchable. In reality, switchable loads with only ON/OFF statuses can also be used in both frequency and voltage regulation. A cluster of dispatchable loads that follows a staged disconnection and staged reconnection can emulate a droop as a whole. The switching between states depends on an internal system state (e.g. temperature as an indicator for the state of charge of a thermal energy storage) and the measured network frequency or voltage. For a switchable load participating in self-regulation, a hysteresis controller can be used. The setpoint is the desired internal state (e.g. temperature level or SOE), and the ON-OFF hysteresis shifts the switching thresholds of the two-state controller.

The ON-OFF thresholds of such a hysteresis controller are formulated in (6)-(7). Note that the ON state means the energy storage is charged.

$$ON_{threshold} = setpoint - 0.5\ hysteresis_{width} \tag{6}$$

$$OFF_{threshold} = setpoint + 0.5\ hysteresis_{width} \tag{7}$$

The hysteresis controller can be configured to stabilise frequency or voltage by adjusting the thresholds accordingly. As an example, the combined frequency response function of different controller logic components for a hysteresis controller can be formulated as below.

$$ON = setpoint - 0.5\ hysteresis_{width} + k_{1s,f} \cdot \left(f - f_{set}\right) + k_{3s,f} \cdot \frac{df}{dt} \tag{8}$$

$$OFF = setpoint + 0.5\ hysteresis_{width} + k_{1s,f} \cdot \left(f - f_{set}\right) + k_{3s,f} \cdot \frac{df}{dt} \tag{9}$$

3.3 Step response performance and damping

Sufficient damping of self-regulation of dispatchable loads is a necessary characteristic to prevent resonance processes or oscillations and to tune a suitable characteristic of the dynamics. The general principle is to pursue a satisfactory dynamic performance, i.e., to avoid any large delay or overshoot.

Power system dynamics can be approximated in a simple case with a second order ordinary differential equation:

$$\ddot{x}(t) + 2\vartheta\omega_0\dot{x}(t) + \omega_0^2 x(t) = 0 \tag{10}$$

where ϑ is the damping ratio, and ω_0 the characteristic angular frequency. A damping ratio of $\vartheta = \sqrt{2}/2$ for a load results in an overshoot ratio of less than 5 %. Acceptable ranges for damping ratio are within a bandwidth of -10 % and +5 % of this value.

3.4 Rebound effects and desynchronization

Switchable loads that react on frequency signals via hysteresis controllers can give rise to rebound effects. [5] In order to avoid oscillations caused by rebound effects and synchronisation of switchable loads, it should be ensured that the aggregated response of loads is always in a dispersed manner, so that a synchronised group of loads quickly diverges and rebound effects are minimized. This can be achieved by several possible approaches, e.g. adding non-deterministic elements in the load's control structure, increasing the heterogeneity of different loads, or converting the ON-OFF hysteresis into a kind of long-duration pulse width modulation.

3.5 Dimmer approach as remote control option

The combination of the P(U) function as a receiver with a P(U) function as a sender (e.g. the on-load tap changer at a substation's power transformer) allows to establish an analogue communication channel. Similar to a dimmer for controlling the light output of a chandelier with filament lamps, which modifies the effective supply voltage, a voltage regulating transformer can influence resistive loads in the downstream grid segment [6]. Varying the mains voltage within the tolerance band of standard voltages will impact the active power consumption of the distribution cell. It is an investment-free option to remotely affect the behaviour of a whole subordinate grid cell.

3.6 Strengthening resilience

The self-regulation concept reduces the risk that cascading failures will propagate, as dispersed forces automatically push the operating point back to normal working conditions during a transient. This self-healing effect also minimises the probability of a system split which may lead to a blackout. Even if a system split does occur, the resulting electrical islands with self-regulating loads are more stable and have a higher probability to survive the disturbance. In the extreme case where the power system needs to disintegrate in small microgrids, self-regulation ensures better island stability with only a few dispatchable loads and generators. Consequently, the approach not only reduces the risk of a major disturbance, but also improves the survivability in the event of such a disturbance.

