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Indirect Control for Demand Side Management
– A Conceptual Introduction

K. Heussen, *Member, IEEE,* S. You, *Member, IEEE,* B. Biegel, L. H. Hansen and K. B. Andersen

Abstract— **The concept of "indirect control" has become a relevant discussion term in relation to activation distributed and small-scale demand and generation units to provide resources for power system balancing. The term and its association with price signals has, however caused some confusion as to its correct definition, either as a control or a market concept. This paper aims to provide a conceptual introduction to "indirect control" for management of small and distributed demand side resources. A review of control concepts and an analysis of "indirectness" features are provided to create a framework for systematic classification of indirect control strategies. The concepts developed then enable a discussion of control performance and valuation of direct- and indirect control strategies.**

Index Terms—**Demand side management, Demand side resources, Control, Indirect control**

I. INTRODUCTION

DEMAND side resource (DSR) refers to the geographically distributed modular power generation, consumption and energy storage systems which are located on the demand side and have the capability of altering their consumption pattern. As a whole, DSR exhibits a significant potential to improve the economics of electricity by facilitating energy management, providing emergency response and ancillary services [1]-[2]. Conventional demand response (DR) programs organized by utilities can be split in two categories. The first group requires a fast and reliable response from DR programs, so that the DSRs are remotely controlled by the utilities in a master-slave manner under bilateral agreements. These programs primarily target medium to large size commercial and industrial DSRs and they are typically limited to interruptability services. A second group of DR programs is aimed at modifying the consumption of a large number of small-scale DSRs by means of economic incentives. These so called dynamic tariff programs include e.g. hourly real time pricing (RTP) and time-of-use tariffs (TOU) but also capacity pricing are used to shift consumption patterns and achieve better system economics [3], with 'dynamics' in the scale of hours to years.

Along with the anticipated increase in penetration of DSR in the distribution systems, both the utilities and the emerging non-utility entities intent on exploiting the added value of coordinating a fast response from these low cost small-scale DSR by means of coordinated control strategies. By providing fast and reliable grid-supporting services such as power balancing, congestion management or voltage regulation, a win-win situation for various stakeholders could be created. These approaches entail the introduction of new control structures to power system operation, often referred to as Virtual Power Plants (VPP) or active demand side management systems (DSM), which could be realized by a number of different control strategies. Using Denmark as a testfield, several ongoing projects e.g. iPower[1], Flexpower[2] and EcogridEU[3] are developing control solutions for DSR management for emerging DSR technologies such as electric vehicles (EVs) or heat pumps. In these projects, DSM solutions are investigated from technical, economic and social perspectives, where the interests of different parties i.e. Transmission System Operators (TSOs), Distribution System Operators (DSOs), Balance Responsibles (BRs, here to be considered mostly equivalent to 'aggregators') and DSR owners are balanced in the context of a deregulated power market.

This paper distinguishes between two control paradigms, namely "direct control" and "indirect control". The former alludes to a conventional control approach which requires DSR state information to compute reference trajectories for the DSR consumption to follow. The latter approach is often associated with broadcasting of incentive signals (prices) with an update frequency of e.g. 5 minutes to the DSRs. Compared to the hourly dynamic tariffs, this update frequency is fast, and falls into the time range of generator ramps, for example. A commonality of these control approaches is the concept of 'aggregation': a larger number of functionally similar units are combined via a control structure to be represented and to behave 'as one' in the energy market or in the supply of ancillary services. However, it is understood that the term 'indirect control' is too generic and DSM examples exist that do not employ uni-directional price signals but do share some 'indirectness' properties.

[1] http://www.ipower-net.dk/
[2] FlexPower homepage hosted by Ea Energianalyse
[3] http://www.eu-ecogrid.net/

A. Indirect control for DSM

Classification beyond this particular example of 5-min-price signals is not straightforward. In particular, the combination of control- and market-oriented concepts makes indirect control a difficult concept to frame.

Two central characteristics of 'indirectness' are to be analyzed for conceptual clarification:

(α) The relationship between control objective and observables is indirect and may be characterized by random unobservable behavior and sometimes large time delays.

(β) The control structure is not purely hierarchical: i.e. independent (economic) decision making at a local level is part of the control strategy, which influences the system response such that a deterministic containment cannot be guaranteed.

