Statistical analysis of the deployment potential of Smart Grids solutions to enhance the hosting capacity of LV networks

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Abstract: Several smart grids solutions to enhance the hosting capacity of LV networks have been proposed, investigated and successfully demonstrated. However, the real deployment potential remains unknown, which is a barrier to a systematic use of them by distribution network operators. This paper presents the results of the work done in the project IGREENGrid on the quantification of the potential of smart grids solutions in LV networks on the basis of a comprehensive statistical analysis of real datasets from two network operators. This work shows a moderate potential for reactive power-based voltage control and a significant potential for voltage regulated distribution transformer in the considered areas.

Keywords: Smart grids, scalability and replicability, voltage control, low voltage networks

1 Introduction

With the massive development of distributed renewable energy sources (DRES) in the last 15 years, the hosting capacity of distribution networks has been exhausted in some areas. In order to efficiently integrate this new generation into distribution networks, alternative solutions to network reinforcement (smart grids solutions) have been proposed in the last years. Voltage rise is often considered to be the main constraint limiting the hosting capacity. Many R&D efforts have been therefore devoted to the development of novel voltage control concepts [1][2]. While some of these concepts have been successfully tested under real conditions in various demonstrators [3], they remain at the case-study or pilot stage and their real potential for large scale deployment has not been fully studied so far.

On the one hand, the actual hosting capacity of low voltage (LV) networks is usually badly known. This is mainly due to their number, the number of loads connected to them and the general lack of detailed network models, making it difficult to estimate the hosting capacity of the potential of smart grids solutions to enhance it. On the other hand, a significant part of the installed photovoltaic capacity is connected to low voltage networks (e.g. about 70 % in Germany [4]), which justifies the need to have a better knowledge of low voltage networks.

Due to the very large number of LV networks, dedicated studies are not possible and statistical analysis are necessary. Considering the sustained growth of DER, the question of the actual replicability potential of smart grids solutions is raised and an answer is expected from different stakeholders (e.g. distribution system operators (DSOs), industry providers). In this context, the European project IGREENGrid [5] aims at assessing in a standardized way the replicability potential of smart grids solutions.

Due to the fact that the diversity of feeders among networks is very high (one network might have several very long feeders and a few very short feeders), the statistical analyses are performed at feeder level, which has also been proposed for example in [6].

The concept of hosting capacity introduced in [7] is restricted to the two most relevant limitations in distribution networks: the maximal admissible voltage rise and the maximal admissible loading. An illustration of this is shown on Figure 1.

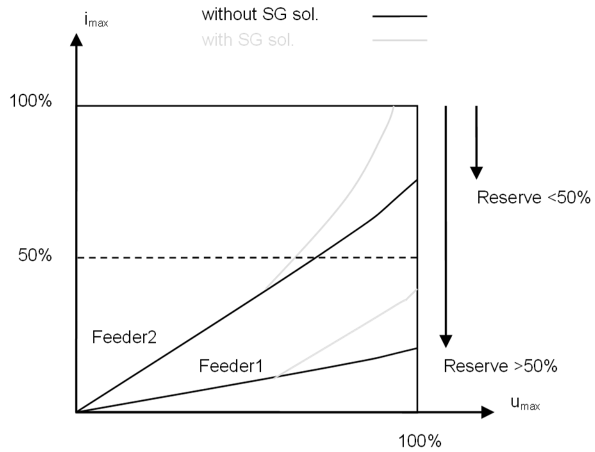

Figure 1 – Hosting capacity visualisation on the U-I plane

2 Method and data basis

In the framework of the project IGREENGrid, the LV networks of the two Austrian DSOs participating to the project (*Netz Oberösterreich GmbH* and *Salzburg Netz GmbH*) have been analysed extensively in order to evaluate the deployment potential of smart grids solutions. The data have been exported from the GIS-database and been imported into the simulation software DIgSILENT PowerFactory [8].

As explained in the introduction, the analysis of the LV networks has been done at feeder level. The first step has therefore been to define automatically feeders for each LV network and to run a series of automated scripts to verify the coherence of the data imported from the GIS-export. Among others, the validation included verifications on the following properties:

- Radiality
- Minimal short-circuit impedance
- Maximal geographical distance between nodes

After this initial validation, a set of about 11.000 LV networks and 37.000 LV feeders was available.

