Utilization of distributed energy resources' flexibility in power system operation – Evaluation of today's status and description of a future concept

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***Abstract*— In the future power system the massive amounts of distributed generation, in particular at low-voltage level, will increase the need for distributed monitoring and control, and for improved resource management in the distribution grid. This paper is based on research from two projects: EU (FP7) ELECTRA IRP (2013-2018) and FME CINELDI (2016-2024). ELECTRA proposes a future (2030+) decentralized control architecture (Web-of-Cells) for balance (including frequency) and voltage control, as opposed to the current centralized control approach typical of Transmission System Operators (TSOs). CINELDI, based on today's status, is exploring the needs for, and the possibilities of, exploitation of flexible resources for power system control towards 2030/2040. In cooperation these research projects can give a contribution to achieve future effective coordination among the stakeholders, in particular between TSOs and Distribution System Operators (DSOs).**

Keywords*— *Smart Grids, ancillary services, distributed energy resources flexibility

I. Introduction

Many power systems today are still characterised by limited operational interaction between TSOs and DSOs. This has always been possible in a grid with unidirectional power flow from the transmission to the distribution level, and with a limited amount of Distributed Energy Resources (DERs)[1] integrated. For the future, instead, increasing critical bidirectional power flows are expected, due to the presence of massive amounts of distributed generation, in particular at low-voltage level. Therefore, more distributed monitoring and control, together with participation of DSOs in system control via resource management in the distribution grid, is foreseen to be required. This is also expected to call for a more flexible interaction between the grid and the connected DERs.

Effective coordination between TSOs and DSOs [1], in particular, is already becoming more and more important, to be able to i) handle the new technologies present in the power system (both the "hardware" ones – e.g. new kinds of electrical appliances, of generators and of measurement devices – and the "software" ones – e.g. control of distributed generation, control of active demand, digitalization, cyber-security,…) to obtain a truly smart grid; ii) secure a reliable, cost-efficient and sustainable system operation; and iii) also facilitate the development of different types of market (or market products), e.g. to handle traditional and innovative ancillary services, supplied by old and new participants [2]-[4].

This paper investigates some fundamental issues about how to support a smooth transition towards the operation of the future power system, from 2030 and beyond, starting from today's status of the DSO/TSO interactions and of the availability of flexible resources. To the purpose, it combines results from two research projects: EU (FP7) ELECTRA [5] and FME CINELDI [6]. This section gives an introduction to the two research projects, together with a summary of the assumed evolution trends towards the future power system. Section II and III, respectively, report some results achieved by each project, while Section IV draws some conclusions and formulates recommendations for further work.

[1] DERs include energy storage, distributed generation from renewable sources and demand response.

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A. Changes in the Power System

There are several widely accepted trends regarding the 2030+ power system. The studies made in ELECTRA IRP summarise these trends in a set of scenarios (compare also [8]), which are presented in details in [8]. From such scenarios, a set of common underlying key assumptions have been derived, and adopted as a starting point for the project work:

- generation will undergo a shift i) from classical dispatchable units, fed with fossil fuels, to units fed with intermittent renewables; ii) from relatively few large units to many smaller units; iii) from central transmission-system-connected generation to decentralized distribution-system-connected generation;
- electricity consumption will increase significantly, e.g. due to electrification of transport (Electric Vehicles – EVs) and of heating/cooling;
- electrical storage will be a cost-effective solution for offering ancillary services;
- large amounts of fast-reacting distributed resources (can) offer reserves capacity;
- developments in Information and Communication Technologies (ICT) will support the pathway towards power systems managed in a more decentralized way.

B. Research Projects

1) EU (FP7) ELECTRA IRP

One of the key pillars in the ELECTRA IRP (*European Liaison on Electricity Committed Towards long-term Research Activities for Smart Grids* Integrated Research Programme) project (2013-2018) vision is that the European political goals for the massive exploitation of renewable generation are not achievable without radical changes in the existing paradigm of power system control due to the above-mentioned changes within the power sector. Therefore, the overall objective of the project is to develop radically new control solutions for the future power system. The considered time horizon is 2030 and beyond. In the project a novel control architecture concept was suggested, and called the "Web-of-Cells" [2] (WoC). The architecture includes, of course, measurement functions and control functions to deal, on the whole, with balance/frequency and voltage stability. The present paper looks essentially at the Work Package (WPs) about system "Observability" in ELECTRA IRP, namely WP5, dealing with observables, variables which are necessary for functioning of controls within the WoC [9].

