Distributed small loads as fast frequency reserves: Impact on system performance

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***Abstract*— This paper discusses the concept of using AMR (automatic meter reading) connected distributed loads as fast frequency reserves (ACFRs). The paper presents high-level analysis on power system response when considerable amount of directly grid-connected rotational reserves are replaced by AMR meter connected loads. In the study, the amount of ACFRs and their response time (i.e. very fast and fast) are varied together with different rotational kinetic reserves of power generation participating in frequency control. For the studies, a general power system and load models for EMT-type software have been established. The results show that ACFR could in principle replace effectively rotating reserves provided that frequency measurement and the coordination of the ACFRs are robust. The studied load shedding patterns and parametrization have less than excepted influence on frequency minimum and system response.**

***Index Terms*—Fast frequency reserves, measurement, distributed load, power system, AMR**

I. Introduction

Ensuring the power balance in electrical energy systems between production and consumption is one of the fundamental tasks of transmission system operators. Any active power imbalance will lead to frequency deviation. Frequency is kept within limits using frequency reserves. In the Nordic synchronous area, there have been traditionally three types of automatic frequency reserves: frequency containment reserves for normal operation (FCR-N), frequency containment reserves for disturbances (FCR-D) and automatic frequency restoration reserve (FRRa) [1]. In a large-scale power system, the frequency reserves have been traditionally realized by large directly grid-connected synchronous generators. Dynamic response and transient stability of power systems is mainly dictated by the amount of directly grid-connected synchronous machines and by their physics (i.e. inertia). In general, the higher is the amount of directly connected rotational kinetic energy in a system, the better is the robustness against frequency deviations.

Due to on-going transition to intermittent, renewable energy generation, the amount of directly connected rotating generators connected into power systems is decreasing, which may impede the robustness of power systems if the impact of this change is not considered. The ongoing change in power systems will increase the value of alternative sources for fast frequency reserves. For example, the Nordic Transmission system operators (TSOs) have established technical requirements for new type of reserve termed as fast frequency reserves (FFR) [2], to counteract the challenges ensued by decreasing amount of directly grid-connected synchronous machines.

This paper presents and discusses different high-level approaches to apply distributed loads as frequency reserves. These reserves are required in large synchronous power systems to counteract large frequency variations due to a loss of large generation unit. The conceptual work presented in this paper was done separately before the development of FFR [2], and therefore it does not align with the FFR related practices and requirements which will be taken into commercial use in 2020. The concept presented and discussed in this paper is referred as small distributed AMR Connected loads as fast Frequency Reserve (ACFR). AMR meter here relates to the advanced smart meter including also frequency measurement capability, which kind of meters are already available in market.

In Finland, the large-scale industrial loads have been participating in regulating power and reserve markets for a long time mainly to counteract large frequency deviations. Recently actions have been made to facilitate participation of aggregated small-scale loads and generation to the reserve markets [1]. This paper takes a step further and considers on a conceptual level the use of large-scale small distributed loads as ACFRs. The paper approaches the use of ACFRs from the perspective of their possible system level impacts. The justification for this relies on low-cost and reliable frequency measurement implementation on smart meters. A high-level study was performed by varying amount of reserve loads and their response time (i.e. very fast and fast) with different rotational kinetic reserves of power generation participating in frequency control. For the studies, a general power system models for EMT-type software has been established. The models have been developed to represent the aspects which are the most relevant of the study.

Although the paper approaches the fast frequency reserves on power system performance from the perspective of AMR

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meter connected loads, the approach and the results presented by this paper can be generalized to demonstrate the benefits, challenges and risks related to variety of small-scale distributed resources as fast frequency reserve. Section 2 presents the background, potential and challenges related to the use of distributed resources as fast frequency reserves. Section 3 addresses the technical areas, which have been identified having a major role in defining the concepts that could be introduced to allow the use of distributed resources as fast frequency reserves. In Section 4, the main results of the study are presented. Based on the results, the impacts of ACFR on system performance are evaluated. Section 5 discusses the applicability of the concept and future work. Finally, conclusions are presented in Section 6.

