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Performance Requirements Modeling and Assessment for Active Power Ancillary Services

Daniel Esteban Morales Bondy, Anders Thavlov, Janus Bundsgaard Mosbæk Tougaard, Kai Heussen
Department of Electrical Engineering
Technical University of Denmark
Roskilde, Denmark
{bondy, atha, kh}@elektro.dtu.dk, janus@tougaard.net

***Abstract*—New sources of ancillary services are expected in the power system. For large and conventional generation units the dynamic response is well understood and detailed individual measurement is feasible, which factors in to the straightforward performance requirements applied today. For secure power system operation, a reliable service delivery is required, yet it may not be appropriate to apply conventional performance requirements to new technologies and methods. The service performance requirements and assessment methods therefore need to be generalized and standardized in order to include future ancillary service sources. This paper develops a modeling method for ancillary services performance requirements, including performance and verification indices. The use of the modeling method and the indices is exemplified in two case studies.**

***Index Terms*—Ancillary Services, Demand Response, Performance Monitoring, Verification.**

I. INTRODUCTION

The power industry is experiencing a significant shift away from being based on fossil fuels towards more generation from Renewable Energy Sources (RES). The tendency is a substantial increase in the amount of RES, often as distributed energy resources (DER), and a growing electrification of the heating and transportation sectors [1], [2]. The non-dispatchable and stochastic nature of RES and the increasing electrification of consumption call for new sources of ancillary services, as conventional generation is pushed out of the market. This alters the traditional distribution of flexibility resources in the sector, where relatively few large power plants provide electric power and ancillary services (AS). New AS resources will be, e.g. demand response (DR) from small-scale entities, such as commercial buildings or private households, whose flexibility in consumption will be harnessed by aggregators [3]–[8], as well as controllability harnessed from new energy sources, such as wind-power plants [9]. With the introduction of new technologies as providers of ancillary services, AS specifications are being adapted, but also prequalification and verification of service delivery need to be adapted to be technology agnostic and suitable for the aggregated service delivery [10]. This revision and adaptation is relevant both due to changing ancillary service providers as well as due to the introduction of new distribution system services [11].

Performance criteria have been formalized with focus on the overall performance of grid operation (i.e. the resulting performance as seen from a grid perspective) for load frequency control [12] or primary frequency control [13]. These criteria cannot directly be employed to evaluate the performance of contributing service providers. For AS providers, the verification of service delivery typically is based on a rigid performance assessment (pass/non-pass) of individual units providing services [14]. Conversely, based upon the FERC order 755 [15], PJM, an American regional transmission operator, has established precedence in using performance metrics for verification of services by implementing a pay-for-performance scheme. This scheme is based on evaluating the performance of frequency regulation units, thus changing the rigid verification procedures currently in place. The definition of the *performance score* PJM has introduced is technology agnostic, but tied to the definition of regulation service [16] in the United States.

This paper presents a method for modeling a general set of active power ancillary service requirements, which are also suitable for distribution system congestion management services and exemplifies their applicability. The novelty in this approach is that we detach the model of the performance requirements from the country/region-specific definition of the service. The concept of a Service Performance Index (SPI) and Quality of Service (QoS) have been treated in previous work [17]. Here, these concepts are expanded and generalized, and a new metric for assessing the non-delivery of a service is introduced. The non-delivery assessment is proposed for verification of service delivery.

The article is organized as follows: the modeling method is presented in Section II and the service performance assessment and verification indices are presented in Section III. The use of the service modeling and indices are shown through two case studies in Section IV and concluding remarks are presented in Section V.

II. SERVICE REQUIREMENTS MODELING

The performance requirements for ancillary service provision are usually based upon a pass/non-pass threshold of the

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generator parameters and response [18]. In order to establish service requirements that are independent of the type of unit providing them, the requirements must apply only to the performance of the response to the service activation. In the case of a single large generator this is measured directly at the unit. In the case of aggregated delivery (either from small-scale distributed generation or demand response), the response evaluation must be done on the aggregated measurements. The aggregation and baseline calculation (in case of demand response) of the measurements is out of scope of this paper.

By utilizing new technologies with different behaviour than traditional generators, new response capabilities can be achieved [19]. Thus, it makes sense to separate service requirements into 1) the ideal service that can be provided and 2) the acceptable service provision. The rest of this section establishes how these two types of requirements can be modeled.

