# Utilizing Flexibility Resources in the Future Power System Operation: Alternative Approaches

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*Abstract*—**Future power system will experience large amount of renewable generation with highly stochastic and partly unpredictable characteristics. To safely operate power system, new Flexibility Resources (FRs) are needed to participate in the operation. Some of the new FRs are linked to the electricity system, but they are managed outside of the electrical network by other energy sectors. To this end, an Integrated Energy System (IES) is needed to exploit such cross-sectoral opportunities. On the other hand, small FRs at the distribution level exist which can play an important role in the future. To exploit existing FRs, however, new operational strategies are needed. In this paper, Transactive Energy (TE) and Control-Based Approaches (CBA) are explained as the two mainstream frameworks in relation to the future energy system operation. The paper investigates benefits and drawbacks of each framework and finally defines a benchmark to better understand the potential of these solutions for the future energy management. The paper also concludes that more comprehensive operational approaches, beyond distribution system management, are required to fulfill the upcoming requirements.**

## I. INTRODUCTION

In the last decades, electricity transmission and distribution systems went through significant changes by introducing large- and small-scale Renewable Energy Resources (RES). These assets are scattered all around the network at different voltage levels. Although RES provide unquestionable benefits to the power system operation, e.g., sustainable and clean energy production and reduction in energy losses and T&D costs [1], they imply some challenges. In fact, RES are characterized by unpredictable and highly stochastic generation, mainly affected by the weather condition. As a result, increasing penetration of RES implies higher risk of local congestion and unbalances that need to be properly handled in real-time. Since energy generated from RES changes instantaneously and it is almost impossible to predict their generation accurately in different time steps, new Flexibility Resources (FRs) are becoming more and more important and valuable. FRs include shiftable and curtailable loads, storage devices, and inherent inertia of other energy carriers. Although the size of provided flexibility could be significant when aggregated, it adds new stream of stochastic behaviour to the power system operation which has to be managed. For instance, different types of flexible load are constrained by end-users' preferences and their behavior. They might not be as reliable as their conventional counterparts, however, predictability of their behavior can become acceptable when aggregated.

In the EU's new legislative proposal, the so-called Clean Energy Packages (Winter Package) [2] released on November 30th, 2016, a power system management that becomes more consumers-centred and, from a grid perspective, more centered around distribution network is encouraged. As a part of the Clean Energy Package, priority of dispatching RES disappears, and the main focus is going to be on Distribution System Operator (DSO) to utilize local FRs and handle grid issues.

Beside small FRs, Integrated Energy System (IES) is a concept that is attracting more and more attention [3], [4], [5]. The concept states that there are synergies between different energy carriers, such as electricity, gas, and heat, which can be exploited for the benefit of secure operation of the entire energy system with large amount of wind and solar power. This way, IES accounts for all the interactions among different energy carriers and large-scale infrastructure including wastewater treatment plants, transport and communication networks, and so on [5]. IES also increases efficiency of the system as a whole, where different assets are called to combine their strengths to work optimally together [6].

However, existing operational strategies in power system do not facilitate participation of new FRs accounting for their inherent stochasticity neither support IES. Therefore, it is crucial to create a smart transmission and distribution management structure that can support emerging FRs and IES potential.

In order to effectively deal with the magnitude of stochasticity and dynamics in the future power system operation by new FRs, dedicated operational strategies (particularly in shorter time intervals for Ancillary Services, AS) are required to be fast (to work as close as possible to real-time operation), cheap (to be a viable solution economically without increasing energy prices), simple (to guarantee feasibility and service continuity), efficient (to allow optimal service at the lowest cost), and to account for space and time differentiation, as shown in Fig. 1 (to focus on the local constraints of the network at different level). In fact, multiple operational levels with unique objectives and constraints are expected to work autonomously, while cooperating with each other on a broader perspective to guarantee global optimality of the entire system operation.

