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Article

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Power system flexibility: A review

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Abstract

Power systems networks are traditionally structured and engineered to effectively accommodate the effects of uncertainty and variability as regards energy demand and availability of resources. In order to transform the present carbon-intensive electricity generation system to one driven largely by clean energy sources, the inclusion of variable renewable energy sources (vRES) is becoming predominant. However, the inclusion of large vRES in the power plant mix increases the uncertainty, variability and consequently flexibility requirements on the power system network. The inclusion of cost effective and environment friendly flexible generators that can cancel the effects of uncertainty and variability is essential on power system networks with high levels of vRES. This study highlights flexibility as it relates to energy transition. It also provides direction for future research on the issues of flexibility in power systems planning.

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Keywords: Power system flexibility; Variable renewable energy sources; Energy transition; Power plant mix; Decarbonization; Generation expansion planning

1. Introduction

In order to sustain modern civilization, adequate access to reliable electricity is very important. This is because electricity has its root established in almost every human sector. It is therefore a burden on utility companies worldwide to make sure that electricity demand is met at all times [1]. This is because every mismatch between the demand and supply of electricity can jeopardize the operational reliability of the power system network. An unreliable supply of electricity has a ripple effect on the socio-economic activities of any society. Although reliable access to adequate electricity can have a positive effect on the society, the method of generation is also very important. For example, it is reported that fossil-fuel powered generating facilities contribute approximately 43% of worldwide CO_2 emission [2]. This contributes to global warming which in turn causes climate change. The effects of climate change are a threat to human existence and must be enthusiastically and adequately put under check.

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This will keep the global temperature rise below 2 °C as suggested by the Paris Agreement [2]. One of the ways of accomplishing this is to move from a carbon heavy electricity generation to a renewable based electricity generation (decarbonization). It has been postulated that renewable energy has the tendency to contribute 100% of the total primary energy needs in some parts of the world [3]. This however comes with its associated challenges. One of such challenges is the issue of power system flexibility. Some pointers of power system inflexibility in modern power systems include; insufficient supply in meeting demand (especially at peak periods), substantial renewable energy curtailments, violation of area balance, volatility, negative market prices and so on [4].

1.1. Energy transition and need for flexibility

A synopsis of the power system industry over the last fifty years shows that there has been and there will be significant transformations across the sector. The foremost transformation involved the deregulation and restructuring of the power system market. The restructuring and deregulation of the electricity market has led to substantial competition, regulatory and technological changes. In contrast to the traditional monopolistic electricity market, restructuring and deregulation has caused a clear separation of "activities" of the major players in the industry. More recently, a significant driver of transformation in the power system industry is the power generation decarbonization. This has increased research activities into the integration of large-scale renewable energy sources (especially hydro, solar and wind) as well as the policy and framework necessary to encourage and increase its penetration. This is expected to reduce emissions attributed to the electricity industry. These transformations are expected to consolidate and satisfy the ever-increasing electricity demand. It will further ensure a sustainable, cost effective, reliable and environmentally viable electricity generation.

Although the penetration of hydro, solar and wind resources is gaining momentum in the global energy mix due to investment cost reductions [5], the integration of large quantities of these intermittent renewable energy resources into the grid comes with some emerging economic and technical challenges. The inherent intermittency and stochastic nature of most renewable generation is constantly modifying the time dynamics of net-demand, increasing its variability and unpredictability. These features of variable renewable energy sources (vRES) cause threats and uncertainty in meeting the energy demand and maintaining power system stability-voltage and frequency regulation [6]. In order to counter the negative technical effects of a high share of renewable energy penetration, there is need to increase the flexibility of power system planning and operation [4,7,8]. This will play a key role in the evolution of modern power systems, as it is crucial for the effective and efficient integration of renewables and the reduction of carbon emissions. From the foregoing, it is evident that the increase in the proportion of vRES on the grid is fast transforming the power system sector and has increased the operational complexities of the power system network.

2. Drivers of power system flexibility

Flexibility describes the degree to which a power system can adjust the electricity demand or generation in reaction to both anticipated and unanticipated variability. Flexibility indicates the capacity of a power system network to reliably sustain supply during transient and large imbalances. A techno-economic definition by International Energy Association states that, "Power system flexibility is the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales" [9].

The rapid inclusion of a large share of renewable energy into the grid is a major factor known to drive investigation in power system flexibility. vRES for electricity generation are becoming cost effective and cheaper to acquire because of government subsidies and the absence of fuel costs. For these reasons and many more, inefficient thermal power plants that cannot compete with the vRES are been replaced with vRES. However, the outputs of vRES are not constant and therefore cause uncertainty. The fluctuation affects the power plant mix, power plant dispatch sequence as well as the frequency. As such, power system flexibility is inevitable. Fuel insecurity (Uncertainty of availability and fluctuation in the price) can also modify the generation mix. Other factors that drive research into flexibility of power systems include, consumers' attitude to the use of new technologies, and changes in both international and local policies and regulations as regards to conservation of the environment.