A. Method for formulation of requirements model

Through analysis of the TSO services defined in [14] and the potential DSO services defined in [20], the method for defining a service model can be summarized by the following six steps:

1) Identify the measurable parameters required for assessing the service delivery and define the quality and accuracy requirements for providing such a measure;
2) Identify the relation between power system state and required service;
3) Quantify the physical volume of the service in relation to the required response and identify tolerated errors that will not affect the ideal system response;
4) Identify the limits of an acceptable response to characterize the boundaries of service delivery;
5) Based on the service requirements identified in steps 2)-4), develop mappings for ideal and acceptable service provision;
6) Establish a measure for acceptable service error.

The time series $\mathbf{x}_{ideal}(t)$ (for ideal serviced delivery) and $\mathbf{x}_{acc}(t)$ (for acceptable service delivery) are derived ex-post based on the established mappings and the recorded service parameters. A service model is formed by these two time series. By defining the models in terms of output performance, not in specific unit capabilities, the models are technology agnostic.

B. Generic Model Components

An agreement for ancillary services should specify mappings for ideal delivery, acceptable bounds, and error metric. As the definition of an ideal serviced delivery is specific to a service, the generic service aspects can be described via the acceptable bounds and error metric. We identify three service model patterns for ideal service delivery: *reference tracking*, *band service* and a *maximum/minimum cap service*. In the following subsections we define the error metric and and acceptable bounds for each of the services types.

1) Reference tracking: The reference tracking error can be calculated as:

$$e(t) = x_{del}(t) - x_{ideal}(t), \tag{1}$$

where $x_{del}(t)$ is the delivered (measured) load/generation and $x_{ideal}(t)$ is the signal to be tracked. This definition will lead $e < 0$ for measured values below the ideal and $e > 0$ for values above the ideal. In this case $\mathbf{x}_{acc}(t)$ will be a band around $x_{ideal}(t)$, and the values of $\mathbf{x}_{acc}(t)$ do not need to be symmetric:

$$x_{acc,max}(t) = x_{ideal}(t) + c_{max}(t), \tag{2}$$

$$x_{acc,min}(t) = x_{ideal}(t) - c_{min}(t), \tag{3}$$

where $c_{min}(t)$ and $c_{max}(t)$ are values defined in the service agreement.

2) Band service: The ideal response in a band service is defined as $\mathbf{x}_{ideal}(t) = [x_{min}(t), x_{max}(t)]$. The error in the band service can therefore be estimated by:

$$e(t) = \begin{cases} x_{del}(t) - x_{min}(t), & x_{del}(t) < x_{min}(t) \\ 0, & x_{min}(t) \le x_{del}(t) \le x_{max}(t) \\ x_{del}(t) - x_{max}(t), & x_{del}(t) > x_{max}(t). \end{cases} \tag{4}$$

In this case, the $\mathbf{x}_{acc}(t) = [x_{acc,min}(t), x_{acc,max}(t)]$ is a set of values that surround the band defined by $\mathbf{x}_{ideal}(t)$. The values of $\mathbf{x}_{acc}(t)$ do not need to be symmetric around the band:

$$x_{acc,max}(t) = x_{max}(t) + c_{max}(t), \tag{5}$$

$$x_{acc,min}(t) = x_{min}(t) - c_{min}(t). \tag{6}$$

3) Cap service: In cap services, error is only tracked when $x_{del}(t)$ is either above or below a given a limit value. Maximum cap error is calculated as shown in (7) and minimum cap can be similarly calculated. In (7), $x_{max}(t)$ is the ideal maximum limit according to the service agreement:

$$e(t) = \begin{cases} x_{del}(t) - x_{max}(t), & x_{del}(t) > x_{max}(t) \\ 0, & x_{del}(t) \le x_{max}(t). \end{cases} \tag{7}$$

In the cap service, $x_{acc}(t)$ is a limit that either lies below $x_{min}(t)$ or above $x_{max}(t)$, in the case of the maximum cap service:

$$x_{acc,max} = x_{max}(t) + c_{max}(t). \tag{8}$$

III. PERFORMANCE ASSESSMENT OF SERVICE DELIVERY

In previous work [17] the two following concepts were introduced:

- *Quality of Service*, QoS, which is an instantaneous measure of how well the aggregator is delivering one service within the contract constraints;
- *Service Performance Index* (SPI), η, which describes the overall performance of the service delivery over the delivery period for the services, or subset of services, it is providing.

Here we provide a formal foundation for these concept, and refine the SPI to scale the measure to time, and extend QoS to account for asymmetry in service delivery. Further, the following new concept is introduced:

- *Service Verification Index*, ϵ, which describes how much an aggregator is breaking the contractual agreements (non-delivering) of the services, or a subset of services, it provides.