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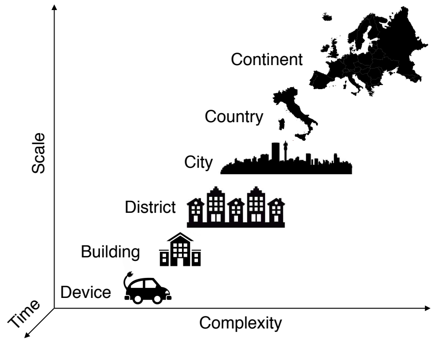

Fig. 1. Schematic of power system operation in different time and space

Nowadays, two mainstream solutions, namely Transactive Control/Energy (TC/TE) and Control-Based Approach (CBA), are preferred for the future energy management of distribution systems. This paper offers thorough analysis of the two energy management systems by addressing integration of FRs in the future smart grid framework. The authors intend to investigate pros and cons of these approaches and identify the caveats which urge more comprehensive solutions for the future power systems.

The paper is organized as follows: Section II presents TE and CBA from a conceptual point of view together with some relevant applications. Direct (DC) and Indirect controls (IC) for CBA are described in detail in Section II. Section III discusses limitations of the two approaches. Finally, the paper is concluded in Section IV, by focusing on the main findings and detailing future possibilities for smart energy management in research.

## II. APPROACHES FOR DISTRIBUTION-LEVEL ENERGY MANAGEMENT

Two different approaches have been proposed in literature to modernize distribution level energy management: Transactive Energy (TE) and Control-Based Approach (CBA). These approaches have been developed to handle new requirements of operation at the distribution level. Specifically, these methods are explained in the next two subsections.

### *A. Transactive Energy (TE)*

According to the definition of the Gridwise Architecture Council (GWAC), TE consists of a set of economic and control mechanisms that allows dynamic balance of supply and demand across the entire electrical infrastructure using a value as key operational parameter. It proposes a scalable coordination approach to electricity distribution system operations [7] while being able to provide services to the upper grid. The approach becomes particularly interesting in presence of high penetration level of DERs, by encompassing the entire electric system to the end-use customer meters [8]. To better understand TE approach, a conceptual block-diagram is shown in Fig. 2. In the top layer, existing wholesale market (both electricity and AS) is considered without any modification in its structure nor functionality. The wholesale market operator (e.g., TSO) communicates with energy suppliers and Balancing Responsible Parties (BRPs) to run power system effectively. In this framework, BRPs and energy suppliers are responsible for any deviation in their generation and/or demand from scheduled values. They have to purchase required balancing services from AS market (in the conventional power system operation) to compensate their variation. TE, however, provides mechanism to procure required services from small FRs at the distribution level through Virtual Power Plants (VPPs) or equivalently Aggregators. In fact, VPPs behave as effective power plants and indirectly represent end-users' flexibility located at the lowest level. VPP can include small- and medium-scale generation, aggregated load flexibility, and storage devices. Any request for up and down regulation services is submitted to the Global Flexibility Agents (GFAs), which are main aggregators to coordinate pools of Local Flexibility Agents (LFAs). This request is then broadcasted to LEAs, which are entities representing and communicating with a pool of end-users directly. By operating in the interest of the end-users, LFAs submit possible price signals to the pool to realize their reaction/responsiveness. Then, end-users receive potential price signal by their Home Energy Management Systems/Energy Management Systems (HEMSs/EMSs). By solving an optimization problem to minimize overall cost of energy, they decide about the reaction to the price considering local preferences set by the user. Optimization results are then communicated back to LFAs in the form of price-quantity bids. Once all end-users feedback is received, LFAs submit the bids to GFAs where information is aggregated and broadcasted to higher level agent. By receiving all the bids from GFAs, VPP is able to aggregate the bids using forward market principles and clear the price. Ultimately, the cleared price will be communicated to the end-users through the channels to procure required amount of service.

In TE framework, Grid Agents (GAs) are also defined as entities whose responsibility is to look after the grid benefits. Utility company and DSO are two examples of the entities which can serve as GA in this setup.

As you can see, the market mechanism in TE uses feedback to determine price and reach balance between supply and demand or procure services. As a result, TE can be defined as "uberization of energy"- for its connotations of personalized on-demand service and elimination of intermediates [9].

Several applications of TE have been developed in the last two decades, a few of which are: Olympic Peninsula Demonstration [10] (USA, 1996-2007); AEP Ohio gridSMART Real-Time Pricing Demonstration [11] (USA, 2010-2014); Pacific North West Smart Grid Demonstration [10] (USA, 2010-2015); Couperus Smart Grid [12] (EU, 2011-2015). These demo projects were evaluated successful by the operators.