Thus, a common characteristic of indirect control concepts is that a conventionally direct relationship between control objective and observable information and between command and response is broken and replaced by an indirect relationship. There are therefore two different types of indirectness: for (α) the actual response to the signal is not observed and for (β), the signal is not a command, but only an incentive. In other words, in case of direct control the power is observed and controlled via power reference commands. In the other extreme case of indirect control by prices, (α) the response is not directly observed, and only (β) an incentitive signal is used, influencing consumption in a desired direction.

B. Value Drivers for Indirect control

Some main drivers for the development of indirect control strategies for DSR management include:

- The independence of local decision-making is an appealing concept in a multi-stakeholder setting;

- Avoiding the need to collect detailed local state information about consumers is favourable to privacy concerns and reduces communication requirements;

- Statistical smoothing enables a significant response of an aggregate, whereas the response in individual contributions would seem very small and unreliable.

On the contrary, for direct control, the effort involved in state-measurement and fine grained, bi-directional communi-cation for large numbers of small units may outweigh the benefits of increased controllability. Note that also for indirect control by prices, power consumption data has to be collected on a corresponding time resolution (e.g. 5min), but it does not require the real-time feedback. The trade-off between direct and indirect control approaches would be balanced differently for different control needs and different capabilities both on the side of the aggregator and on the side of the consumer.

The objective of this paper is to present a conceptual basis for classification and analysis of indirect control strategies. This paper is organized as follows. First, a brief summary of relevant control concepts is provided in Section II. In Section III, some definitions for the aggregated control of DSR are introduced and Section IV presents the classification of indirect control. Section V discusses the valuation of indirect control as control strategy in context of direct control concepts. Section VI concludes.

II. BASIC CONCEPTS AND NOTATION

To prepare for the encoding employed for the classification at hand, some basic relevant control concepts as well as the notation shall be clarified.

A. Notation

S	Objective as well as further information required for a meaningful value judgement
r	Control reference (command)
y_p, y_{fcn}	System output and feedback: p … power; fcn … functional variable (e.g. room temperature)
e	Control error
d	disturbance
$(.)^*$	Forecasted variable
$[i]$, $[1..i..N]$	Single vs. multiple signals (correspondingly: thin arrow: single signal, thick arrow: signal bundle)
DM	Decision maker – a computational entity capable of (formalized) value judgement.

B. Local Control Patterns

Open-loop control and *closed-loop control* or feedback control are two basic control principles. Both aim at effecting a desired response (*control objective*) in one end of the system, targeting a *controlled variable* (e.g. a voltage level), by means of adjusting another *manipulated variable*, utilizing the interactions within the system (e.g. excitation voltage). For closed loop control the controlled variable has to be *observable* by means of direct measurement or model-based inference (observer). The system behavior is then incorporated directly into the generation of a control action by means of a control law (also: *controller*). In open loop control, only an understanding (model) of the system enables the computation of a control action.

Objectives (e.g. cost minimization)
Exogenous inputs (e.g. knowledge of the global and local enviroment)
Endogenous inputs (e.g. knowledge of the plant dynamics and physical contraints)
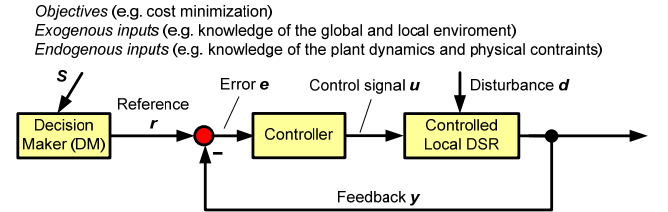
Fig. 1. Cascade pattern of open-loop decision making and closed-loop reference tracking.

Because open-loop control does not require an immediate mapping of observations to decisions, it typically allows the consideration of more contextual information. Here the term Decision Maker (DM) is employed, to refer to an entity that considers trade-offs with respect to a more complex external environmnent and is capable of taking independent-value-oriented decisions. However, an open-loop configuration

cannot provide the stabilizing and disturbance rejecting properties of closed-loop control. A common *pattern*, combining both properties, is therefore the cascade of "open-loop" decision making with a closed-loop disturbance rejecting and reference tracking control, as depicted in Fig. 1.