We formaly define the performance requirements as:

$$\text{[P-R}_1\text{]:} \quad \eta = f_P(x_{del}, \mathbf{x}_{acc}, t), \quad \eta \in [0,1], \tag{9}$$

$$\text{[P-R}_2\text{]:} \quad \epsilon = f_R(x_{del}, \mathbf{x}_{acc}, t), \tag{10}$$

where η is a SPI and ϵ is a reliability measure. The measured output is defined by x_{del}, and the service bounds are defined by $\mathbf{x}_{acc}$, as defined in Section II. $f_P(\cdot)$ is a function that evaluates service performance normalized by $\mathbf{x}_{acc}$ and time *t*. Similarly, $f_R(\cdot)$ is a function that evaluates service reliability based upon $\mathbf{x}_{acc}$.

A. Quality of Service

Quality of service (*QoS*) is an instantaneous measure of quality of service delivery, given by:

$$QoS(t) = e(t)C_n(t) \tag{11}$$

where *e(t)* is the error measure in service delivery introduced in Section II, and $C_n(t)$ is a normalization factor that can be time varying. In order to fulfill the requirement [P-R$_1$], we define:

- $QoS \geq 0$;
- for $QoS \leq 1$ the service is considered delivered within the contractual constraints;
- and $QoS = 0$ is a perfect service delivery.

In order to meet these requirements, the normalization factor $C_n(t)$ must be calculated from $\mathbf{x}_{acc}(t)$ thus:

$$C_n(t) = \begin{cases} \frac{1}{x_{acc,max}(t) - x_{max}(t)}, & e(t) \geq 0 \\ \frac{1}{x_{acc,min}(t) - x_{min}(t)}, & e(t) < 0 \end{cases} \tag{12}$$

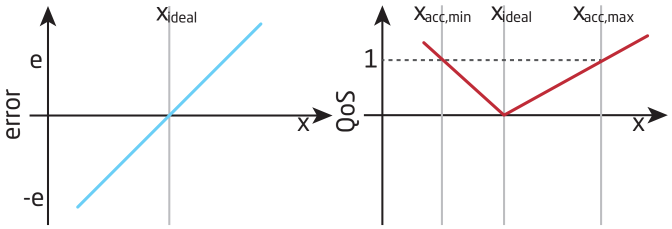
where $x_{acc,max/min}$ and $x_{max/min}$ are part of the service model defined in Section II. In the case of *reference tracking*, Eq.12 becomes:

$$C_n(t) = \begin{cases} \frac{1}{x_{acc,max}(t) - x_{ideal}(t)}, & e(t) \geq 0 \\ \frac{1}{x_{acc,min}(t) - x_{ideal}(t)}, & e(t) < 0. \end{cases} \tag{13}$$

By defining $C_n(t)$ in this way, we take into account the possibility of asymmetry in the values of x_{acc}, and ensure that *QoS* is a positive value. A visual representation of this scaling can be seen in Fig. 1–Fig. 3, where the *QoS* for the three kinds of services are presented.

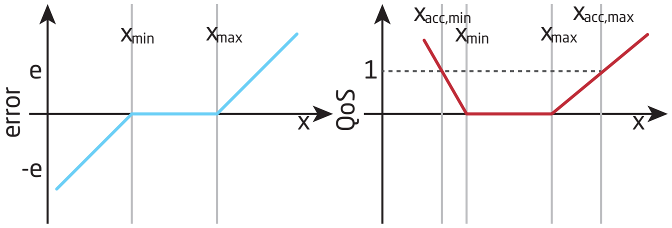
Note that in (12), $C_n(t)$ is not defined for $x_{acc}(t) = x_{ideal}(t)$. This is a corner case, in which:

$$QoS(t) = e(t), \quad x_{acc}(t) = x_{ideal}(t) \tag{14}$$



(a) Error (b) Quality of Service

Fig. 1. Error and *QoS* for tracking services, note that the acceptable band do not need to be symmetric.



(a) Error (b) Quality of Service

Fig. 2. Error and *QoS* for band services.