In order to characterise LV feeders and to quantify the potential deployment of smart grids solutions, suitable indicators have been introduced.

- Descriptive statistics-indicators
- Hosting capacity related indicators

The descriptive statistics-indicators include for example the short-circuit impedance at the weakest node, the R/X ratio, the feeder length, the equivalent sum impedance [9], the number of lines and network connections, the average number of and distance to neighbours, the mesh-factor…

The hosting capacity related indicators are based on a calculation of the hosting capacity for specific scenarios (assumptions). One of the basic assumptions is the distribution of the generation along the feeder (DRES scenario). In this work, 3 scenarios were defined for this purpose. They are briefly defined below, using the example of the indicator hosting capacity:

- “uniform”: generation placed uniformly along the feeder (at all connection boxes) and then scaled-up to reach the hosting capacity (loading limit or voltage limit is reached).
- “weighted”: generation distributed according to the summed annual consumption at the connection boxes) and then scaled-up to reach the hosting capacity. This scenario is relevant when assuming that most of the further DRES deployment will be close to the loads and driven by self-consumption.
- “eof” (“end of feeder”): generation connected at the “end node” which is defined as the node with the highest voltage for the uniform scenario.

Beside the DRES scenarios, smart grids solutions have been considered in a simple way:

- Reactive power-based voltage control (cosφ(P) and Q(U))
- Voltage band extension through the use of voltage regulated distribution transformer VRDT (transformer with On-Load-Tap-Changer (OLTC))

The control-cosφ(P) has been parametrised according to [10] and the Q(U)-control has been according to recommendations from previous projects [11], [12]. In order to investigate the benefits of a voltage regulated distribution transformer, the voltage limits have been extended as proposed in [13] (sensitivity analysis of the impact of the allowed voltage rise on the hosting capacity). Current connection rules [14], [15] foresee a maximal voltage rise of 3 % for the generation embedded in the LV network. In the sensitivity analysis on the impact of the voltage band on the hosting capacity, the maximal voltage rise has been increased up to +8 %. This value of 8 % has been chosen considering that a VRDT allows decoupling the LV from the MV network in terms of voltage level. With an equal allocation of the voltage band to loads (voltage drop) and generation (voltage rise) and a controller dead-band of ±2 %, the maximal voltage rise can be extended to +8 %.

For each of these scenarios, the indicators (e.g. hosting capacity) have been evaluated. Note that loads have not been considered in this work and that the generation is considered to be symmetrical (possible mitigation measures to voltage unbalance caused by unsymmetrical generation can be found in [16]–[19]).

3 Deployment potential of smart grids solutions

This section summarises the most interesting results of the analyses of the hosting capacity of LV feeders. In a first sub-section, a general characterisation of the LV feeders is done one their behaviour when reaching the hosting capacity.

3.1 Basic relevance of voltage control solutions

Figure 2 shows the location of the LV feeders on the U-I place (see Figure 1) for the dataset from the DSO1. The x-axis shows the maximal voltage and the y-axis the maximal loading. The planning limits considered here are 3 % voltage rise and 100 % loading). Each point on the main part of the graphic represents a feeder. The colouring is done according to the constraint reached first: blue if the voltage-constraint is reached first and red if the current-constraint is reached first. This colouring has been used in the whole paper.

The left part and the lower part of the diagram show the marginal distribution of the feeders (according to the maximal lading and voltage respectively). This figure shows that about 90 % of the feeders are voltage-constrained. In addition, this figure shows that most of the voltage-constrained feeders (blue) are far from the upper-right corner (voltage and current constraint): the maximal loading of most of the voltage-constrained feeders is not too close to the 100 %-limit. For 50 % of the voltage-constrained feeders, the maximal loading is below 37 % which means that there is a significant reserve to the over-loading. This means that there is, a priory, a large deployment potential of smart grids solutions aiming at controlling the voltage without taking the risk or reaching the overloading, which is unobserved in the considered solutions.

Figure 3 shows the same results for the DSO2. A comparison between Figure 2 and Figure 3 shows that the share of current-constrained feeder is more than twice larger for DSO2 which is due to the characteristic of the supplied area (significantly larger share of urban area). Further analyses showed that the impact of the DRES scenario (“uniform”, “weighted” and “eof”) is rather small.