II. AMR METER CONNECTED LOADS AS FAST FREQUENCY RESERVES

A. Background and principles

Switching loads on and off is an old concept, which has been applied traditionally using large bulk loads for example, for system protection or load shedding schemes to counteract extreme frequency deviations and thus, as the final measure to maintain system integrity. In some publications, as [3] and in [4], the load shedding scheme is presented as a valuable option but in most cases, this option is referred as a last countermeasure to prevent cascading failures in large scale power systems. Load shedding schemes have proven to be efficient as the switching has hardly any delay and the impact of the disconnection (or connection) on power balance is immediate.

The switching allows very fast response times, which would allow also support of frequency much faster than using synchronous machines where mechanical as well as steam, gas or water dynamics slow down the response times of the reserve resources. The time frame for the whole process starting from identification of significant frequency deviation to the time to reach the requested change in the power output of the distributed resource can easily be in order of some 100 ms. Such response times would allow not only the use of distributed resources as part of the traditional frequency containment reserve required to act within time frame starting from few seconds up to some tens of seconds, but rapid response would also allow their use in similar manner that has been introduced for fast frequency reserve. This concept is illustrated in Fig. 1 [1].

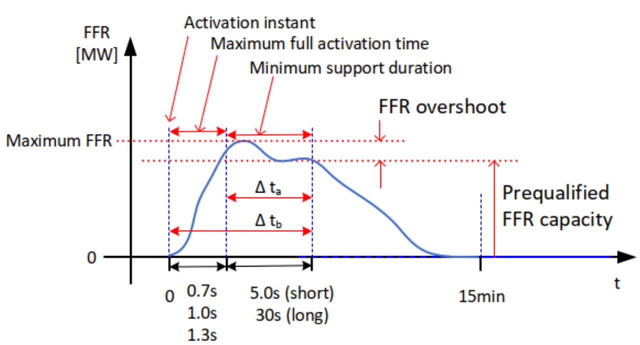

Fig 1. Requirements for FFR activation [1].

The use of AMR meter connected loads as distributed resources is basically very straightforward. The AMR meter switches on or off one or many of the loads, which are measured by the AMR. The challenge in practice is that how this can be arranged in coordinated and robust manner so that the validation of the correct activation can also be confirmed. These practical challenges are briefly elaborated in the sections 2.C and 2.D.

B. About potential of the concept

The potential of distributed resources as fast frequency reserves can be considered inherently significant only because domestic and small industrial loads present significant share of the total power system load throughout the year. Due to the wide diversity in the nature, distributed resources offer a new type of resource with different and in some cases even better characteristics than the large units thus extending the reserve portfolio. With appropriate business models, distributed resources may become also a cost-effective solution. This could be realized especially if the same assets could be applied also for other types of demand response applications when not allocated as fast frequency reserves, which could further enhance the operation of the power system.

C. Risks related to the concept

The main generally identified risk of switching on or off large amount of distributed resources is continuous uncontrolled connection and disconnection of distributed resources. This has been demonstrated, in different context though, in "what-if" -analysis of the central European system split, so called "4N event", back in 2006 [5]. As incorrect switching could be one of the root causes for realization of the risks, also the quality and performance of the frequency measurement becomes of interest.

D. Challenges

Two main challenges were identified regarding the large-scale application of AMR meter connected loads as fast frequency reserves: the coordinated disconnection of loads to manage the risks identified in section 2.C and need to validate the correct activation of reserves. The risk related to un-coordinated disconnection should become manageable if the reduction of load or generation is not based on single threshold, but follows a predetermined gradient or droop allowing linear decrease or increase of power as function of frequency decrease or increase, respectively. For AMR meter connected loads, the same risk management could be implemented e.g. by introducing same droop by selecting the threshold values for connection and disconnection according to a droop profile.

The validation related challenge could be in principle addressed by reporting about each activation with an event report. An example about the content of such report is illustrated in Fig 2. The event report would contain detailed information about the activation and thus, over time also provide understanding about the inherent uncertainties related to the factors that cause stochastic variations in the level of distributed loads and generation.