TE, beside providing mechanisms to activate small FR potential at the lowest level of the grid, has several advantages which are summarized below:

- **End-users' Reaction**: It requires a feedback from end-users to know their reaction to a potential price. This way, uncertainty in end-users' behavior is minimized. In other words, TE does not need to model end-users' reaction in an abstract/aggregated way to predict their behavior and preferences. Therefore, there is a better chance for operator to procure required services without any surprises.

- **Privacy**: In this framework, no sensitive information from end-user is needed to be shared with any agent because local operation and decision-making occur at the end-users' level. The exchanged information is only price and energy quantities which in turn reduces privacy and security issues and threats.
- **Scalability**: The TE framework operates based upon receiving bids from participants and clearing the market accordingly. Therefore, numerous bids can be aggregated and the approach can be used in high scale. Also, market operation can be distributed among multiple LFAs and GFAs to accommodate more FRs.
- **Accommodating IES**: Very recently, studies emerged to show applicability of TE approach in IES operation [13], which provides larger amount of flexibility for power system operation.

Although TE satisfies some of the main requirements of the future smart grid in terms of exploiting new FRs, it comes with its limitations, as explained in the following items:

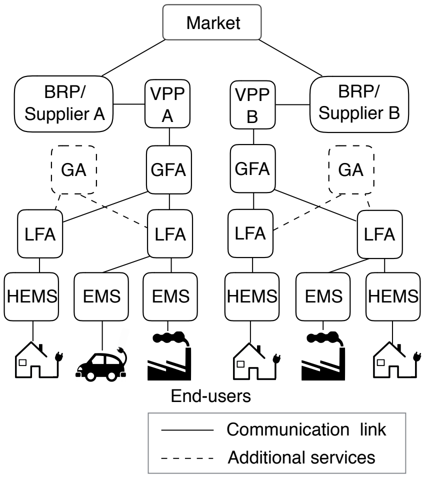

Fig. 2. Conceptual block-diagram of TE

- **Over-simplification**: The actual dynamics of the system is widely ignored in this approach. Every interaction among agents ends up with a price-quantity bid which is a linear representation of the underlying system. It is very difficult, if not impossible, to integrate stochasticity, true dynamics and non-linearity of FRs and power system operation through a set of linear supply and/or demand bids.
- **Computational effort**: As explained earlier, TE framework requires a cycle of bid-clearing mechanism whenever a new service request is received by VPPs. Basically, EMS/HEMS are invoked upon receiving a new price signal to generate new set of price-quantity bids. This requires to solve an optimization problem which is computationally expensive. Then, bids aggregation and market clearing should take place which requires additional computational efforts. As one can realize, the entire process seems to be computationally intensive considering the fact that there could be millions of FRs participating in this structure.
- **Slowness**: Service request from wholesale market participants are generated according to the wholesale market operation, which is updated every 5 minutes or so. Compared to actual changes in power system operation, 5 minutes is a long time to deal with true system condition. Additionally, every iteration of TE operation, as explained earlier, requires intensive communication, computation, and market processes which makes it substantially slow. Communication delay also plays an important role in slowing down the whole process.
- **Security**: While TE framework respects end-user's privacy, many communications between end-users and system's agents makes the framework vulnerable to cyber-attacks. It further threatens the power system operation in real-time. Additionally, relying on too many instances of communication increases sensitivity of power system operation with respect to communication malfunction.
- **Sub-optimal Solutions**: If TE is going to be scaled up so much to accommodate millions of FRs while accounting for physical limitation of the network, more VPPs, LFAs and GFAs are required. These agents are operating autonomously which means that their solution for power system operation might not be globally optimal.