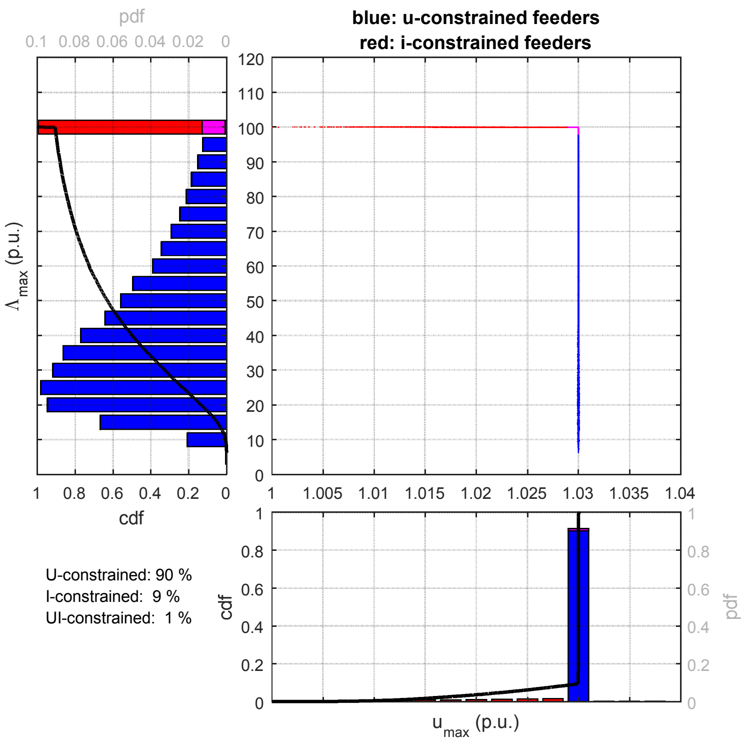

Figure 2 – Share of voltage and current-constrained feeders – DSO1

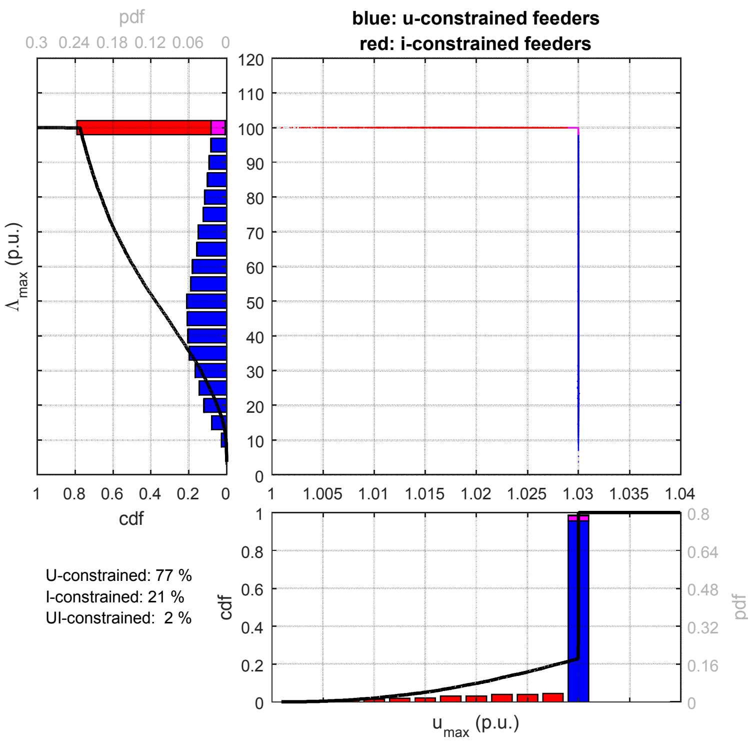

Figure 3 – Share of voltage and current-constrained feeders – DSO1

3.2 Deployment potential of voltage regulated distribution transformers

Figure 4 shows the result of a sensitivity analysis run to investigate the impact of the allowed voltage rise on the share of voltage and current-constrained feeders for the DRES scenario "uniform". For this, the maximal voltage has been changed from 1.01 p.u. to 1.08 p.u. (meaning in fact that the allowed voltage rise has been varied between +1 % and +8 %).