3.7 Technical pros and cons

A P=const controller poses a negative differential resistance, as a decreasing voltage will lead to a higher current. This corresponds to a positive feedback, as the voltage drop will be even higher due to the rising voltage drop along the line. Consequently, the decline of effective short circuit power is expected, as smaller charges in the local network load will lead to higher fluctuations in system voltage.

While a remote-controlled scheduling can address each device individually, a new setpoint may nevertheless follow the P=const behaviour. The emulation of an ohmic resistor will counteract this effect. Further-more, the ohmic behaviour of distribution networks may also help TSOs that the causal loop of power system stabilisers will not lose its effectiveness. Modulated system voltage at transmission level is translated to corresponding changes of active power consumption at distribution level, which dampens low frequency inter-area oscillations.

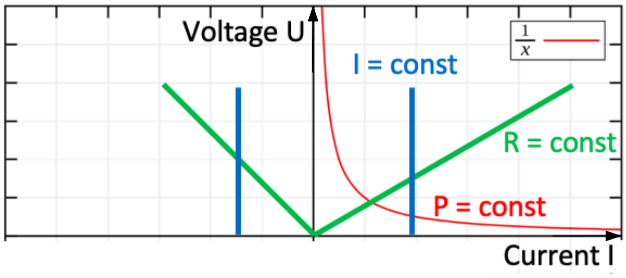

Figure 5 Schematic overview of the hyperbolic function of a P=const control, compared with R=const and I=const.

The proposed approach has a disadvantage in that units cannot be controlled individually. However, this also means that there is no need to bother about legal requirements regarding personal data protection, as personal data is neither transmitted, stored, nor processed.

3.8 Testing

At IEC, project TS 62898-3-3 (Self-regulation of dispatchable loads) has been recently approved. If will be published in the coming months.
In the past, when wind farms became significant for system operation (usually connected at MV level) or when PV systems became significant (mainly at LV level), shortcomings had been identified in grid connection requirements, such as the missing UVRT capability of MV wind turbines or the 50,2 Hz issue with LV PV inverters. Consequently, grid connection requirements needed an update and retrofit schemes (SDLWindV, SystStabV) have been initiated to amend existing hardware. The above-mentioned project was developed by SC8B / JWG1 (Microgrids), the technical specification mainly refers to the use case of microgrids, which allows a confined test environment and proving ground. If something goes wrong, the failure is restricted to a small sandbox. TSOs can use microgrids as a test lab to doublecheck new requirements and chosen parameters for advanced capabilities in new grid operation.

However, as the principle of self-regulation is not only beneficial for islanded microgrid operation but also for extended interconnections, the scope of the above-cited document allows: “If agreed between system operator and grid user, the self-regulating principles outlined in this document can also be applied to loads in other electricity networks, see IEC/ISO Directive 1, Edition 18.0, Annex C, clause C.4.3.2, Example 1.”

4 Economic Assessment

The benefits of the self-regulation scheme can be evaluated on the one hand by the savings, which are possible in the power system itself resulting from the use of distributed flexibility in the form of dispatchable loads. On the other hand, we may also look at the different possibilities of how to activate these flexibility options, in which case we compare the self-regulation technique with telecontrol channels, e.g. via a smart grid infrastructure.

4.1 Macro-economics

4.1.1 Frequency stabilisation

The most obvious benchmark for the frequency droop in dispatchable loads is the price for primary control reserve, also called frequency containment reserve (FCR). The proportional controller in power plants needs to be fully activated within 30 s e.g. according to requirements in the Central European Interconnection. Most of the distributed loads which offer flexibility can realise a much faster reaction, with step response times faster than 1 s, with power electronics even less than 200 ms seems to be easily achievable. Assuming "faster is better" (e.g. in a major disturbance such as a system split with a rate of change of frequency (ROCOF) of 1-2 Hz/s or even more [7]), then the system response from loads is even more valuable than the usual primary control reserve. Related ancillary services are in preparation under the term fast frequency reserve (FFR) in Australia and Italy. [8-9]

Regarding an inertial response, proportional to the ROCOF and therefore a differential control function, no market so far serves as a yardstick, as inertia is inherently part of synchronous machines. Future synthetic inertia may be activated in grid-connected converters, either as a legal or contractual obligation [10].