C. Plant Model

Open-loop and model-based control functions require a representation of the controlled system (plant model) to compute control actions. Typically these models are formulated as differential- or difference- equations, derived either by analytical or automated learning methods. Uncertainties associated with the plant dynamics or projected disturbances can also be considered explicitly for robustness or risk hedging purposes. The structure of uncertainty can be captured e.g. by uncertainty sets associated with model parameters or explicitly by probabilistic models.

D. Control Structure & Coordination Patterns

Control structure captures how control is organized with respect to *control objectives, observables, actuation* and *decision making,* and the *controlled process.*

In real systems, there is commonly a set of independent control objectives, for example safety objectives or local process requirements, which would not be organized under the same control hierarchy. Objectives of a realistic system are therefore organized in a *heterarchical* structure due to over-lapping scopes of control [4]. In this case, the system's degrees of freedom need to be organized in a design phase to allow for non-conflicting operation (decentralized control, coordination-by-design).

If also the decision-making aspect would be decentralized, a *coordination strategy* has to be devised that guarantees the reflection of mutual interests (e.g. by employing a mutual value exchange) in the decision-making problems. Such a coordination strategy can be market-based or follow other organizational strategies. An example for a market based strategy has been presented in [5].

E. Conventional Indirect Control

The control literature defines indirect control as a control strategy in which the control variable is only indirectly associated with the actual control objective. The relationship between actual controlled variable and objective is modeled, e.g. via a inverse model or look-up table [6]. Using this understanding of indirect control, here indirect control is defined as follows:

Definition: *An* indirect control structure *is a control structure in which the control objective does not coincide with observables, and the relationship between observables and objective is established by means of a model.*

Using the inverse model as the open-loop part, also indirect control can be illustrated by the basic pattern presented above (Fig. 2). Note that according to the above definition, there is no decision making involved in this pattern.
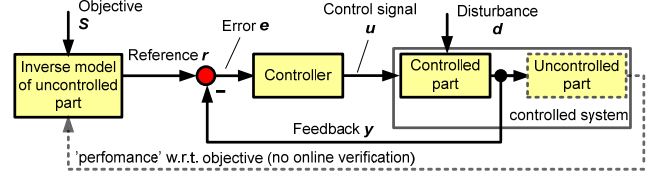

Fig. 2. Conventional indirect control pattern as described in [6].

III. INDIRECT CONTROL OF DSR: DEFINITIONS

The term "indirect control" has been coined to emphasize a contrast to "direct control" in context of DSR management (DSM). The general setup for DSM consists of a central 'aggregator' controller (typically representing a balancing responsible party or an associated service provider) managing a large portfolio of small DSR units which are also controlled locally. In any case, DSM consists therefore of a bi-level setup, where available flexibility at a local control level is employed to satisfy further control objectives at a central level. In order to define the meaning of 'indirect' in a control setup in opposition to direct control, first the aggregator-based direct control concept is introduced. Then definitions for the classification of indirect control are developed.

A. DSR Management via Direct Control Aggregators

In general, direct control refers to a setup where an agreement/contract exists between aggregator and a number of DSRs allowing the aggregator to directly control the DSRs within the framework of the contracts. In this setup, a synchronized two-way communication exists between aggregator and DSRs: the DSRs controllers reports local information to the aggregator and the aggregator sends control commands based on this information, as illustrated in Fig. 3.
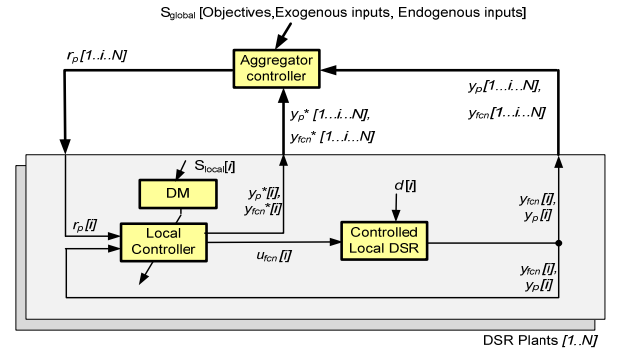
Fig. 3. Schematic of 'direct control' with aggregator controller and local controller.