As expected, the share of voltage-constrained feeders decreases when the allowed voltage rise increases. When doubling the voltage rise allowed according to current planning rules [14], [15] (+3 %), the share of voltage and current-constrained feeders changes from 90 % / 10 % to 60 % / 40 %. The extension of the allowed voltage rise to +8 % would correspond to a scenario in which all the secondary substations have a voltage regulated distribution transformers, reserving a voltage dead-band of ±2 %. In such as case, about 43 % of the feeders would still be voltage-constrained. In other words, this means that the maximal increase of the hosting capacity offered by a voltage regulated distribution transformers can be actually used in about 43 % of the feeders (large share due to the fact that most of the supplied area is rural).

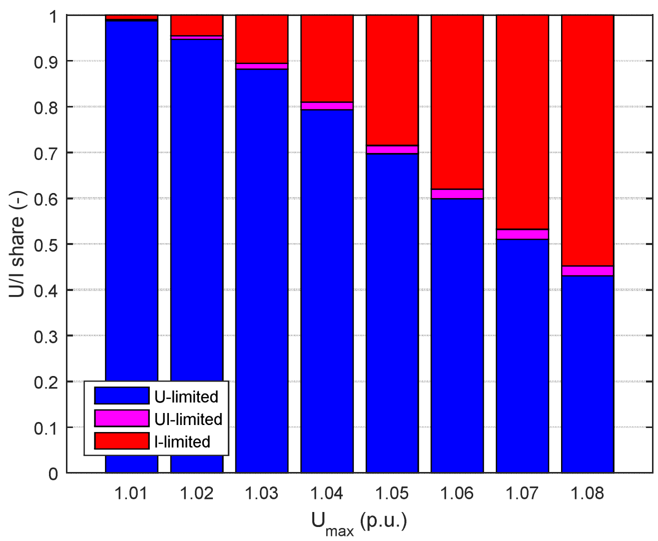

Figure 4 – Share of voltage and current-constrained feeders – sensitivity on the voltage band – DSO1

The average feeder hosting capacity increases for feeders which remain voltage-constrained from about 44 kW to 123 kW (+179 %) when increasing the allowed voltage rise from +3 % to +8 %. In other words, the expectancy value of the hosting capacity increase for an extension of the voltage band for feeders which can actually benefit from it is very high: +179 %.

3.3 Deployment potential of reactive power-based voltage control

Reactive power-based local voltage control has been intensively investigated in the last years [20]–[22]. The most two common forms of controlling the voltage according to current standards are cosφ(P) [10], [14] and Q(U) [23]. Before going into the details of the type of control, the basic benefits of reactive power-based voltage control has been evaluated.

Figure 5 shows the hosting capacity increase with cosφ=0.90 compared to the reference hosting capacity (without reactive power control). According to this figure, the expected hosting capacity increase

- exceeds +30 % for about 17 % of the feeders
- is between +20 % and 30 % for about 28 % of the feeders
- is below +20 % for about 31 % of the feeders
- is negative (decrease) for about 14 % of the feeders

Figure 5 should however be carefully interpreted since it does not take into account the constraint corresponding to the operation with reactive power control. The actual benefit of reactive power control should, only be evaluated for feeders remaining voltage-constrained when considering that the loading is unobserved. The inflexion point at a hosting capacity of about 23 % corresponds to 150 mm2 cables having a R/X ratio of 2.6 which leads to a hosting capacity increase of about 23 % at cosφ=0.90.