The price development at the German FCR market during the last decade is shown in Fig. 5. During the first years, the price fluctuated between 2500 – 5000 €/MW/week (ca. 130 - 260 €/kW/a). With the year 2016 the use of battery energy storage systems (BESS) began to enter the FCR market with a rate of almost 100 MW/a. This lets the more expensive service providers disappear as the total operating costs of a BESS were lower than e.g. the wear and tear in steam generators of thermal power plants. The market price began to decline. In the years 2019/20 the price went down to 1000 - 2000 €/MW/week (ca. 0,5 - 1 ct/kW/h). It is expected that the prices will decline further with falling costs for battery cells (learning rate ~20 % [11]). Since 2021 FCR prices rose significantly, as remaining thermal plants in the primary reserve market have higher opportunity costs during times of escalating fuel prices.

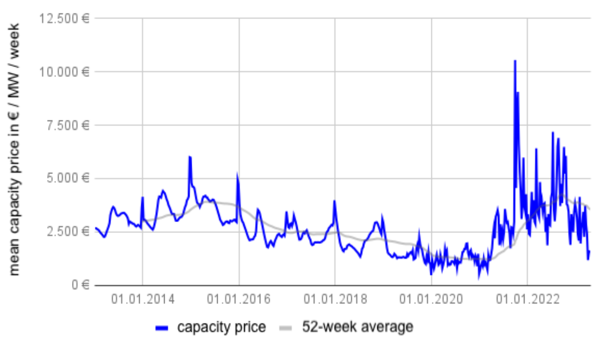

Figure 6 Historic overview of prices for primary control reserve (FCR) in Germany since 2013 in €/MW/week [12]

In the future, the FCR price is expected to fall again, when BESSs will dominate and compete with each other. The prices may even go beyond the level, which is needed to refinance the initial CAPEX, if the battery is operated in a dual or multiple use mode. Then, FCR is a joint product while the main revenue stream is generated elsewhere. Arbitrage (selling high, buying low) at the spot market may be a future area of activity; the real option of a BESS may be evaluated by techniques known from financial options such as the Black-Scholes model.

4.1.2 Voltage stabilisation

A P(U) controller for distributed loads is not only helpful for stabilising the voltage in the distribution grid. As MV and especially LV lines have a high R/X ratio, the mains voltage is a sign of the load flow on the connecting feeders. Consuming electricity if the voltage is rather high and reducing its use if the voltage is rather low will balance the current flow in the lines. This principle is explored e.g. by the German utility LEW in the FLAIR project (FLexible Assets Intelligently Regulated), which argues: "Voltage rises when electricity from distributed generation, usually photovoltaic systems, is fed into the corresponding line section of the local grid. Then the FLAIR control tries to increase the local electricity consumption by switching on the heat pump or charging the electric car." [13]

In a cellular energy system, local balancing reduces the need to exchange power with other cells via transmission lines (cf. subsidiarity principle). Therefore, the value of local flexoptions can be estimated by determining the costs of the grid infrastructure. A future mix of grid expansion and flexoptions will help to cope with non-dispatchable generation. In the end, the solution will be neither the extremum of a copperplate nor a highly flexible isolated microgrid - rather something in between. An economical equilibrium can be assumed if both options show the same costs, i.e. the CAPEX for grid extension (shift in space) is near the expenses for flexibility (shift in time).

Implying that grid operators do not overcharge their customers and presuming that grid tariffs mirror the real costs, then the price for a 24/7 baseload usage of the grid reflects the full cost of the specific grid capacity. Table 1 shows the 2022 costs of this baseload usage with four German TSOs and the Guangdong and Shaanxi provinces in China. [14-18] 1 kW transmission capacity saved means 120 €/kW/a; assuming an annuity factor of 10 (e.g. 7 % with a payback time of 20 years) this results in a net present value of 1200 €/kW, which is a rough estimate for the NordLink HVDC transmission's CAPEX between Germany (non-dispatch-able RES) and Norway (storage hydropower). [19]

Table 1 Grid costs of baseload usage with four German TSOs and the Shaanxi and Guangdong province in China.