### *B. Control-Based Approach (CBA)*

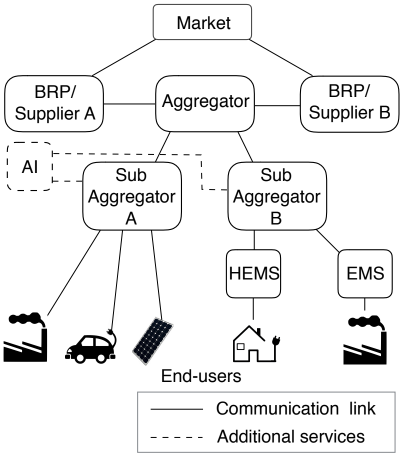

Fig. 3. Conceptual block-diagram of CBA

CBA primarily is developed based on the application of control theories for managing FRs at the distribution level [14]. The main idea is to replace slow and linear market principles in FRs procurement with control problems which can accommodate stochasticity, non-linearity, and true dynamics. To do so, CBA offers a real-time pricing mechanism for FRs operation at the lowest level of the grid. In this approach, every Sub-Aggregator (SA) defines a control problem to determine appropriate varying price signals. To do that, SA needs to model end-users' response to different prices which creates a certain change in consumption/generation of the rational end-users. To model end-user's behaviour, no real-time communication is needed in CBA. In fact, one-way communication channel from SA to the end-user's EMS/HEMS is the only required communication in real-time operation. At the consumers' level, a control/optimization problem (e.g., model-predictive control (MPC)) is solved to act upon receiving the price signal. Contrary to the TE approach, local end-users do not send feedback or share any information with other agents which makes the whole process very fast and secure.

For a comprehensive understanding, the CBA entities and operation is shown in a block-diagram for CBA in Fig. 3. At the highest level, similar framework to the one for TE, existing wholesale market is maintained including wholesale market operator, energy suppliers and BRPs. When BRP or suppliers encounters deviation from their schedules, they submit a service request to the aggregators. The aggregator submits the request to numerous Sub-Aggregators (SAs) scattered all around the network. According to the end-users' price-responsive model, which is created offline using aggregated data, SAs are able to generate price-quantity blocks of bids to participate in the wholesale market through aggregators at the top level of the grid. The top aggregator is then responsible to receive all the bids, aggregate them, and participate in the wholesale market on behalf of SAs. When market is cleared and prices are determined, top aggregator dis-aggregates the market schedules and communicate prices and quantities to the SAs. Later, SAs submit new prices to their associated pool of FRs to achieve a certain amount of service, as awarded in the market. Additional Information (AI) are agents with information which can improve SAs operation. It could be an agent with information about weather which helps SAs to generate more appropriate price according to the ambient conditions.

It can be realized that TE and CBA have many operational characteristics in common. An example of up and down bid generation based on end-users' reaction to a certain price signal is presented in the flexibility curve of Fig. 4 (for the case of supermarket refrigeration system [15], [16]). The figure shows the correlation between rebound effect and a modified consumption response. The adoption of these curves is based on the simplification of flexibility characteristics where stochasticity and non-linearity are not effectively represented. This is effective when load response of end-users can be controlled directly. If no direct control is assumed to the loads, an impulse response function is preferred, as presented in Fig.5. The figure shows reaction of a pool of responsive loads to varying price signal in a real-world demonstration in North West Project [10]. By increasing price at time 5:00, overall consumption decreased.

So far, CBA with Indirect Control (IC) to the FRs is presented. Alternatively, each SA can coordinate the pool of end-users through Direct Control [17]. The main difference between them is that DC directly alters power consumption of load, while IC activates flexibility response through time-varying price.

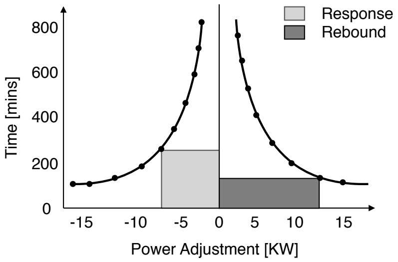

Fig. 4. Proposed bidding mechanism for CBA

In this study, we present both DC and IC methods for the sake of completeness. However, IC method is considered as the optimal solution since it requires very simple communication infrastructure while preserving end-users' privacy.