Perhaps the key challenge here is, however, the life-cycle of the AMR meters. To take full advantage of this possibility, large amount of meters should have the same capabilities for parameterization and provision of the validation related features. Thus, the large-scale application of these features could be realized not only after the standard approach for parameterization and validation would be agreed and implemented, but it would require also roll-out of a new generation of AMR meters after this or at least existing AMR meters having capabilities of frequency measurement and remotely updated software.

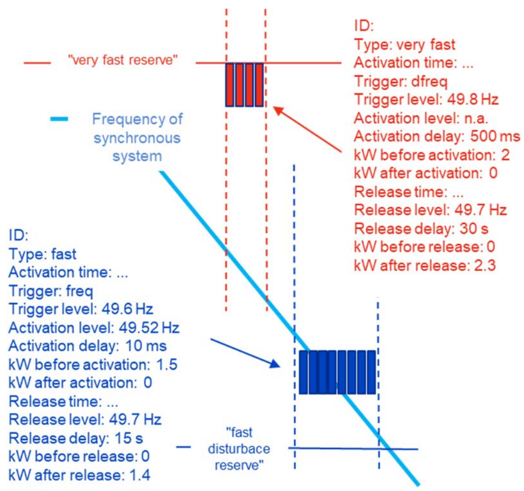

Fig 2. An example of FFR activation patterns and thresholds.

III. Target of the Study and Description of the Study Models

E. Target of the study

The main target of the study was to assess transmission system level impact when large amount, lumped distributed loads are used as ACFR. In the study, the impact of different load switching patterns of ACFRs on transmission network performance was analyzed on high level using compact power system model presented in section 3.B. Also, the changes on dynamic response when part of the rotational reserves are replaced by fast frequency reserves and the factors effecting on robustness of AMR based fast frequency reserves were assessed.

F. Power system model for analysis of fast frequency reserves

The effect of AMR meter connected fast reserves has been studied using a compact model presenting the main characteristics related to the frequency dynamics of a large synchronous system. An equivalent model dedicated for analysis of the frequency behavior after the loss of significant generation was established. Using this model, the effect of the concepts is studied in order to analyze their impact on system performance in connection of loss of generation or load. Such assessment is highly interesting considering the one key aspect of feasibility analysis of the concept: under which circumstances the way the concepts have been implemented, may have adverse effect on system technical performance.

The model was built by connecting large lumped generators and loads into the same high voltage bus. Fig. 3 illustrates the main components of this model. This model allows testing of the basic concepts and rules as well as risk assessment. The model comprised two synchronous generators, five transformers one constant power load and the ACFRs were modelled as pure resistances. For this study the parameters were selected so that the model is feasible for analysis of frequency variations in large synchronous system and models facilitating the analysis of large amount of distributed loads contributing to fast frequency reserves. The kinetic energy of directly-connected rotating masses is 110 GWs.

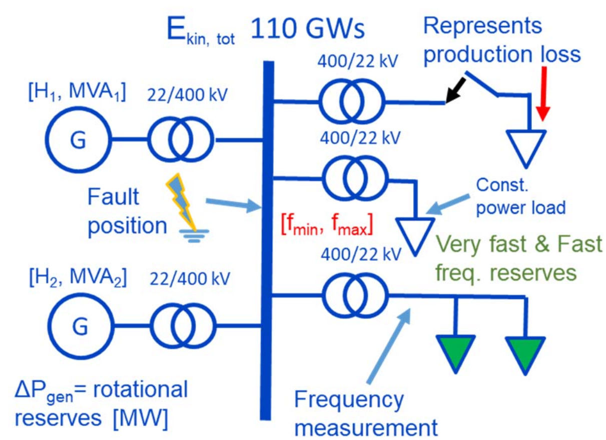

Fig. 3. Power system model for ACFR-studies.