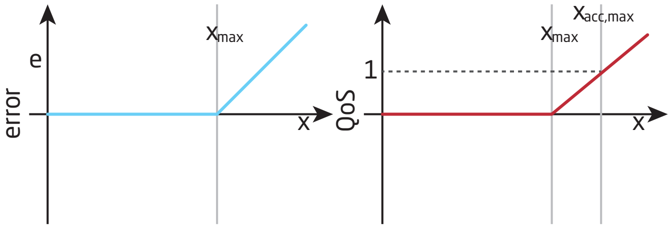
B. Assessing service delivery quality

Based on the above instantaneous measure for the quality of service delivery, we can evaluate the service delivery as a whole. The SPI is defined by η^{AS} in Eq. (16), but before calculating the index, the non-delivery incidents (which are measured apart) must be sorted out. This is done by restricting $QoS^{AS}_{meas}(t)$ (the measured Quality of Service for the specific AS) such that it does not account for $QoS > 1$:

$$QoS^{AS}(t) = \begin{cases} QoS^{AS}_{meas}(t), & \forall QoS^{AS}_{meas}(t) \leq 1, \forall t \\ 1, & \forall QoS^{AS}_{meas}(t) > 1, \forall t. \end{cases} \tag{15}$$

This means that $\eta_{AS} \in [0,1]$ is a measure of the quality of service provision within the contractually acceptable limits, where η close to zero represents a good performance, while η close to 1 represents a (barely) acceptable performance.

We can therefore express the SPI as $\eta_{AS} = f_P(QoS^{AS}([t_0,t],t)$. In practice, the measurement and calculations are done in discrete time (time horizon t_N). As a



(a) Error (b) Quality of Service

Fig. 3. *QoS* for a maximum cap service, a minimum cap service is defined similarly but with x_{min} and $x_{acc,min}$ values.

design choice we propose a root mean square (RMS) as error metric for the SPI. The RMS error weighs values closer to breaking acceptable limits stronger than values closer to the ideal service delivery, and facilitates scaling the error with the time horizon of the service delivery:

$$\eta^{AS} = \sqrt{\frac{\sum_{t=0}^{N}\left(QoS_t^{AS^2}\right)}{t_N}} \quad , \tag{16}$$

Other indices, such as a (rolling) average QoS, may be considered.

C. Verifying service delivery

Requirement *P-R*$_2$ defines a reliability measure. To address this requirement, an index ϵ^{AS}, similar to the SPI, is defined for verifying the delivery of AS[1]. Also, a non-delivery measure for the AS provision, ND^{AS}, is defined according to the expression:

$$ND^{AS}(t) = \begin{cases} QoS_{meas}^{AS}(t) - 1, & \forall QoS_{meas}^{AS}(t) > 1, \forall t \\ 0, & \forall QoS^{AS}(t) \leq 1, \forall t. \end{cases} \tag{17}$$

Eq. (17) shows that whenever the *QoS* of a service exceeds 1, i.e. the limit of what is an acceptable service provision, the amount with which it breaks the acceptable constraint is measured by *ND*. ϵ^{AS} can be calculated in the same way as η^{AS} using $ND^{AS}(t)$ instead of $QoS^{AS}(t)$:

$$\epsilon^{AS} = \sqrt{\frac{\sum_{t=0}^{N}\left(ND_t^{AS^2}\right)}{t_N}} \tag{18}$$

where $\epsilon^{AS} \in [0, \infty]$. This expression satisfies [P-R$_2$].

Thus, ϵ is used to assess the severity of non-delivery events. For some systems it is critically important that $QoS(t) \leq 1$ at any time, in which case ϵ should be close to zero for the contract to be considered respected. Other systems can tolerate $QoS(t) > 1$ for some period, which leads to a higher acceptable ϵ. A service delivery is verified if $\epsilon \leq \epsilon_{max}$, and this contractual limit, i.e. the value of ϵ_{max}, must be assessed individually depending on the nature of the system.

As in [17], non-delivery may also be assessed using a non-delivery counter (NDC) which counts time samples for which non-delivery is detected. In contrast to ϵ, the NDC does not account for time span of non-delivery and the magnitude of the violation.

The interpretation of SPI and SVI is defined in the agreement between TSO/DSO and service providers; the agreement may account with economic reward for a low SPI, and should define economic penalization or contract termination by defining threshold SVI values for defined time periods.

IV. CASE STUDIES

A. Frequency Containment Reserve in Western Denmark

Frequency Containment Reserve (FCR) is utilized to contain frequency excursions deviating from the nominal 50 Hz in *ENTSO-E RG Continental Europes synchronous area* of which western Denmark (DK1) is part of. The Danish TSO, Energinet.dk, is obliged to provide a proportional share of ± 23 MW [14] out of the total synchronous area need of ± 3000 MW. Energinet.dk buys these reserves at daily auctions. The service specifications are defined in [14].

