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A comprehensive survey of flexibility options for supporting the low-carbon energy future

Marco R.M. Cruz[a], Desta Z. Fitiwi[b], Sérgio F. Santos[a], João P.S. Catalão[a,c,d,*]

[a] C-MAST, University of Beira Interior, Covilhã 6201-001, Portugal
[b] Economic and Social Research Institute, Dublin 2, Ireland
[c] INESC TEC and the Faculty of Engineering of the University of Porto, Porto 4200-465, Portugal
[d] INESC-ID, Instituto Superior Técnico, University of Lisbon, Lisbon 1049-001, Portugal

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ABSTRACT

As a result of the increased awareness of the dangers posed by global climate changes (mainly caused by growing global energy consumption needs), the quest for clean and sustainable energy future is becoming of paramount importance. This can be largely realized via a large-scale integration of variable renewable energy sources (RESs) such as wind and solar, which have relatively low carbon footprints. In many power systems, the level of integration of such resources is dramatically increasing. However, their intermittent nature poses significant challenges in the predominantly conventional power systems that currently exist. Among others, frequency and voltage regulation issues can, for example, arise because of improperly balanced and largely uncoordinated RES supply and demand. Generally, the higher the integration level of intermittent power sources is, the higher the flexibility needs are in the system under consideration. Flexibility, in a power systems context, refers to the ability of such a system to effectively cope with unforeseen changes in operational situations, which are mainly induced by the inherent uncertainty and variability arising from the supply side, demand side or any other external factors. In the absence of appropriate flexibility mechanisms, it is increasingly difficult to manage the imbalances between generation and demand as a result of their natural variations in real-time. This paper presents an extensive and critical review of the main existing and emerging flexibility options that can be deployed in power systems to support the integration of “carbon-free” and variable power production technologies. Starting from a broader definition of flexibility, we highlight the growing importance of such flexibility in renewable-rich energy systems, and provide insights into the challenges and opportunities associated with various flexibility options provided by different technologies.

1. Introduction

Driven by several factors such as favorable RES integration policies and growing environmental concerns, investments in variable RESs such as wind and solar have been recently outpacing investments in conventional ones. And, this trend is largely expected to continue even in a more pronounced manner amid the ambitious emission reduction targets put in place by many states across the world. The European Union (EU), for example, has a target to reduce greenhouse gas (GHG) emissions in 2050 by 80–95% compared to the 1990 levels. This can only be achieved by integrating “clean” energy technologies, mainly, wind and solar [1]. In particular, wind and solar power sources are expected to provide half of the electricity consumption in the EU by 2050 [1]. This indicates that the installed capacities of wind and solar technologies will have to dramatically increase in the near future both at transmission and distribution levels [2,3]. Increased quantities of such resources creates enormous technical challenges especially in distribution systems [4]. This is because conventional distribution networks are not simply designed to accommodate generation sources. The presence of generation sources means distribution systems will face bidirectional power flows, making control, safety and flexibility more relevant issues [4]. Under these circumstances, maintaining the standard levels of reliability, security and power quality is not an easy task [2,5]. To effectively integrate wind and solar power, additional reserve capacity is needed [6,7]. It is known that conventional power plants often provide majority of the reserve capacity needed in power systems. But this may not be sufficient in the future because of the inherent variability and uncertainty of wind and solar which dramatically increase the amount of reserve required to maintain a healthy operation of the system. Moreover, under such circumstances, the traditional way

* Corresponding author at: INESC TEC and the Faculty of Engineering of the University of Porto, Porto 4200-465, Portugal.
E-mail address: catalao@ubi.pt (J.P.S. Catalão).

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of firming reserves may not be economical in the first place, and environmentally friendly in the second place [6–8]. However, the use of various flexibility options can substantially reduce the negative effects of integrating RESs such as this one. Note that flexibility should be understood as the ability of a power system to cope with the imbalances in generation and demand created as a result of abrupt changes in system conditions (which are triggered by unpredictable nature of some renewable power generation sources, contingency situations, etc.). Traditionally, such flexibility is largely provided by conventional power sources. However, due to the advent of new technologies and concepts such as demand response, this role has been changing especially in recent years. There are various emerging technologies that can provide efficient flexibility options (which are the subject of this paper). Therefore, the future energy sector is expected to provide secure, reliable and affordable energy services to end-users. For this, the sector needs to be highly efficient and possess environmentally-friendly energy sources [9]. In this context, flexibility options play a crucial role in achieving the required efficiency, reliability, cost effective tariffs for end-users and simultaneously reducing GHG emissions worldwide.