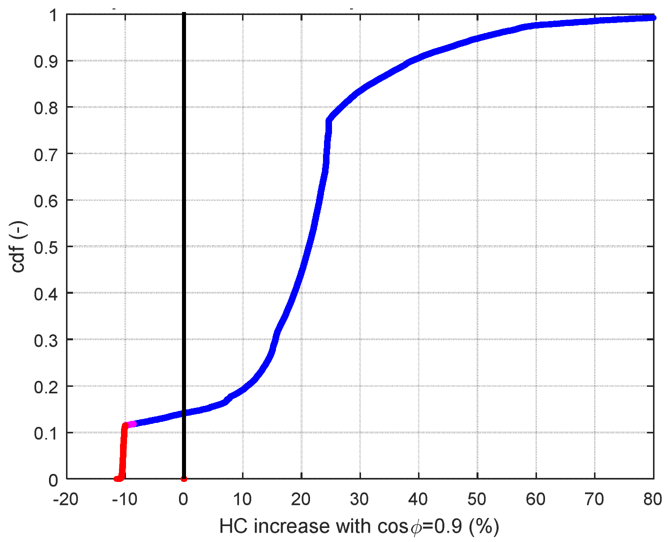

Figure 5 – Hosting capacity increase with cosφ=0.90 – DSO1

Figure 6 shows the distribution of the hosting capacity without reactive power control (x-axis) and with reactive power control (y-axis). The reactive power control implemented is a cosφ(P) control according to [10] and the colouring is done individually for both cases.

Figure 6 shows as expected an increase of current-constrained feeders. The full potential offered by reactive power control (cosφ=0.90) can be actually used in 81 % of the feeders (which remain voltage-constrained with reactive power control) and leads to an average increase of the hosting capacity by about +25 % (increase of the average feeder hosting capacity from 63 kW to 79 kW). In other words, the expectancy value of the hosting capacity increase for reactive power control for feeders which can actually benefit from it is moderate compared to the voltage band extension: +25 %. Note that transformers are not considered here and can lead in some cases to a non-negligible contribution (about 1 percentage point [12]). For the DSO2, the potential of reactive power-based voltage control is limited to 61 % of the LV feeders and represents on average an increase of hosting capacity of about +23 % (increase of the average feeder hosting capacity from 88 kW to 108 kW).

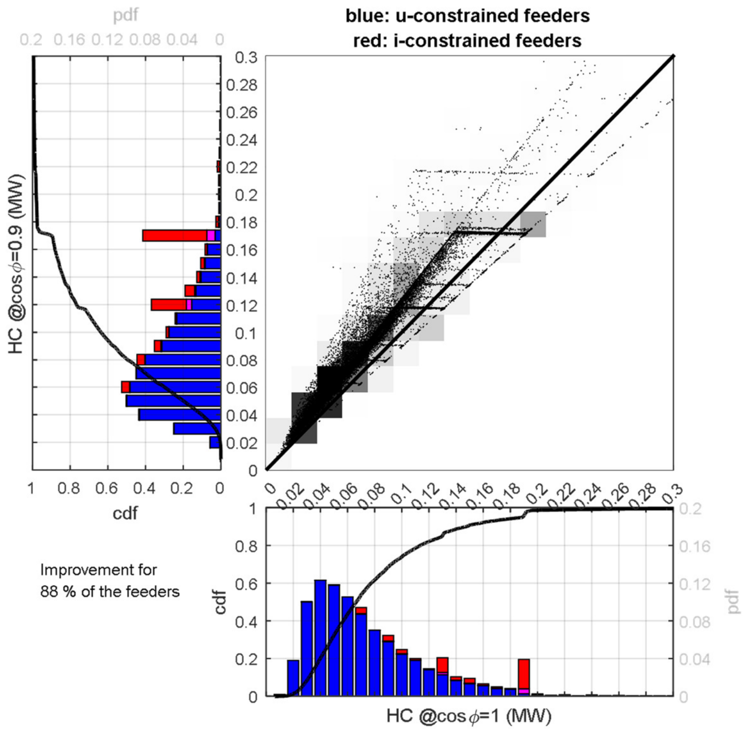

Figure 6 – Hosting capacity increase cosφ=0.90 vs. cosφ=1.0 – DSO1

Figure 7 shows a comparison between the effectiveness of the Q(U) and the cosφ(P) control. The Q(U) control generally leads to a lower reactive power consumption since reactive power is only consumed when the voltage is actually high. However, the effectiveness of the Q(U)-control is necessarily lower than the effectiveness of the cosφ(P) control since not all the generators are fully contributing (only those at the end of the feeder).

Figure 7 shows that for most (95 %) of the voltage-constrained feeders, the effectiveness of the Q(U) is not significantly lower (<4 %) than the effectiveness of the cosφ(P). This means that the difference between both controls in terms of effectiveness is very small and confirms previous work on this [11].