A set of N DSRs are under the jurisdiction of an aggregator controller. Each DSR is controlled by a local controller via control signal u_{fcn} and subject to local disturbances d. The local controller is configured by a Decision Maker, which here represents the user interface or intelligence in reflecting user requirements to the control constraints, setting the local objectives S_{local}, such as a desired household temperature range; the local controller also receives control commands r_p from the aggregator which the DSR will seek to track, monitoring local power consumption y_p and the local

functional state variable y_{fcn} (e.g. the current temperature). In addition to receiving control signals from the aggregator, the DSRs report local power consumption y_p and the local functional state variable y_{fcn} to the aggregator – this completes the direct control two-way communication structure. Finally, the DSRs may be able to provide predictions of future power consumption and constraints y_p^*, y_{fcn}^*, to the aggregator, which may be considered a 'flexibility forecast', in case of varying requirements.

B. Definition of "Indirectness" Criteria

As discussed in Section I.A, two key criteria enable the classification of indirect control strategies:

(α) "breaking of the control loop"

(β) "independence of local controller"

Both of these criteria have been employed independently in the literature to motivate the term 'indirect control'. The first is motivated purely from a conventional control perspective whereas the latter criterion requires the integration of a value-oriented (economic) decision-perspective.

1) Loop-breaking: Aggregation-based indirect control

The loop-breaking (α) in DSR management is enabled by an aggregation of similar units, for which a combination of strongly correlated behaviours overlaid with uncorrelated random processes enable a statistical smoothing effect with a controllable mean. The larger part of indirect control concepts for DSR employ this aggregation effect. The control strategy exploits the aggregation effect reducing the need for dedicated bi-directional communication and detailed local state information. This key aspect can be defined as:

Definition: The aggregation effect *is a smoothing by summation of diversity (due to uncorrelated random processes) in combination with a strongly correlated (coherent, modelizable) response to observable exogenous variables or control signals which can be captured in an aggregated model.*

The aggregation effect is thus fundamentally associated with the law of independent random processes (cancelling mutual fluctuations) on the one hand. On the other hand and it requires the existence of a behavioural commonality of elements in the controlled system.

The nature of the uncorrelated processes varies for different indirect control approaches. It includes for example: unsychronized processes, forecast uncertainties, independent decision-making, etc. Also the commonality aspect varies: e.g. common thermal properties of a collection of households, or a predictable economic response to an economic incentive.

2) Independent local control

The independency of local control is achieved by employing a value-oriented decision maker (DM) at the DSR plant 'in-the-loop'. In contrast, for a non-independent local control structure, the control reference is a command defining an objective for the local controller to pursue and achieve, thus binding the respective degrees of freedom of the DSR plant. In such a control strategy a local decision maker would be contractually bound to stay 'outside the loop', free only to influence remaining degrees of freedom – and of course with the choice of opting in or out of the respective contracts.

The DM 'in-the-loop' will trade off benefits and costs of electricity consumption at every instant. Which means that information exchanged with the respective aggregator does not have the character of command, but rather of coordination. Coordination between higher-level control objectives and local control objectives is established on the basis of a coordination scheme ensured e.g. by a market. It appears that two definitions are required:

Definition: A DSR with decision-maker is independent*, if its intentional behaviour only results from a local judgement of preferences, based on locally decidable trade-offs based on available value-related information.*

Definition: An aggregator control structure with independent local control *utilizes value-oriented information exchange, but no commands, to coordinate the response of independent DSR plants.*

It is open, whether these independent local decision makers should be considered "controlled" in the classic sense. The term "coordination" appears more appropriate here.

IV. INDIRECT CONTROL CLASSIFICATION

Using this classification approach, three conceptually different indirect control strategies have been identified:

A. Only (α): Pure aggregation based indirect control;

B. Only (β): Independent local control;

C. (α)&(β): Price signal based indirect control.

Note that aggregation concepts that purely apply commercial aggregation with no control structure at the aggregator level, such as conventional consumption responsible parties, have been excluded.