2) FME CINELDI

FME CINELDI (2016-2024) - *Centre for intelligent electricity distribution* is an 8 years Research Centre under the FME-scheme (Centre for Environment-friendly Energy Research). The objective of CINELDI is to enable a cost-efficient realisation of the future flexible and robust electricity distribution grid, which will pave the ground for increased hosting of distributed generation from renewable resources, electrification of transport, and more efficient energy end use. The focus in the research is on 2030/2040. CINELDI is structured into six different WPs, and one of these (WP3) is focusing on the DSO/TSO interactions, with the objectives to develop concepts and solutions for increasing observability between the distribution and transmission systems and to develop business models for utilization of flexible resources – mainly DERs, including demand response by customers – in different market products and ancillary services. This paper, in particular, presents the results from a survey mapping today's status and future expectations related to using flexible resources in power system operation.

II. ELECTRA IRP METHODOLOGY – WEB-OF-CELLS CONCEPT

A. WoC – New Control Concept for the Future Power System

The WoC architecture concept suggested within ELECTRA IRP is based on dividing the (future) power system into a set of cells, so that balance (including frequency) and voltage control are dealt with in a coordinated way among the cells - called "Web-of-Cells". An ELECTRA cell is a portion of the power grid able to maintain an agreed power exchange at its boundaries by using the internal flexibility of any type available from flexible generators/loads and/or storage systems. The total amount of internal flexibility in each cell shall be at least enough to compensate uncertainties in the cell generation and load in normal operation [8], [10]. In particular:

- an ELECTRA cell is connected to one or more neighbouring cells via one or more physical tie-lines;
- there is no restriction in how cells are interconnected;
- an ELECTRA cell can span one or more voltage levels;
- it is not required that a cell is self-sufficient (i.e. capable to balance internal generation and load), but it is possible.

In Fig. 1, an example of WoC is presented, with different cells and their interconnections; internal topology of individual cells is not shown because, as already hinted at, it is not relevant. Each cell is managed by a so-called Cell Controller (CC), which is under the responsibility of a Cell System Operator (CSO) role, similar to present TSOs and DSOs, that supervises its operation and, if needed, is able to override it. A CSO can operate multiple CCs and therefore operate more cells also non-adjacent. The CC provides autonomous control of balance/frequency and voltage, also in coordination with other CCs [10]. More precisely, in the WoC, six high-level control functionalities, the so-called Use Cases (UCs), are introduced: Balance Restoration Control (BRC), adaptive Frequency Containment Control (aFCC), Inertia Response Power Control (IRPC), Balance Steering Control (BSC), Primary Voltage Control (PVC) and Post Primary Voltage Control (PPVC).

BRC is aimed at matching the cell actual net active power import/export profile to the forecasted profile. The system balance, as well as frequency, is restored based on local observables (cell tie-line power flows). BRC is faster than the present frequency restoration control [11], since it runs at the

[2] "Web-of-Cells"" is a pending trademark.

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same timescale as frequency containment control (and therefore contributes to frequency containment as well).

As to aFCC, frequency droop devices in each cell continuously monitor frequency deviation from the nominal value (df) and inject/absorb active power according to their dP/df droop setting; this, in turn, is received for each timestep, e.g. every ¼ h, based on the cell dP/df droop, i.e. on the Cell Power Frequency Characteristic (CPFC). The CPFC is adapted, for each timestep, to respond to real-time frequency deviation from the nominal value and tie-line power flow deviation from the scheduled value. Adaptation of the CPFC is with respect to the nominal value, which is, in turn, the cell's contribution to the system (WoC) Network Power Frequency Characteristics (NPFC) for the next (¼ h) timestep.

IRPC supplies additional, synthetic inertia to complement the physical inertia left in the system. A cell central df/dt droop slope determination function receives a cell's moment of inertia setpoint (cell's contribution to the system inertia) for the next timestep, and it determines df/dt droop slope setting for the next timestep for Rate Of Change Of Frequency (ROCOF) droop devices in the cell. Such devices continuously monitor df/dt and inject/absorb power according to their droop slope setting.