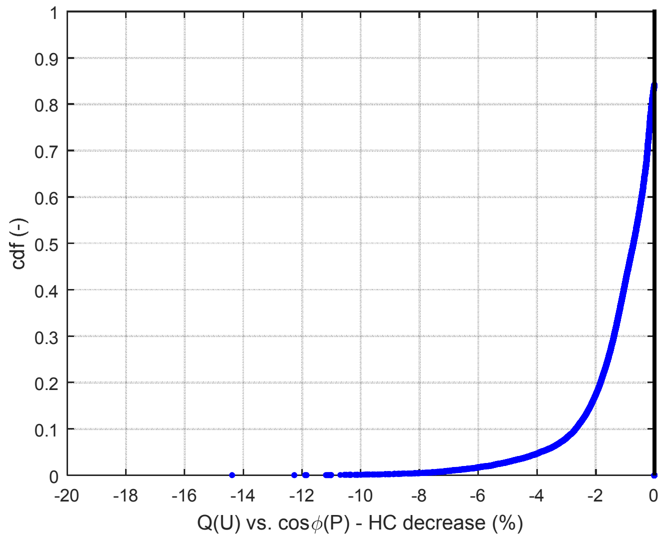

Figure 7 – Hosting capacity increase with reactive power control: Q(U) vs. cosφ(P) – DSO1

4 Conclusions and outlook

Conclusions

The work done in the framework of the project IGREENGrid allowed quantifying the basic deployment potential of smart grids solutions in LV feeders. Of course, another major component which has not been considered here is the actual expected DRES penetration: the actual need to deploy smart grids solutions (or to reinforce the network when cheaper) will be determined by the actual DRES penetration.

The two smart grids solutions considered in this study (voltage band extension through the use of voltage regulated distribution transformer and reactive power-based voltage control) are purely distributed solutions which only control the voltage without any “centralised” observer. For this reason, they should be only implemented in feeders which are “clearly” voltage-constrained. For this reason, the evaluation was done according to criteria:

- identification of the feeders which can actually benefit from these solutions (“clearly” voltage constrained feeders)
- quantification of the benefits in terms of hosting capacity increase.

The very first analysis of the feeder behaviour shows a large dominance of voltage-constrained feeders against current-constrained feeders (ratio 90 %/10 % for DSO1 and 77 % / 23 % for DSO2). On this basis, the general deployment potential of smart grids solutions aiming at controlling the voltage to increase the hosting capacity can be expected to be high. While the DRES scenario (distribution of the generation along the feeder) has of course strong impact on the hosting capacity (especially for voltage-constrained feeders), it proved to have a rather limited impact on the feeder behaviour (e.g. share of voltage and current-constrained feeders).

The full potential offered by a VRDT (more than doubling of the available voltage band) can be actually used in 43 % of the feeders (which remain voltage-constrained) for DSO1 and 21 % of the feeders for DSO2. The use of a VRDT leads on average to increase of the hosting capacity by about +179 % for DSO1 and DSO2. This replication potential (43 % and 21 % respectively) might appear to be small but it stands for feeders which can benefit of the full potential offered by a VRDT (i.e. an extension of the voltage band by 5 % here). For a smaller voltage band extension, the share of feeders remaining voltage-constrained and therefore benefiting from it increases.

The full potential offered by reactive power control ($\cos\varphi=0.90$) can be actually used in 81 % of the feeders for DSO1 and 61 for DSO2 (feeder remaining voltage-constrained with reactive power control) and leads to an average increase of the hosting capacity by about +25 % for both DSOs.

Outlook

This study is based on a very large number of scenarios and simulations to evaluate the hosting capacity and the deployment potential of smart grids solutions. It does not consider the DRES potential in each feeder. Even when having data allowing to estimate the DRES potential (e.g. available roof area), numerous assumptions are still needed to convert this potential in DRES penetration. Despite the complexity of this work, it can be highly automated and an additional added value is expected.

This paper only considered the purely technical aspects of the considered smart grids solutions. The final decision on deploying smart grids solutions will be dictated by the economic performance of these solutions against the network reinforcement.

Another major part of the work done on the deployment potential of smart grids solutions in LV networks in the framework of the project IGREENGrid has been the attempt to classify LV feeders on the basis of the indicators mentioned in section 2. For MV networks, an extensive analysis has been conducted on a set of 29 representative networks from 8 European DSOs. The results of this work will be presented in the near future.

Acknowledgment

This work as partly done within the project IGREENGrid which has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 308864.

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