A. DSR Control With Indirect Functional Variables

One case of indirect control which applies the principle (α) is presented in [7]: a control loop aggregating thermostatically controlled loads, as illustrated in Fig. 4, when the local functional variable $y_{\text{fcn}}[i]$ is a local temperature. A locally associated control objective is a desired temperature (range), which is specified by a local decision maker (likely manually in this case). Neither local temperature reference $r_{\text{fcn}}[i]$ nor local state are measured or known by the aggregator controller. A "secondary", not locally measured variable is the power consumption $y_p[i]$, which also has no associated local control objective. In this example, the aggregated local feeder power $y_{\text{p,sys}}$ was measured as input to the controller. The momentary power consumption is indirectly controlled by adjustment of a functional constraint as a common global reference $\Delta r_{\text{fcn,constraints}}$, e.g. the thermostate limits, which constrains the local controller's switching behavior. In this approach, a statistical model is employed by the aggregator to characterize the relationship between the measurable/estimated aggregated feedback $y_{\text{p,sys}}$ and the global control reference $\Delta r_{\text{fcn,constraints}}$ and to generate the reference setpoints.
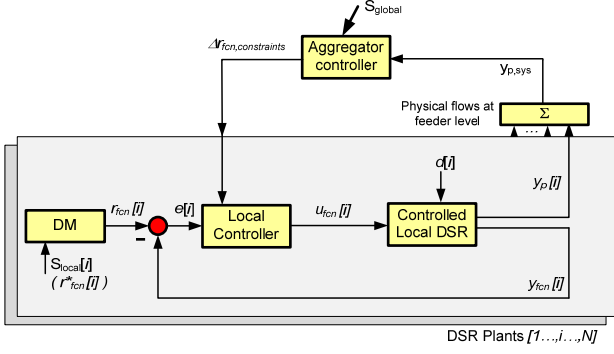
Fig. 4. DSR control with indirect functional variables.

No local data was collected and yet the local feeder power flow could be manipulated within specifiable performance bounds sufficient to supply secondary regulation. The control scheme is indirect in the control sense that there is only a statistical relation between controlled and manipulated variables and no local state information is shared with the aggregator. The concept is sometimes presented as innovative direct control scheme, since the performance of the controlled system corresponds to the performance of directly controlled systems.

B. DSR Control with Internal Market Platform

With market based control schemes, as in Fig. 5, the aggregator creates an exchange market for the DSRs to trade products, e.g. power, energy and flexibility. An aggregator has to translate his technical/commercial needs into market bids/offers and use the marketplace to retrieve the desired response from the DSRs.
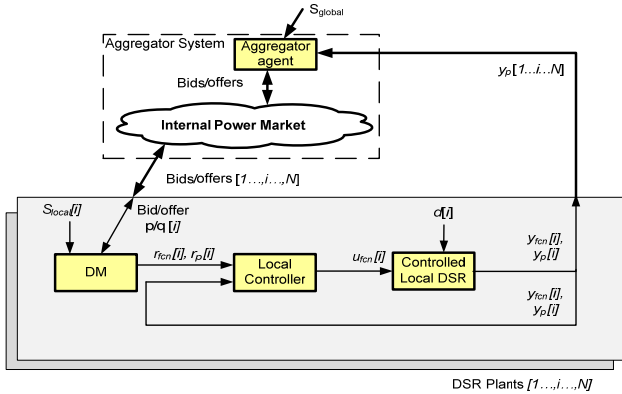

Fig. 5. Market based indirect control.

In a double-sided auction bids and offers are submitted by all parties, and the market prices are derived by means of market clearing mechanisms. The resulting control reference for the DSRs is then the power it previously bid at the clearing price [8],[9]. Due to the choice of a market with double-sided bidding (e.g. bids: [price q, power p], or more complex bids) as coordination instrument, there is an automatic independence of a local decision maker in the sense of indirectness type (β).

Event though the local DM is independent in bid-selection, therefore, the response after market clearing is deterministic.

The communication effort for this type of control is relatively high, but no local, unit-specific information has to be communicated.

C. Indirect Control via Price Signals

In a single sided auction uni-directional price signals are distributed by the aggregator and market clearing is performed by the voluntary reponse of the DSRs [10],[11]. In case that the aggregator has information about the operational status of a electrical network, a control loop with optimal pricing can in principle be formulated to address grid issues such as real-time power balancing and network congestion [12]-[14]. The use case considered here is the purpose of reducing the portfolio imbalance of a balance responsible party. The basic control structure is outlined in Fig. 6.
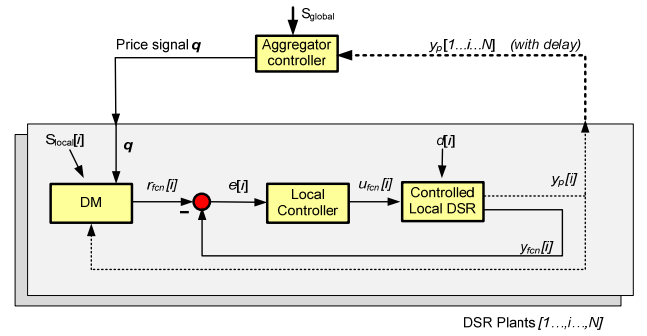

Fig. 6. Price signal based indirect control.