G. Modelling AMR meter connected loads

The distributed AMR meter connected loads are presented in the study using two large lumped loads; one presenting load allocated and parameterized for very fast and other one for fast loads. To model the behavior of large group of AMR meters, the power reference for the loads was selected as variable. The variable was controlled according to logic based on the predetermined parameters that were selected to present different desired responses of the aggregate AMR connected load. The logic applied to vary the level of the two loads is presented in section 3.D. Information of when and how much of fast reserves are shed at certain frequency interval can be found on also in section 3.D.

The frequency measurement is located at the 22 kV feeder at the same node in which ACFRs are located. Fig 4 illustrates the frequency measurement method, which is based on synchronous reference phase-locked loop (SRF-PLL) method.

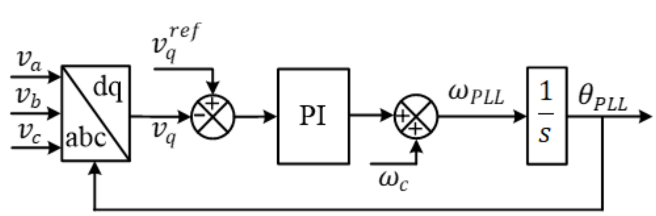

Fig 4. Schematic representation of the SRF-PLL-based frequency measurement.

SRF-PLL is a fast and robust frequency estimation method for balanced three phase systems, but it is prone to error due to unbalanced conditions.

H. Parameterization of the load

For the study, four different load shedding patterns and parameterization thresholds were done for both types of reserves. This makes a total of 16 load shedding combinations. The effect of the parameterizations was first tested to understand if they have some fundamental impact on the minimum frequency. The objective was to avoid such patterns and parameterization thresholds which could cause such a response that all the ACFRs were to be disconnected as once. The parametrization and load shedding patterns are presented in Table I.

TABLE I. PARAMETRIZATION AND LOAD SHEDDING PATTERNS.

#	Very fast	Fast
1	All @ 49.85 Hz	Flat: 49,85 – 49,50 Hz - 1/8 activates for each 50 mHz
2	Flat: 49,85 – 49,70 Hz - 1/16 activates for each 10 mHz	Flat: 49,70 – 49,50 Hz - 1/5 activates for each 50 mHz
3	Flat + 250 ms delay: 49,85 – 49,70 Hz - 1/16 activates for each 10 mHz	Linear: 49,85 – 49,50 Hz - 20% activates @ 49.85 Hz, 5% remains after 49.50 Hz
4	Linear: 49,85 – 49,70 Hz - 14% activates @ 49.85 Hz, 1% remains after 49.70 Hz	Linear: 49,85 – 49,50 Hz - 5% activates 49.85 Hz, 20% remains after 49.50 Hz

Fig. 5 Illustrates the implementation of the first load shedding pattern and parameterization shown in Table 1 for both fast reserve types.

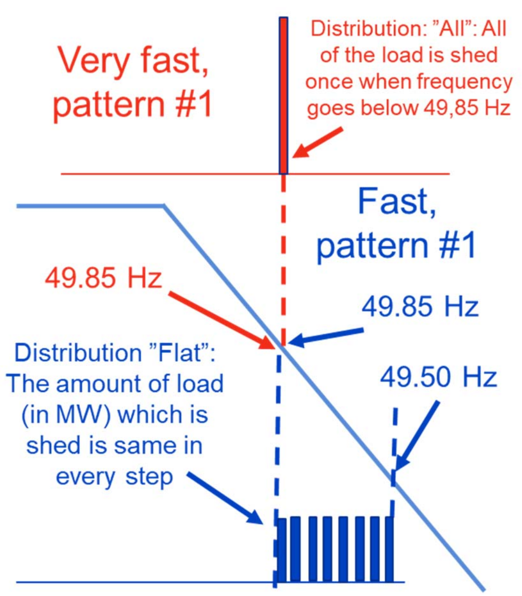

Fig. 5. Load shedding pattern and parameterization of the Type 1 for Very fast and Fast reserves.