BSC implements a distributed/decentralized coordination scheme where neighbouring cells mutually agree on changing their tie-line active power flow setpoints – without violating operating limits – and this way reduce the amount of BRC reserves that would be activated in each cell based on local observables. This can be considered as an example of a localized imbalance netting mechanism. Specifically, BSC here determines new setpoints for the BRC controller, thus causing the deactivation of resources previously activated by BRC.

Voltage control functions (PVC and PPVC) are active at all voltage levels, to correct voltage deviations that cause voltage limit violations and also to minimize power-flow losses. PVC is assumed as it is already in use today. The proposed PPVC determines setpoints for all resources able to contribute to voltage control (and loss minimization). The cell central PPVC function is activated either by a system-level trigger or when one of the pilot nodes, which autonomously monitor their local voltage, reports a voltage violation. When activated, PPVC computes, via an optimal power flow, new voltage setpoints, based on information about availability of voltage reserves, reactive power-flow profile setpoint at the cell tie-lines, and load and generation forecasts. The calculated setpoints are sent to the PVC droop nodes, controllable Q nodes, capacitor banks and on-load-tap-changer-transformers (OLTCs).

The UCs are characterized by three fundamental features:

- solving local problems at cell level;
- responsibilization of the CSOs, with local neighbour-to-neighbour collaboration;
- ensuring that only local reserves-providing resources, whose activation does not cause local grid problems, will be used.

During the ELECTRA IRP project, the proposed control schemes were tested in both simulation and laboratory environments, see [9] for more details.

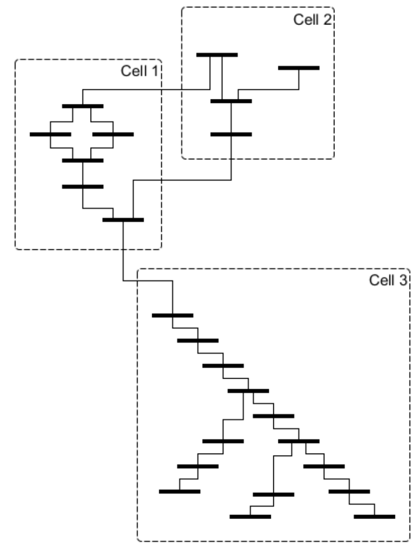

Fig. 1. Web-of-Cells example. Source [8].

B. *Observables Required for a WoC*

Within the project an observable has been defined as a uniquely valued function of a number of measurable quantities in a physical system. An observable can be either a scalar or vector quantity that is calculated from measured or estimated values in the present or past. A dedicated multi-step framework for testing accuracy and robustness of algorithms to determine the observables, especially the new ones, has also been developed [9]. Mapping of the observables which have been applied in the six WoC controls, i.e. in the six UCs, has resulted in the definition and selection of 40 observables altogether [12]. This has been followed by a clustering process, which has been carried out by grouping "similar" observables according to the following parameters:

1. Control Topology Level (CTL): in this case, physical (single)-device level (CTL0), aggregated-device level (CTL1), cell level (CTL2) or inter-cell level (CTL3);
2. Input signal (-s), i.e. the signal(-s) actually measured from which the observable is derived: e.g., the voltage waveform, the current waveform, the tie-lines active power and frequency;
3. Input device/component (when possible), e.g. Phasor Measurement Unit (PMU), Field/Voltage transformer.) Input Device/component.

Eleven clusters have thus been defined:

Cluster A: local Rate of Change of Frequency (ROCOF), at CTL0 and CTL1;

Cluster B: ("Equivalent" inertia time constant or "equivalent" (i.e. either physical or synthetic) moment of inertia)

Cluster C ("Equivalent" inertia time constant setpoint or "equivalent" moment of inertia setpoint)

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Cluster D ("Equivalent" inertia time constant or “equivalent” moment of inertia, at CTL0 and CTL1;

Cluster C: equivalent inertia time constant setpoint or equivalent moment of inertia setpoint, at CTL0 and CTL1;

Cluster D: equivalent inertia time constant or equivalent moment of inertia of a cell or of a WoC, at CTL2 and CTL3;

Cluster E: equivalent ("Equivalent" inertia time constant setpoint or "equivalent" moment of inertia setpoint for a cell or a WoC, at CTL2 and CTL3;

Cluster F: centre-of-inertia frequency and related ROCOF, at CTL2 and CTL3;

Cluster G: tie-line power, at CTL2;

Cluster H: frequency observation in the cell, carried out mostly at CTL0;

Cluster I: voltage, at CTL0;

Cluster J: imbalance estimation, at CTL2;

Cluster K: grid impedance estimation, at CTL0 and CTL1.