The six steps outlined in Section II are used to model the ideal and tolerated service response.

1) The physical parameters are grid frequency (accuracy of ± 10 mHz or better), generator reserve power output, and timing of service delivery (accuracy of 1 s or better).
2) The reserve must be supplied linearly at deviations of ± 200 mHz relative to 50 Hz, with a ± 20 mHz dead-band around 50 Hz.
3) The physical size of the service depends on the reserve bid size; here we consider a generic fraction of this bid volume. According to the service requirements, a ± 1% tolerance of the reference tracking x_{ideal} is defined.
4) The first 50% of the service must be supplied within 15 s and 100% must be supplied within 30s. The ideal response can be defined as a response with an instant 100% power ramp [21].
5) The ideal and tolerated response of this service provision is plotted as x_{ideal}, $x_{acc,min}$ and $x_{acc,max}$ in Fig. 4, which assumes that a reserve power set-point has already been established based on the values from step 2.
6) In this case we assume that the service error is defined for a *reference tracking* service, as defined in (1).

Fig. 4 shows a simulation of primary regulation active power ramp x_{del} for the time interval $[-5, 35]$ s. The service delivery performance index and non-delivery verification index are $\eta^{AS} = 0.5295$ and $\epsilon^{AS} = 0.7131$, calculated using (16) and (18). Identifying a threshold ϵ_{max}^{AS} would allow a service provider to anticipate its penalization or the contract termination $\epsilon^{AS} > \epsilon_{max}^{AS}$.

B. PowerMax in a distribution system

The *PowerMax* service was first described in [20] and further specified in [22]. It is a DSO service, where the DSO can make a tender for a load reduction ΔP^{DSO} to a max level P_{max}^{DSO} in parts of the distribution system that are forecast to experience congestions during some periods (e.g. hours 17-20 during winter months).

In order to identify its service needs, it is assumed that the DSO is able to separate the total consumption forecast $\hat{P}_{tot}$ in the congested part of the distribution grid into a controllable load forecast $\hat{P}_{CL}$ and a base load forecast $\hat{P}_{BL}$:

$$\hat{P}_{tot} = \hat{P}_{CL} + \hat{P}_{BL} \tag{19}$$

$$\hat{P}_{CL} = \sum_{Agg} \hat{P}_{CL,Agg}, \quad Agg \in \mathbf{A} \tag{20}$$

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[1] This can also be interpreted as evaluating non-delivery of service.

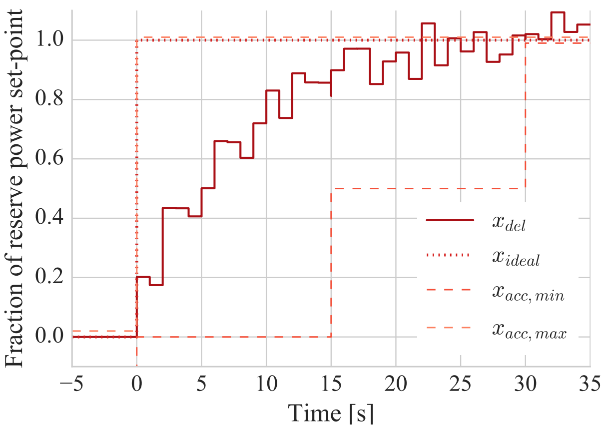

Fig. 4. Simulation of a DK1 primary reserve power response together with x_{ideal} and x_{acc} values.

where $\mathbf{A}$ is the set of all aggregators in the considered part of the grid. Only the aggregators *Agg* that bid for the service tender make up $\hat{P}_{CL}$, while the rest of $\mathbf{A}$ is part of $\hat{P}_{BL}$. The aggregators must be contracted to deliver a total power reduction ΔP, such that the system operational limit $\bar{P}_{sys}$ is not violated by the peak base-load forecast and the peak controllable load forecast:

$$\hat{\bar{P}}_{BL} + \hat{\bar{P}}_{CL} - \Delta P \leq \bar{P}_{sys}. \tag{21}$$