I. Study scenarios

1) Effect of the shedding pattern and parameterization on frequency minimum

In the first part of the study, the effect of the load shedding patterns and parameters presented in the section 3.D was analyzed on power system performance after loss of generation. The target of these sets was to get an overview if the shedding patterns have different impact on frequency minimum with different amount of rotating reserves and different thresholds.

J. Effect of different amounts of AMR connected reserves on frequency variations after frequency disturbance

The target of the second part of the study work was to analyze the changes on dynamic response when part of the rotational reserves are replaced by ACFRs. The results are compared to that of reference case in which rotational reserves constitute all of the needed reserves. In all the cases, the total amount of reserves remains constant which means that rotational reserves are decreased when the amount of ACFRs are increased.

K. Study description

The length of 100 milliseconds three phase short circuit at the 400 kV bus is applied at the time of 10.0 second with 30 % remaining voltage. Immediately after the fault is cleared, 1300 MW or 300 MW production is lost. Production loss is modelled by increasing the load by the same amount respectively via straightforward operation of circuit breaker. Frequency restoration process is accomplished together with the operation of rotational reserves and ACFRs in all except the reference cases. In the reference case, only the rotational reserves are used in frequency restoration. Control of the ACFRs is based on the SRF-PLL measurement.

IV. Study Results

L. Effect of the parameterization approach on frequency minimum

The results of this study are presented in Fig. 6. Almost all the deviations originate from the cases in which the shedding pattern and parameterization of ACFRs was in category four illustrated in Table 1. The simulations showed that all the other combinations gave virtually identical results measured as frequency minimum after the fault.

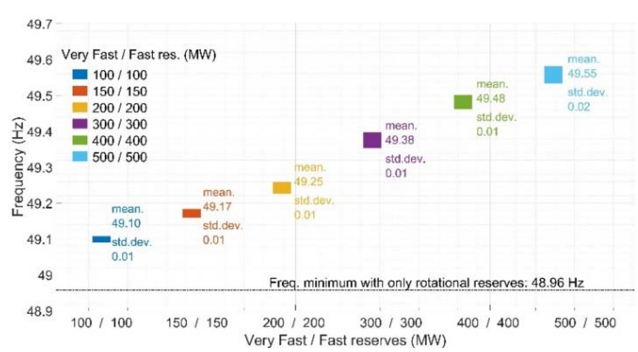

Fig. 6. Results of shedding pattern and parameterization on frequency minimum with different load shedding schemes.

Based on the analysis, the fastest shedding combination of the ACFRs, i.e. 1/1 in Table 1, was selected for more extensive analysis. The justification was that this shedding combination gave the most erroneous results in frequency measurements.

M. System response to the loss of largest (1300 MW) generation unit

Fig. 7 and 8 present the system response to the loss of 1300 MW production unit. The control of the ACFRs is based on SRF-PLL frequency measurement.

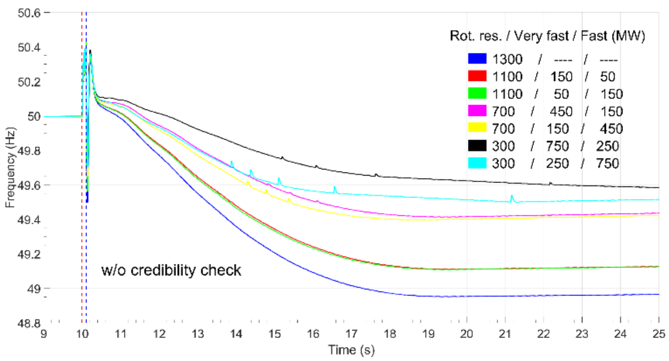

Fig. 7. Measured system frequency response after 1300 MW production loss with different amounts of ACFRs.