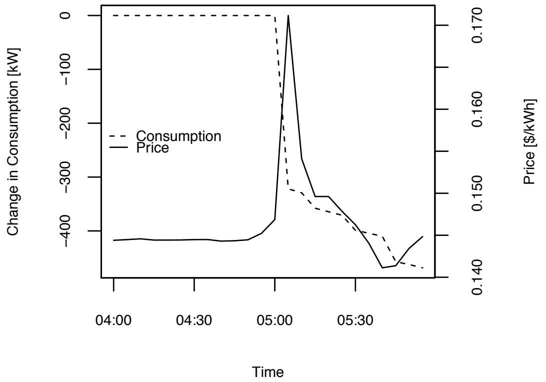

Fig. 5. Correlation between Price and Consumption from the North West Project Data [10] on March 23, 2013

*1) Direct Control (DC):* DC is based on a two-way communication where FRs are directly controlled in a closed-loop feedback. In Fig. 3, this type of control is adopted by sub-aggregator A, which centrally runs an optimization problem. MPC is a popular application of DC, optimizing a sequence of control moves over a finite prediction horizon [18]. Such moves are computed at each time step as a solution to the optimization problem [14]. The strength of MPC is that predicted behaviour and constraints are directly formulated into the design of the problem, exploiting the full flexibility of the resources. Also, adding predictions in the controller improve control performance. A mathematical formulation of MPC is provided in Eq. 1 [14]:

$$\begin{aligned} \min_{x,u} \quad & \mathrm{E}[\sum_{k=0}^{N}\sum_{j=1}^{J}\phi_j(x_{j,k},u_{j,k})] \\ \text{s.t.} \quad & x_{k+1} = Ax_k + Bu_k + Ed_k, \\ & y_k = Cx_k, \\ & y_k^{min} \leq y_k \leq y_k^{max}, \\ & u_k^{min} \leq u_k \leq u_k^{max} \end{aligned} \tag{1}$$

where $k = 0, 1, ...N$ is the prediction horizon; $x$ is the state; $d$ is the disturbance (e.g., outdoor temperature); $y$ is the output of the system (e.g., indoor temperature); $(A, B, C, E)$ represent the discrete time state-space model [14]; $u$ is the control input (e.g., electrical power). $\phi$ represents the aggregator objective function to be minimized. It tracks a reference power consumption profile by manipulating total power consumption $z_k = \sum_J u_{j,k}$ via individual FRs [19]. The reference to track is formulated in Eq.2, where $\lambda$ represents penalization factor related to control moves.

$$\phi_{track} = \sum_{k=0}^{N} \sum_{j=1}^{J} ||z_k - z_{ref,k}||_2^2 + \lambda ||u_{j,k}||_2^2 \tag{2}$$

In MPC, it is also possible to consider individual costs related to FRs' consumption, formulated in Eq. 3.

$$\phi_{eco} = \sum_{k=0}^{N} \sum_{j=0}^{J} p_{j,k}^T u_{j,k} \tag{3}$$

This way, MPC should achieve a trade-off between tracking and economic objective, as expressed in Eq. 4.

$$\phi = \alpha \phi_{track} + (1 - \alpha) \phi_{eco} \qquad \alpha \in [0, 1] \tag{4}$$

*2) Indirect Control (IC):* IC consists of one-way communication in real-time where SA formulates and submits varying price signals to the pool of rational end-users to influence their generation/ consumption patterns. In Fig. 3, this type of control is adopted by sub-aggregator B, as end-users of its pool are equipped with controller and the optimization is run in a distributed way. Operating in an open-loop scheme, IC does not need any feedback in real-time. However, SAs require end-users' behaviour model which has to be created based on aggregated offline data. Such a data is available today at the distribution system substations. Therefore, CBA-IC only requires one-way communication in real-time from SAs to the end-users' EMS/HEMS. Optimization problem of a SA can be formulated as follows:

$$\begin{aligned} \min_{p} \quad & \mathrm{E}[\sum_{k=0}^{N} w_{j,k} ||\hat{z}_k - z_{ref,k}|| + \mu ||p_k - p_{ref,k}||] \\ \text{s.t.} \quad & \hat{z}_{k+1} = f(p_k) \end{aligned} \tag{5}$$

where $N$ is the length of the regulation horizon; $\mu$ is the penalization factor related to the deviation from the reference in price; $w_{j,k}$ is the penalization factor related to the deviation from the reference in load.