Although the prices theoretically can be updated on the scale of seconds, in practice they are generally updated on the time scale of 5-60 minutes in order to reduce the transaction cost and the volume of information flow.

The locally metered response would be based on smart meter data. It can be collected by the aggregator with a certain time delay and is also made available to the local decision maker, as indicated by the dotted line in Fig. 5. The prices are meant to adequately reflect the needs of the aggregator. A control strategy for the aggregator would create price signals based of its power needs (e.g. current imbalance) and the expected price-responsiveness of the DSR plants, but would not exceed the imbalance cost incurred if the demand side response is insufficient.

This final category of indirect control combines aggregation based indirect control (α) with the independence of the decision maker (β).

V. VALUATION OF INDIRECT CONTROL

Indirect control that integrates independent (economic) decision making in a control structure marks a qualitatively different paradigm of control. To understand the benefits of an indirect control design requires a clarification of the relevant trade-offs, which will be discussed in this section.

A. Perfomance as a Control Structure

The performance of a controller is typically measured in terms of its ability to minimize the mismatch between control objective and actual process response, as illustrated in Fig. 6

(sometimes also the control effort).

In power systems, the performance requirements for example for the delivery of a power balancing ancillary service (e.g. secondary control) are composed of firm dynamic response and reliability requirements. Failure to follow a control command (the control objective) in such a framework is a failure to meet a contractual agreement. The delivery of ancillary services thus requires the ability to support the system at a contractually specified level of dynamic performance and reliability (purely technical requirements).
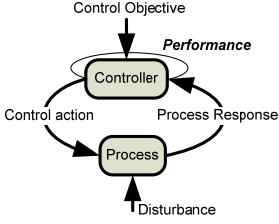

Fig. 6. Control performance based on mismatch and control effort.

In principle, a *performance measure* for aggregation-based indirect control designs can be established straightforward by establishing the difference to a direct control equivalent loop. For the case of indirect control with functional variables, it has been shown that a specifiable performance level can be achieved [7]. In cases where this performance basis for comparison can be established in a meaningful way, direct and indirect control could be compared on the basis of implementation requirements etc.

In particular price-signal based indirect control cannot be expected to deliver such performance: as the DSRs' response to the price signals is dependent on the end users' time varying preferences i.e. availability and willingness to respond to economic incentives, this control approach may not be able to achieve a consistent responsive control – and also highly volatile price signals could result, potentially exceeding the value of the desired response. To achieve a fully reliable balancing control, a price signal based control would have to be combined with other control structures in a portfolio.

B. Assigning Value to Indirect Control

The exact tracking of a power reference is not necessarily a meaningful requirement for control structures based on independent decision-makers. In a framework of economic decision-making for profit, as is the case for a Balance Responsible Party (see Fig. 6), the full value of a control contribution is reflected on the balance sheet: The trade-off for an ancillary service is in the value of the compensation minus the cost of delivering the required control performance minus the penalties incurred for failure to deliver the required control performance. Due to steep penalty cost, it is then acceptable to focus on strict control performance requirements in such cases. However, for example in the use case of reducing the portfolio imbalance for balancing responsible (BRs), the commercial value of flexible demand is not driven by the controllability according to firm reliability requirements but by the potential of directly matching of regulation cost with imbalance cost. A reduction of portfolio-

internal balancing requirements at a consistently cost lower than the imbalance cost carries value for a BR.

The real benefit of β-type DSR aggregators is thus that they are operated directly on a value based trade-off between cost and utility. This value-oriented controllability provided by is meaningful if smooth economic objectives are tied to the control response, as is the case for BRP imbalances.
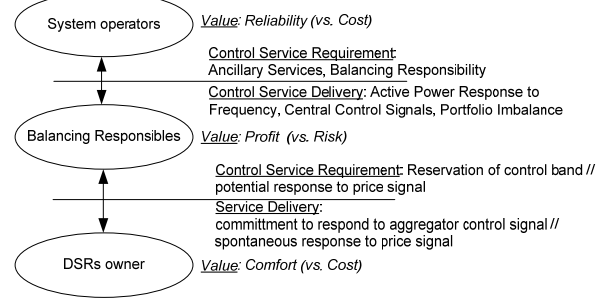

Fig. 6. Value Generation: Value based trade-offs vs. control services[4].