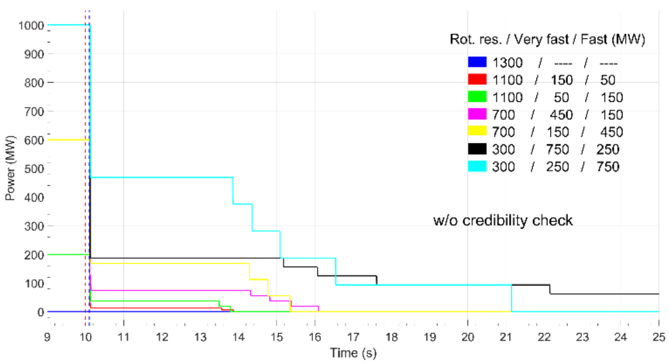

Fig. 8. Load shedding response after 1300 MW production loss with different amounts of ACFRs w/o credibility check.

Fig. 7. shows that there exists notable differences on minimum frequency only with highest amount of ACFRs. Fig. 8 shows that major portion of the loads are disconnected during the fault due to the erroneous frequency measurement results due to voltage transients. The ACFRs response in Fig. 8 are unacceptable so the next step was to implement credibility check on frequency measurement to avoid undesired and erroneous load shedding responses during the faults. The criteria was based on the knowledge of maximum range of rate-of-change-of-frequency values in the studied system. The credibility check was implemented on the logic controlling the ACFRs.

Fig. 9 and Fig. 10 show the system frequency response with the mentioned credibility check. As a result, all the ACFRs stay connected during the disturbance although the frequency measurement is clearly erroneous. In general, the disconnection pattern and shedding amounts of the ACFRs are correct. The frequency measurement errors at the time of 11 seconds are caused mainly by the disconnection of very fast reserves. In Fig. 7 similar errors are mixed with the errors due to the fault itself. If the frequency measurement method is not robust there is a risk that erroneous measurement will result repetitive connection and disconnection of ACFRs.

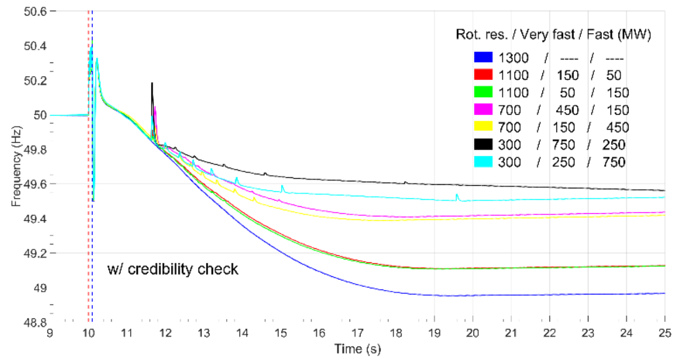

Fig. 9. Measured system frequency response after 1300 MW production loss with different amounts of ACFRs w/ credibility check.

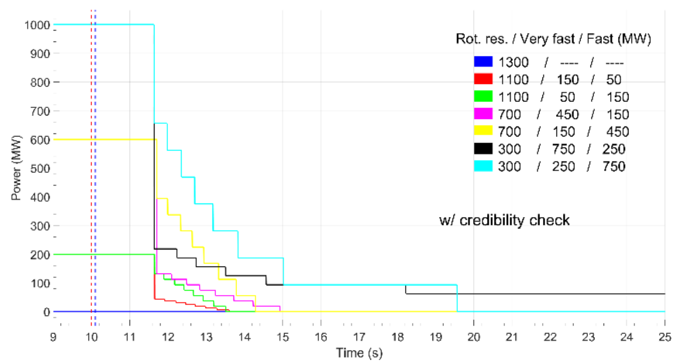

Fig. 10. Load shedding response after 1300 MW production loss with different amounts of ACFRs w/ credibility check.

N. System response to loss of 300 MW generation unit

This part was conducted in order to analyze responses when the loss of generation is clearly smaller than it was studied in the previous section. The likelihood for overfrequency conditions may increase in a case in which ACFRs constitute major part of total reserves while the amount of rotational reserves is restricted. Fig. 11 shows the system's frequency response in a same manner than it is illustrated in Fig. 9 and 10.