CBA has been implemented in several projects over the last decade. The most prominent ones are CITIES [20] (a Danish Research project, 2014-2020) and SmartNet [21] (an EU project, 2016- 2019), results of which are reported in [22], [14], [19], [23], [24]. Several advantages can be identified from CBA-IC approach, as listed below:

- **Suitable for Real-World Applications**: CBA turns power system operation into a set of control problems where the model of system, devices, and services can be non-linear, dynamic and stochastic. It requires one-way communication, which is faster and cheaper solution. CBA-IC can be updated fast, in the range of seconds if needed, to compensate for the sporadic changes in RES and consumers' behaviour.
- **Privacy**: CBA does not imply any privacy issue because there is no real-time feedback from end-users to the system operators. Only offline historical data are needed to develop consumers' price-responsiveness model which is created by using aggregated data.
- **Security**: In CBA-IC, a price signal is submitted to the end-users from SAs to address a certain behaviour. Therefore, communication is not intensive and system operation does not depend on the feedback signal from end-users. As a result, lack of real-time feedback diminishes risk of communication malfunctions and cyber attacks.
- **Cost**: Due to the one-way communication structure, CBA offers a cheaper solution in terms of implementation and regular maintenance costs. The limited need of measurements to control grid condition (e.g., over-voltage) further contributes to a lower management cost, where all expenses for distribution-side measurement equipment are avoided.
- **Interaction between Energy Carriers**: CBA simplifies interaction among energy carriers (e.g., shifting consumption from electricity to gas) by reducing the problem to creating several prices.

Although CBA looks promising in addressing several requirements in the future smart grid, it comes with limitations that are identified in the following items: [12]:

- **Uncertain End-Users' Reaction**: End-users do not provide real-time information to SAs in CBA-IC. This way, uncertainty related to the end-users' behavior implies a risk if not properly estimated. The changing behaviour of the end-users and the difficulty to include proper explanatory variables in a model can also lead to wrong estimation in consumer's behaviour. This could be dangerous for power system operation in real-time.
- **Market Inefficiency**: In [12], market inefficiency is mentioned as an issue of CBA. In economic terms, market inefficiency asserts that market prices are not always accurately calculated and tend to deviate from the true discounted value of their future cash flows.
- **Slowness**: Similar to TE approach, CBA operates according to the wholesale market requirements. Therefore, slowness and linearity in the wholesale energy and AS markets can also affect CBA operation.

## III. NECESSITY OF A COMPREHENSIVE SOLUTION

TE and CBA offer substantial improvements over existing operational approach, which does not provide any solution to use FRs at the lower levels of the network. The two methods are able to accommodate FRs in the power system operation. However, these solutions have been formulated exclusively for distribution system management while maintaining the existing energy and AS market structures at the transmission level. As a result, CBA and TE inherit slowness from wholesale markets. Additionally, the wholesale market cannot deal with the magnitude of stochasticity and non-linearity introduced by large penetration of renewable generation. In the current structure of TE and CBA approaches, incapability of the wholesale market deteriorates the effectiveness of the FRs for power system operation. In other words, FRs cannot properly be managed in the proposed TE and CBA approaches.

Moreover, both approaches seem to be incapable of properly addressing stochasticity, dynamics and non-linearity. The reason is that FRs operation is represented by simple and linear price-quantity bids at the end. Although local EMS/HEMS might consider stochasticity and non-linearity to full extent, the true operational condition of FRs is ultimately reduced to several blocks of linear bids submitted to the LFA. This undermines the capability of TE and CBA methods to model stochastic, nonlinear, and dynamic behaviour of the end-users in the system operation.

The other drawback of the two approaches is the complexity in their structure where many agents and entities are considered to deliver services requested from FRs. Malfunction in any of these entities will result in the failure of the approach completely. For these reasons, we still need more comprehensive solutions for the future energy management. Such an approach ideally replaces existing electricity and AS markets with more suitable solutions, deals with complexity characterized by new RES and FRs, and allows system operators at different level of space and time to fulfill their requirements.

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## IV. CONCLUSIONS

This paper explains two approaches, namely TE and CBA, for distribution energy management in presence of high stochasticity due to RES. From analyses, it emerges that CBA and TE offers new capabilities which are needed in the future smart grid, and mechanisms to deal with FRs by considering end-users' behaviour. However, they still do not satisfy all the requirements for a future optimal energy system operation, such as extension to the entire electricity system and real-time operation. More comprehensive solutions are therefore needed in the future to optimally exploit FRs.

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