This inequality can be fulfilled by setting a peak limit $\bar{P}_{CL}$:

$$\bar{P}_{CL} = \hat{\bar{P}}_{CL} - \Delta P \tag{22}$$

where ΔP and $\bar{P}_{CL}$ are the variables for the DSO service tender. In order to formulate a service tender, the magnitude of these variables must be estimated taking into account the uncertainty of the forecasts, giving the following expressions:

$$\Delta P^{DSO} = \sum_{Agg} \Delta\hat{P}_{CL,Agg} + \text{Risk}\{\hat{P}_{CL} + \hat{P}_{BL}\} \tag{23}$$

$$P^{DSO}_{max} = \hat{\bar{P}}_{CL} - \Delta P_{DSO} \tag{24}$$

where $\Delta\hat{P}_{CL,Agg}$ is the estimated power reduction for the individual aggregator bid, $\text{Risk}\{\hat{P}_{CL} + \hat{P}_{BL}\}$ is the risk associated to the load forecast uncertainty. $Agg \in \mathbf{A_C}$ and $\mathbf{A_C} \subseteq \mathbf{A}$, i.e. $\mathbf{A_C}$ is the subset of aggregators that bid on the tender. After the DSO has identified a suitable P^{DSO}_{max} and ΔP^{DSO} to solve the congestion issue, the DSO formulates a service tender for which aggregators can bid their ΔP^{Agg} and P^{Agg}_{max}.

The method from Section II is used to model *PowerMax* ideal and acceptable response.

1) The physical parameters are P^{Agg}_{max}, ΔP^{Agg} and the months/days/hours the service shall be delivered.
2) The service has a fixed volume and does depend on dynamic system parameters.
3) As an example, the service tender defines $P^{Agg}_{max} = 200$ kW and $+1\%$ allowed deviation $P^{Agg}_{max,acc}$.

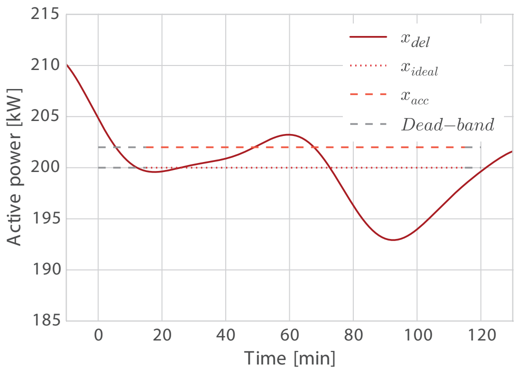

Fig. 5. $x_{ideal} = P^{Agg}_{max}$, $x_{acc} = P^{Agg}_{max,acc}$ for the considered *PowerMax* example. The activation Dead-band is the time period, where the aggregator is allowed to non-deliver.

4) In this example we use 120 min service provision time with allowed non-delivery in the first 15 min, and the last 5 min, of the service delivery (following the service definition in [20]) and the ideal service delivery is the one that respects P^{DSO}_{max}.
5) Fig. 5 plots x_{ideal} and x_{acc}. The *Activation Dead-band* indicates the regions where the aggregator is not obliged to deliver the service because of the tolerances defined under step 4.
6) The service is a maximum cap service and the error is measured as in (7).

An example of a load curve $P_{Agg} = x_{act}$ is presented in Fig. 5. The service delivery and verification are evaluated using Eq. (16) and Eq. (18), yielding $\eta^{AS} = 0.5074$ and $\epsilon^{AS} = 0.2701$ respectively. As with the performance assessment of the FCR in DK1, it is not within the scope of this paper to asses the value of ϵ^{AS}_{max}, yet a qualified assessment can be made. To asses ϵ^{AS}_{max}, the DSO must analyze the dynamics of the problem the service is helping relieve. For *PowerMax*, the dynamics are governed by the heating of the overloaded equipment (e.g. transformer or cable), which deteriorates over time due to overheating. A feeder might be tolerant to short term overloads and therefore the DSO might set ϵ^{AS}_{max} higher than in the FCR case.

V. CONCLUSION

A method for modeling and assessment of ancillary service performance requirements was presented.

The method focuses on the performance of service delivery, rather than the properties of the units providing the service, and therefore applies to both traditional large-scale units as well as new types of entities, e.g. aggregators of small-scale consumption and generation. Consequently, the method is considered to be technology agnostic.

The method defines two performance indices to evaluate the quality of a service delivery, i.e. the performance is assessed by means of a service performance index and a service verification index. The use of the modeling method and the indices are illustrated through two examples. The main purpose behind the development of the modeling method and the indices is to expand the current service verification methods to be suitable for future sources for ancillary services.

The performance assessment of ancillary service delivery is an important element in integrating new sources of ancillary services in the power system. These new sources are expected to play an important part in the security of the future power system.

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