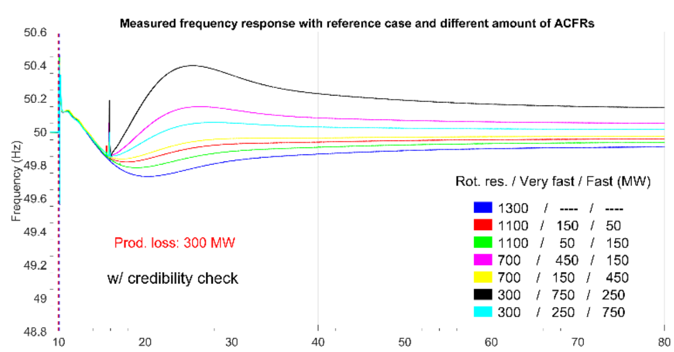

Fig. 11. Measured system frequency response after 300 MW production loss with different amounts of ACFRs w/ credibility check.

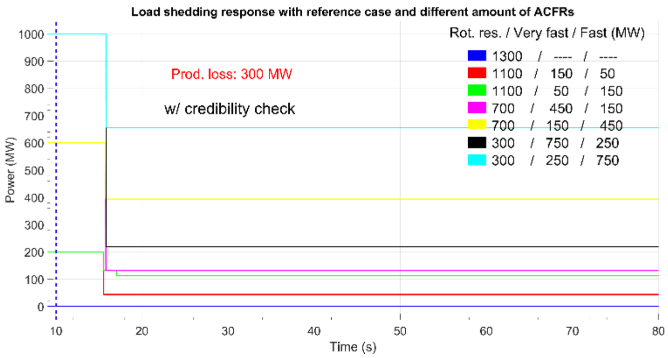

Fig. 12. Load shedding response after 300 MW production loss with different amounts of ACFRs w/ credibility check.

As expected, high threshold for large amount of very fast reserve may results into overfrequency and fluctuations around the nominal frequency. However, this happened only in the case in which the amount of very fast reserve was 750 MW. With other amounts of fast reserves, the frequency stayed close to the nominal. Based on these results, it seems that only large amount of fast reserves can cause significant overfrequency response with the chosen value of rotational kinetic energy of the system.

V. DISCUSSION AND FUTURE WORK

Based on the high-level study, ACFRs can be utilized as frequency reserves provided that frequency measurement and the coordination of the ACFRs are robust. In the study, robustness of frequency measurement during system transients was ensured by implementing a credibility check to ensure that no unselective disconnection of the load occurred. Another approach would have been enhancement of frequency measurement algorithm to ensure that no erroneous frequency measurements appear during transient system events. Also, the robustness of different frequency measurement approaches for ACFR application has been studied and will be reported in companion paper.

In the simulation model, the fast reserves were lumped and though the correct load shedding pattern and parameterization were straightforward to implement. In practices, this might be challenging to accomplish due to the high numbers and distributed and intermittent nature of the ACFRs. Also, the study conducted comprehended only certain selected combinations of rotational reserves and ACFRs with one specified amount of directly grid-connected total kinetic energy of rotating machines. In order to make more comprehensive and general conclusions related to opportunities and challenges related to ACFR, further studies should cover representative combinations of following aspects:

- Conditions with lower value of total kinetic energy,
- frequency disturbance with different amount of loss of generation and load,
- different ACFR parameterization combinations and allocations of different share between fast and very fast frequency share,
- amount of rotating reserves,
- frequency measurement approaches,
- realistic representation of the distributed load to demonstrate especially the uncertainties e.g. the actual load level which will be disconnected from the large-scale power system.

The combinations should be studied especially for two sets of cases. The cases, where the nadir of the frequency after the disturbance is equal or very close to the threshold values determined for the ACRF, would likely provide valuable information about the importance about the droop that could be obtained with "flat" or "linear" profiles. Similarly, the value and possibly also the risks related to parameterization could be further studied with cases where the allocated loads for ACFR is significantly higher than the total rotating reserves.

VI. CONCLUSIONS

The study demonstrated the use of AMR meter connected distributed loads as a part of total system reserves. The results show that ACFR could replace effectively rotating reserves provided that frequency measurement and the coordination of the ACFR are robust. The studied load shedding patterns and parametrization have less than excepted influence on frequency minimum.

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