Clusters A-F refer to IRPC; G-H to aFCC; G-H again to BRC; G, H and J to BSC; I and K to PVC; I to PPVC.

The idea of clustering is based on the assumption that in several cases observables can be generated based on metered values (input signals) obtained from the same measuring device, as already recalled via parameter 3. above.

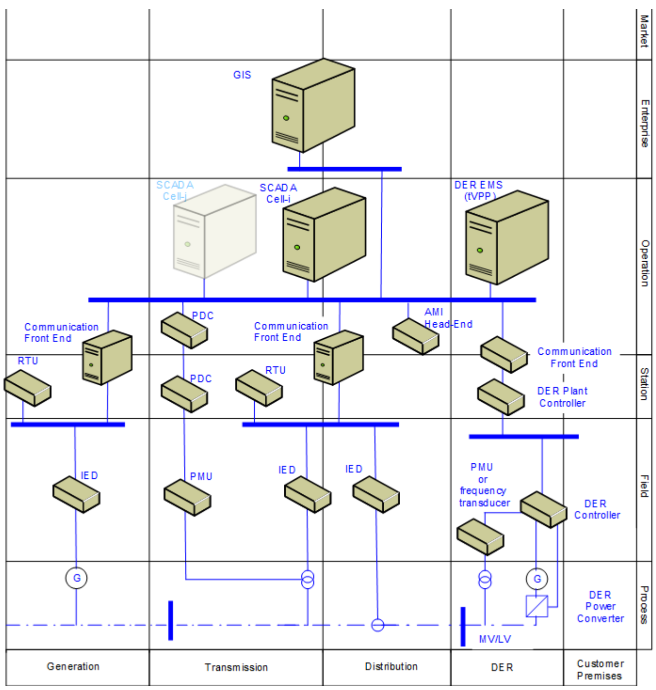

Fig. 2. SGAM component layer for the combination of controls required for the WoC concept. Source [12].

This division of the observables has allowed to make an implementation proposal for each cluster, i.e. to define/describe the technical specifications of components to obtain the observables, and to make a mapping of these devices to the component layer of the Smart Grid Reference Architecture (SGAM), for each type of control or its corresponding UC. Finally, the SGAM mappings of *all* control UCs have been collected into an overall one single component layer mapping (see Fig. 2).

Finally, a mapping of all control Use Cases to one single component layer was prepared, making a possible implementation proposal for the Web-of-Cells.

III. DSO/TSO Interaction – Current Status and Future Expectations

WP3 in CINELDI is focusing on DSO/TSO interactions for the timeframe towards 2030/2040. To be able to discuss the transition towards this long-term period, the assumed starting point has been a survey mapping today’s status and future expectations about the DSO/TSO interactions, and focusing especially on how and how much flexible resources are and will potentially be utilised in the power system operation [13] and also on what kind of information it is necessary to monitor.

A survey among selected Norwegian DSOs was performed during the winter 2018. Its results are presented in [14], and the main ones are reported in this section.

A. *Performing the Survey*

The survey was sent out in January 2018 to 12 DSOs (most of the largest ones in Norway), and 7 responses were received (so the response rate was 58%). All the DSOs receiving the survey are partners within CINELDI. The results from the survey have been further quality assured by the expert group within WP3.

B. *Results from the Survey – Use of Flexible Resources*

In the survey the DSOs were asked about the use of flexible resources in the operation of the power system today, and how the DSOs expect this would be in the future (2030/2040). The flexible resources in focus were demand, Distributed Generation (DG) and storage.