Apart from improving techniques such as modeling and forecasting fundamental to the indirect control design both on the aggregator and the local control side, a BR or aggregator therefore also needs to consider a risk hedging strategy that combines the benefits directly and indirectly controlled DSRs in their balancing power portfolio.

In a broader perspective, controllability of DSR has to be valuable for society as a whole, and therefore it is also relevant to consider the benefits for all involved actors. Consider the primary value trade-offs for System Operators (SO), Balancing Responsibles and DSR owners as suggested in Fig. 6. Chief concern for system operators is the reliability of the power system and cost improvements are only considered meaningful if overall reliability is not at stake – by specifying service requirements, 'reliability contributions' can be outsourced to commercial entities (the BRs), seeking to compete for cost-efficient service delivery at a profit. For a DSR owner, the conventional service value from a DSR is the energy service, comparable to that of a non-controllable unit. In addition to (reliable) cost reductions that do not put the service level at stake (the focus of direct control), indirect control might offer an opportunity to the DSR owner to directly choose the trade-off between cost and comfort, dependent on the users current situation (given that this concern is of importance to the user). The development of appropriate contracts as well as user interfaces with DSR owners that realize the mutual benefits for both DSR owners and the aggregator are a key concern for all DSM technologies.

C. Technical Challenges

Beyond the challenges of conceptually understanding indirect control, there are a number of technical challenges and

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[4] The primary value driver for these respective entities depends on their mutual role in relation to the infrastructure [4]. The reduction of DSR owners values to a simple consumerist 'comfort vs. cost' trade-off is only for the current argument's sake. Other trade-offs could be relevant for e.g. commercial or particularly environmentally minded consumers.

uncertainties that will influence the deployment on indirect control for DSM.

1) Modeling and predicting the aggregated DSR response

For the single sided aution indirect control setup, to generate a precise control signal that results in the expected response from the aggregated DSRs requires advanced modeling techniques that can chacterize the relationship between price signal power response to support the decision making of an aggregator. Although the aggregation effect supports smoothing of the response, human local decision making can be difficult to model and predict when the populaton in an aggregated system is small.

2) Measuring the aggrated DSR response

The complexity of modeling and predicting the aggregated DSRs' response is simplified when some online local or aggregate measurements are fed back to the aggregator, as in the case discussed in Section IV-A, where the aggregated power output is measured at substatition or feeder level. Under present competitive retail market in most of Europe, a commercial entity such as a BR will not have access to such grid-related measurements, which renders the respective control example currently infeasible in Europe.

3) Stability of indirect control

For power systems with real-time markets the market stability can be coupled with the controlled system stability [15]. Also oscillations of the aggregated plug-in hybrid electric vehicles (PHEV) in response to price signals and delayed reponse from the aggregated DSRs have been observed in [15]. Price oscillation (volatility) in itself can also be a stability concern – representing a potential market failure [17]. In mitigating such failure of the ecomic coordination functions, a control-oriented thinking about price-signals could help defining appropriate pricing mechanisms [18].

4) Coordination and interoperability of control solutions

From the perspective of power system operation, an integrated control system is requested to maintain the reliability and the security of a power system. The emergence of indirect control requires system operators to carefully examine the interoperability between various direct and indirect control solutions for different regulating purposes. For instance in a distribution grid with a high penetration of electric vehicles, several aggregators would offer independent economically driven charging. Then the distribution system operator DSO may consider the possibility of coordinating potential congestion issues. In this case it is important to develop and understanding of the interoperability of control solutions in order to coordinate system requirements with competitive interests of aggregators [19].

VI. CONCLUSION

This paper presented a conceptual understanding and classification of indirect control strategies. Existing and proposed solutions have been reviewed and classified into the presented conceptual framework. An elaboration on the valuation and technical challenges of indirect control provide a reference for further investigations..

In particular the identification two categories indirectness,

one remaining within the control engineering domain, and one that integrates economic decision-making (or more generally: value-oriented deliberation) will support the further discourse on active demand side management.

Further work will address the integration and valuation of mixed portfolios of direct and indirect control as well as the further analysis of co-existence of such control-solutions with respect to overall control architecture of the power system.

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