	capacity price	energy price	total costs at 8760 h/a
50Hertz, DE	70.37 €/kW/a	0.50 €ct/kWh	114.17 €/kW/a
Amprion, DE	67.55 €/kW/a	0.50 €ct/kWh	111.35 €/kW/a
Tennet, DE	78.36 €/kW/a	0.50 €ct/kWh	122.16 €/kW/a
TransnetBW, DE	72.81 €/kW/a	0.43 €ct/kWh	110.48 €/kW/a
Guangdong, CN	(32+23) ¥/kW/mo	0,0212 ¥/kWh	845.71 ¥/kW/a
Shaanxi, CN	(31+22) ¥/kW/mo	0,0604 ¥/kWh	1165.10 ¥/kW/a

Balancing non-dispatchable generation with dispatchable loads will stabilise the utilization factor of the grid, otherwise the full-load hours of PV generation (1000 h - 2000 h depending on the location) will dominate the load factor of the of upstream network. The latest amendment of the German Renewable Energy Sources Act (EEG) targets 215 GW photovoltaic in 2030 and 400 GW in 2040 [20] within a system which so far had a peak consumption of 80 GW.

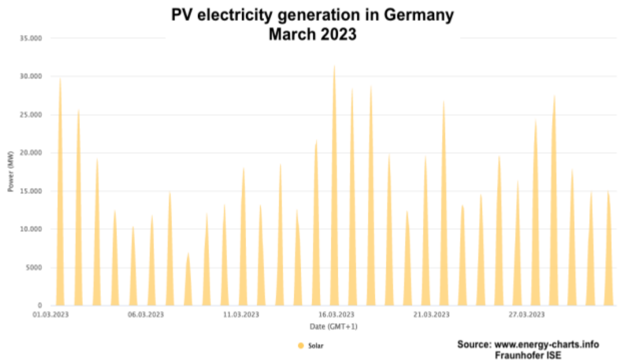

Figure 7 Spiky shape of the cumulative feed-in of PV power (Mar 2023) in Germany, which is connected mostly to the distribution grid at low and medium voltage level

4.2 Micro-economics

From an individual economic viewpoint, the implementation of a self-regulation scheme does not need extra hard-ware such as a real-time bidirectional communication link, preferably with low latency. The update of the load's controller software is sufficient. Furthermore, the self-regulating control scheme is easy to sustain, as the unchangeable laws of physics govern the behaviour of the dispatchable loads and therefore need no regular version updates to maintain compatibility with upstream ICT infrastructure.

In the mass market of LV devices, incentive schemes with low transaction costs are needed; otherwise the small-scale benefit of each unit may not outweigh the expenses for the financial compensation. Traditional methods such as known from FCR markets include prequalification and require individual proof of work records, which is not suitable for a large cluster of tiny LV units because of the inherently high transaction costs. In contrast lump sum payments in combination with a certification system using type approval of mass-market products are a pragmatic option to reach the necessary objective of low transaction costs.

5 Conclusive Outlook

Electrification of the transportation sector and the heating sector is growing rapidly, because of climate change concerns [21] and the increasing scarcity of fossil fuels. The impact of greenhouse gases on current weather patterns has become more and more visible; price escalations for coal, oil and gas since the 2nd half of 2021 raise concerns about the long-term supply of these energy resources. [22] It may be reasonable to argue, that political support measures will speed up this development by boosting the deployment of electric vehicles and heat pumps. This means rapidly rising shares of dispatchable loads at the household level, which are small in individual size but large in total numbers. [23]

The proposed method of self-regulation has technical, economical and organisational advantages for integrating distributed flexibility in electric power systems. It is an easy-to-implement method, which follows the approach of type testing electrotechnical requirements, which have already been proven in the mass market of distributed generation. Frequency and voltage responses, P(f) & Q(U), are already state of the art in small-scale generators. Furthermore, self-regulation of loads is already well known in power engineering, which means the emulation of this effect by new power-electronic load types is familiar to the industry. It does not rely on a complicated telecontrol infrastructure for remote control, which may fail. In contrast, self-regulation supports the emergence of a resilient behaviour in self-organising systems, which is essential for the rapid ramp-up of grid-friendly loads.

6 Acknowledgements

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