1) *Today’s status (2018)*

The first part of the survey was focusing on today’s status related to the use of flexible resources (demand/DG/storage). The survey results are presented in TABLE I. -TABLE III.

TABLE I. Status Today – Flexible Demand

Resource type	**Utilization**	**When is this in operation?**
Flexible /unprioritized demand with an agreement of disconnection through a reduced grid tariff (especially electric boilers)	Disconnection in periods with overload/ strained operation (interruptions, planned outages or peak load)	Handling error situations and temporary problems with limited grid capacity
		To avoid/postpone grid investments
		Reducing bottleneck towards transmission grids

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TABLE II. STATUS TODAY – DISTRIBUTED GENERATION

Resource type	Utilization	When is this in operation?
Regulating capacitors/ batteries/ generators (MVAr generation)	Reactive power exchange	Voltage regulation
Generation/ unprioritized generation	Bottlenecks in the distribution grid	Maintenance/errors
Generation units connected to system relays	Disconnected when outages of specific parts of the grid occur	Increased utilization of weak grids
Small hydro power plants (run of river)	Limitation on the electricity fed into the grid (specified in operation agreement)	Avoid overload, postpone need for grid investments
	Upward/Downward regulation of generation	Contribute to voltage stability if interruptions occur
Sun/Wind/ Small hydro plants	Regulation of DG is simulated in pilot projects	High load on transformer

TABLE III. STATUS TODAY - ENERGY STORAGE

Resource type	Utilization	When is this in operation?
Battery	Pilot project with a grid-connected battery. Charged and discharged according to price and available capacity (Active power)	In periods with high load on transformer
Power plant with reservoir	Increased/reduced generation. Upward/Downward regulation	Under disturbance (strained operation)
		Interruptions, planned outages changing the grid structure

2) Expectations for the future – 2030/2040

The second part of the survey was focusing on the future expectations related to the use of flexible resources (demand/ DG/storage) in the future power system, and for what purpose. The survey results are presented in TABLE IV. - TABLE VI.

TABLE IV. FUTURE EXPECTATIONS – FLEXIBLE DEMAND

Resource type	Utilization (When is this in operation?)
Demand Response (all types of customers)	Reserve capacity in HV[3] distribution / transmission grid (Interruptions and planned outages)
	Load levelling in normal operation in HV distribution grid (Postpone grid investments)
	Stationary voltage support in LV[4] distribution grid
Today's customers with tariff for interruptible loads	Handling situations with limited grid capacity, voltage problems, etc.
Industry	Interruptible loads (Disconnecting automatically in case of emergency situations)
Larger customers (Commercial loads)	Balancing services (in grid operation) (Interruptible loads are already in use for such services, but in the future they could also be used for other purposes)
Households	Balancing (An aggregator is necessary to be able to utilize demand response from small customers)
Electric boilers, heating appliances, electric water heaters	Disconnected in peak load periods, in periods with limited grid capacity or when balancing services are needed (Some appliances can be evaluated as thermal storages)
Data centres/ Bitcoin mining	Disconnected in periods with limited grid capacity or when balancing services are needed

TABLE V. FUTURE EXPECTATIONS – DISTRIBUTED GENERATION

Resource type	Utilization (When is this in operation?)
Hydrogen used as energy storage	Extra source for energy in grids with limited capacity
Local generation (sun, wind, small hydro plants)	Levelling out peak load
	Back-up/ Island operation (Interruptions and planned outages)
	Voltage regulation, balancing reserve (frequency – primary reserve, situations with limited grid capacity, or problems with voltage quality) Remark: PV[5] panels cannot be regulated, and should be combined with flexible demand and/or storage to be flexible. The inverter connected to the PV system can be used to counteract disturbances
	Charging batteries
Emergency power supply	Increased area of use from resources that today is only available for emergency purposes