The unique feature of power systems is the need to match demand and supply in real time. Power systems require flexibility to continuously match demand with supply both of which are subject to high level variation and uncertainty [10,11]. When the penetration level of renewables gets higher and higher, traditional flexibility mechanisms (mostly provided by conventional power plants) are not simply sufficient. New flexibility options are required to ensure a proper balance between supply and demand [10,12]. Another issue is that sustainable energy management endeavors are being affected by an increased demand, ineffective production practices and insufficient power supply [13]. The flexibility options can take part in efficient strategies to integrate variable RESs in power grids [5]. Flexibility options are resources that help the system to effectively deal with imminent changes in operational conditions [5,12,14]. Such flexibility is also associated with frequency and voltage control, a useful tool in handling uncertainty and variability of power systems and ramping rates [7,8,10,14]. Flexibility options can also be used to defer investments in certain components of power systems, which implies that such systems operate optimally [14,15]. Correspondingly, an increased usage of carbon-free technologies requires greater flexibility, and enhances the “active management and better use of existing network-related” resources [16,17].

Flexibility options can be provided by technologies deployed at the supply, network and/or demand sides. The present work largely structures the flexibility options based on such hierarchical classifications. The flexibility options from the supply side, which will be shortly discussed in this paper, include enhanced ramping capabilities of conventional power plants, flexible generation, diversification of power generation, wide-area generation expansion, RES power curtailment, etc. Flexibility mechanisms on the demand side such as demand response, energy efficiency, electric vehicles, etc. are also broadly described in the following section. Electricity networks can also provide some flexibility options via optimal network reconfiguration, smartification of the grids, dynamic line rating, wide-area interconnections, meshing, etc. Apart from all these, energy systems integration, energy storage systems, effectively designed regulation and energy markets can also provide essential flexibility in power systems, and enable large-scale integration of intermittent resources. Fig. 1 schematically summarizes the increasing need for flexibility options and their main sources.

2. Review of flexibility options

As stated earlier, flexibility can be provided by different components of power systems placed at the supply, network and/or demand side. The flexibility options reviewed in this work are mostly structured into these main pillars. However, the review also encompasses flexibility options provided by emerging technologies such as energy storage systems which can be optimally placed at either side of power systems. In addition, the main institutional mechanisms such as energy systems integration that have proven or foreseen capabilities to enhance power system flexibility are broadly reviewed.

2.1. Demand-side flexibility options

In power systems, it is widely known that the demand side has huge potential for flexibility provisions. Such flexibility options mostly come as a result of changes in the consumption patterns of end-users in response to financial and non-financial incentives and/or dynamic price signals. The resulting changes could be permanent (such as energy efficiency) and/or temporary (demand response such as shifting energy consumption from peak to off-peak hours). Generally, demand side flexibility mechanisms are emerging as the most viable and “least cost” means of enhancing power system flexibility, and thereby increasing the integration of intermittent power sources. Among the most prominent sources of flexibility options reviewed here are demand response, energy efficiency and new forms of electricity consumption.

2.1.1. Demand response

Demand Response (DR) is one of the flexibility options obtained from the consumers’ side, and involves alterations of energy consumption levels and/or patterns of end-users in response to dynamically changing prices and incentives (for example, see in Figs. 2 and 3). In other words, properly designed DR programs make electricity demand more flexible, responsive and adaptable to economic signals [2,18]. As shown in Fig. 3, the alterations could be in the form of reduction, shift in energy consumptions or both depending on the consumers’ price elasticities of electricity demand. Note that an elasticity index quantifies the relative change in consumption as a result of marginal changes in an electricity price. When the values of such indices are high, more dramatic changes will be observed in consumption patterns. As illustrated in Fig. 3, higher self-elasticity values lead to higher peak shaving and valley fillings, and hence, a flatter demand profile along the day.

Demand response can be either incentive-based or price-based. The former category is characterized by changes in the consumers’ electricity consumption in response to non-price signals (often, financial or non-financial incentives). Whereas, the second one relies on price signals to change consumption patterns. Incentive-based DR include demand side programs such as direct load control, curtailable load services, demand bidding or buyback programs and emergency DR among others. Price-based DR on the other hand mainly includes time-of-use (ToU), critical peak pricing (CPP), peak time rebate (PTR) and real-time pricing (RTP) programs. The example shown in Fig. 3 falls in the second category, specifically, in the RTP program.

Apart from the flexibility perspective, demand response has wide-range benefits, which can be found in the extensive body of literature in this subject area. Even if the benefits of DR are widely recognized, its penetration level is not significant in many power systems due to several limitations such as lack of appropriate market framework, effective forecasting tools, and communication and control strategies. However, the interest in DR has been growing in recent years because of many factors such as increasing level of variable power generation which in turn builds up the flexibility requirements in such systems, significant advances in IT and continuously improving forecasting tools, etc. Generally, there is a strong body of evidence on the potential of DR in reducing costs for end-users and improving the integration of variable RESs [2,19]. There is no cloud of doubt that DR will be part of the solution to the endeavors in creating a sustainable energy future, and addressing a multitude of global as well as local concerns such as climate change and energy security.

Demand response is normally achieved by introducing a new competitor in the market, called aggregator, to control the operation of