2.1. Increase in vRES penetration

Modern civilization is heavily reliant on electricity for its daily activities. As such, a large share of the electricity generation is based on fossil fuel. Presently, electricity generation is responsible for about 43% of global CO_2 emission [10]. Anxieties over the sustainability of fossil fuel, global warming, and the environmental impact of climate change has precipitated research efforts and relevant environmental policies that will enhance the use of renewable energy sources for the generation of electricity [11]. Some of the emerging renewable energy technologies for large scale electricity generation are wind turbines and solar (PV and thermal). These two sources are intermittent in nature.

The intermittent nature of the electricity generated from solar (solar thermal and photovoltaic) and wind energy technologies are caused by the variability features of the solar and wind resources and has an effect on the distribution and transmission networks [12]. The intermittent features of these resources are caused by changes in weather conditions and can reduce the capacity of wind turbines by 100% on calm days and up to 70% for solar-powered plants on cloudy days [13]. These values are greater than that experienced due to the use of conventional generators and variability in load demand. As the penetration of vRES on the power system network increases, this problem becomes significant and more challenging to manage [5,14,15]. Hence, a need for inclusion flexibility on the power system network arises.

2.2. Fuel price uncertainty

Fluctuations in conventional fuel price and its availability especially natural gas and coal, is also a major source of uncertainty during generation expansion planning. It is reported that the coal price is moderately stable, with an annual average increase of 2% while the price of natural gas is largely unpredictable [16]. The share of electricity generated by natural gas in 2017 is slightly more than one-fifth of the entire mix [10]. Natural gas is relatively the most expensive fuel in the mix [16], and its volatile prices cause a high level of uncertainty.

3. Sources of flexibility

Conventionally, the issue of flexibility is not a major problem because vRES are very limited on the grid. As such, in the past, power system networks achieve flexibility using dispatchable power plants (e.g. gas turbines) which can be rapidly brought on and offline. In the wake of high penetration of vRES, flexibility is also attained through other means. Some of the other techniques of ensuring power system flexibilities include flexible demand (demand side management and demand response), reinforcement of distribution and transmission facilities, energy storage systems, electric vehicles, unit commitment, and generator output curtailment (Fig. 1).

3.1. Demand side management and demand response

In demand side management (DSM) and demand response (DR) practices, consumer loads are strategically controlled (technically or through incentives) by utilities to respond to imbalances in power level on the grid. Connected loads can either be switched off, or its time of use shifted to off-peak periods when energy prices are lower. DR and DSM delay the addition of new facilities to avoid the need for the modification of generation levels. Implementation of DSM and DR practices will encourage and ensure that consumers take part in load control schemes which are based on price signals. DSM and DR are usually moderately inexpensive to achieve but entails following a set of strict rules and guidelines with respect to valid demand-side resources, response time, reliability and minimum magnitude. Some demand response activities include; smart greed, time-of-use tariffs, direct load control by utility, interrupted load control, curtailed load, critical peak pricing, demand bidding, real time pricing, smart metering, etc [10].

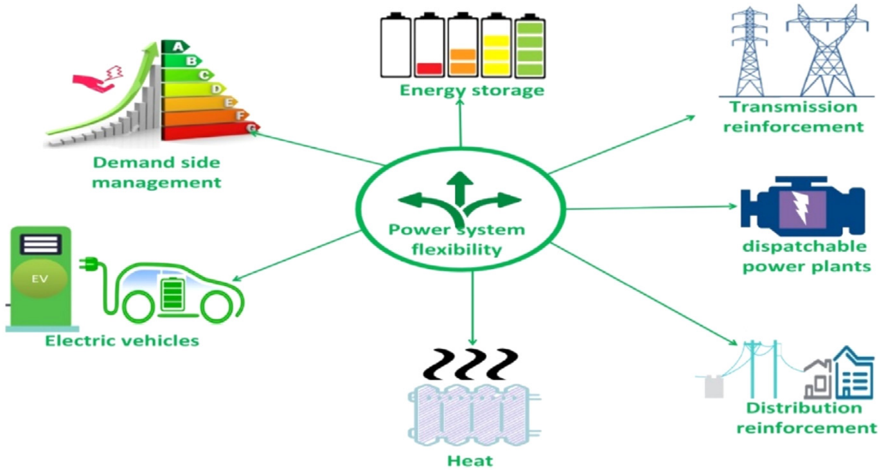

Fig. 1. Sources of power system flexibility.

3.2. Energy storage facilities

Energy storage technologies are used in storing energy generated during the periods of surplus and cheap electricity from vRES and then used when the need arises. Storage devices are usually used as peaking sources. When compared to demand response, demand side management and other sources of flexibility, the investment cost spent on deploying energy storage technologies is higher [17]. In recent times, more research efforts has been directed towards the implementation of large scale energy storage facilities on the transmission network and medium and small scale energy storage facilities on the distribution network. The combined effect of these facilities increases the flexibility on the power system network. The most common examples of large scale energy storage technology are the pumped hydro storage, thermal storage and compressed air energy storage. On a decentralized scale, super-capacitors, batteries, electrolysis, flywheels and fuel cell are some of the available energy storage.