TABLE VI. FUTURE EXPECTATIONS - ENERGY STORAGE

Resource type	Utilization (When is this in operation?)
Stationary battery at the customer's premises (behind the meter)	Handling situations with limited grid capacity (peak load) (voltage control, balance service provision, frequency regulation, congestion management, etc.) The main challenges are more related to technology and business models, than the actual location and type of battery Short-time support of short circuits in the LV distribution grid (Contribute to increased support for short circuits) Reducing voltage dips and flicker in the LV distribution grid Operation in the energy market (buying at low prices/selling at high prices)
Mobile batteries (EVs)	
Grid connected battery	
Groups of batteries	
Energy storage supporting short circuits (e.g. supercapacitors)	Short-time support of short circuits in the LV distribution grid (Contribute to increased support for short circuits)
Energy storage for voltage support (e.g. supercapacitors)	Reducing voltage dips and flicker in the LV distribution grid
Electric water heater (thermal storage)	Load shifting in peak load periods in areas with limited grid capacity

3) Evaluation of the Results from the Survey

According to the survey, the use of flexible resources today is mainly related to disconnection of unprioritized demand units that have an agreement for disconnection through a reduced grid tariff. Typically, these loads can be disconnected for an unlimited period, and the customers have alternative energy carriers that they can use when the electric load is disconnected. Based on experience, these loads are disconnected in periods with temporary problems with limited grid capacity, but this

[3] HV = High Voltage
[4] LV = Low Voltage
[5] PV = Photovoltaic

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agreement for disconnection is seldom in use. In the future the DSOs expect that there will be an increasing focus on flexible resources, and not only to be used in periods with limited grid capacity in the power system. Due to technology development combined with reduced costs for different technologies (for example PV panels, electric batteries and communication and control technologies), flexible resources are evaluated as a new source to be included in cost efficient operation of the power system. In other words, it is expected that a wider variety of flexible resources will be available in 2030/2040, and that these will also be used in normal operation of the grid. Each of the three kinds of flexible resource examined is now discussed in more detail.

Comparing the status today with the expectations for the future shows that, as for demand, only unprioritized demand is in use (TABLE I.), but in the future a larger variety of demand units is expected – both in terms of the type of demand (also without an alternative energy carrier) and in terms of variations in the type of customer offering the flexibility (TABLE IV.). To be able to utilize smaller resources to support grid operation, an aggregator is expected to be required.

DG units are used as flexible resources today (TABLE II.) and they are disconnected if there are, e.g., problems with the local voltage or overload conditions. In Norway today distributed generations are typically small hydro power plants (run of river). In the future (TABLE V.) the types of resources are expected to increase, and both hydrogen-fuelled systems, PV panels and wind turbines are mentioned to be used for voltage regulation and balancing services.

The availability of energy storage is expected to increase towards 2030/2040. Today (TABLE III.) hydro power plants with reservoirs are mentioned as resources for grid operation, but there are some on-going pilot projects with battery storage systems. In the future (TABLE VI.) several types of energy storage are expected to spread. Both electric batteries located at the customer (behind the meter) or in the grid (grid connected) are mentioned as important resources – to be used both for balancing services (bottlenecks in the grid or operating in the market) and for supporting short circuits and for contributing to voltage support. Additionally, thermal storages, in particular those represented by electric water heaters, can be used for load shifting in peak load periods.

IV. Discussion and Concluding Remarks

This paper focus on utilizing flexible resources to support stability and security in power system operation. For the future in view of a large expansion of distributed generation, large generation units are expected to be replaced by medium-small ones often fed with non-programmable energy sources and spread especially at low-voltage level, so less centralized regulating resources are expected to be available, on the one hand, and local critical issues are expected to increase, on the other hand. Therefore, new control functionalities and even new control architectures, relying heavily on distributed flexible resources (both from generation and from demand), could be necessary, together with new observability requirements: these concerns have been taken into account by the ELECTRA IRP project, which has proposed a preliminary control architecture based on a Web-of-Cells concept. To support a smooth transition from the operation of today's power system to the future power system, the current status of resource utilization and of the control functions already under development by TSOs and DSOs, has to be taken as a starting point. CINELDI, indeed, has carried out a comparison of the present and possible future status of distributed generation, storage and demand response flexibility, as a result of information collected from DSOs.

CINELDI highlight a variety of flexible services which can be supplied by large amounts of dispersed, but flexible, resources. An interesting challenge will be to include an efficient management scheme for such resources in the ELECTRA control architecture, thus creating synergy among the two projects. More precisely, new control functions could be added to the WoC architecture, to enable the mentioned resources to participate in the provision of new ancillary services, according to the needs specified by the DSOs in the survey.

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