3.3. Flexible generation

Flexible generation is usually provided by power plants that can quickly be brought online when a power imbalance arises. One of the main futures of these types of flexible source is quick ramp up and ramp down rates, fast start up and shut down and efficient operation at a lower minimum level throughout periods of high vRES output [15,18–22]. It is essential that these power plants have minimal marginal cost for them to effectively compete as a source of flexibility. Some of these plants included hydro plants, conventional gas-fired power plants, and dispatchable renewable power plants (biomass, geothermal plants etc.).

4. Power system flexibility planning

Power system flexibility planning is a complex optimization problem which involves various components and phases [5]. In order to properly plan power system flexibility, an audit of the existing level of flexibility is essential so as to determine the present and future needs. If there is a deficiency in terms of flexibility needs, then there may be a pressing need to invest in sources of flexibility. An urgent need may change the preference list of the flexible sources alternatives based on cost effectiveness and gestation period. If there are no current needs for flexibility, then a plan for future flexibility needs must be initiated. When appraising the present level of flexibility, it is important to model the generation costs along with the under-generation, curtailment level, and excess generation, adequacy of reserve margin, network analysis (to check for violations) etc. If there is a deficiency, the utility may consider unlocking existing flexibility sources. Otherwise, the utility intensify efforts on accessing future needs for flexibility. This planning process is depicted in Fig. 2.

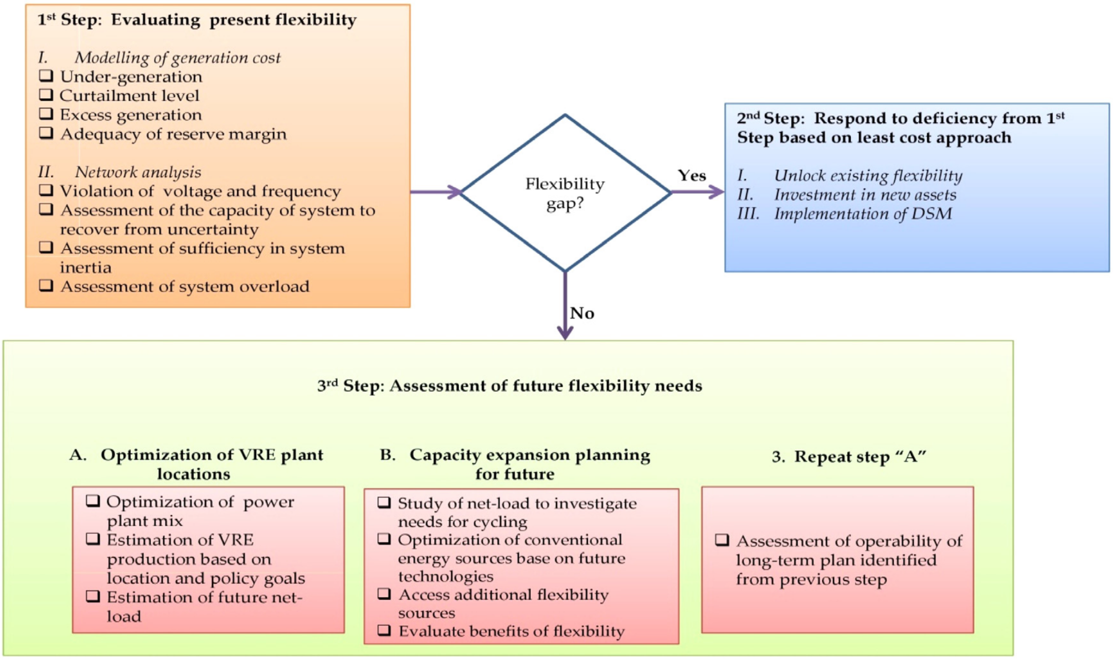

Fig. 2. Power system flexibility planning [3].

5. Conclusion and future trends

The concept of power system flexibility has been briefly reviewed in this paper. This subject is of importance because of the emerging operational needs caused by the inclusion of large vRES in the power plant mix. The inclusion of flexibility has been reported to make the mathematical formulation of power system planning non-linear and complex [5]. Hence, obtaining solutions to them are typically difficult and computationally tasking. It is therefore essential for future studies to propose and implement solution algorithms that are computationally efficient and traceable in handling the power system planning models. Because the inclusion of flexibility entails additional costs, in a budget constrained environment, a model that estimates the minimum level of flexibility needed to accommodate a particular level of renewable energy is essential. Furthermore, the economic significance offered by both operational and technical flexibility is also another aspect that requires further research efforts. Most research effort directed at including flexibility into power system planning mostly focuses on the use of conventional power plant. The concomitant inclusion of other flexibility sources could also be investigated in future.

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