Renewable and Sustainable Energy Reviews 76 (2017) 974–988

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Large-scale integration of distributed generation into distribution networks: Study objectives, review of models and computational tools

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ARTICLE INFO

Keywords:
Distributed generation
Distribution network
Power quality
Reliability
Power system computational tools

ABSTRACT

In terms of the improvement of reliability and efficiency, integration of distributed generation (DG) into distribution network has gained significant interest in recent years. However, existing distribution systems were not designed considering large-scale penetration of DG. Due to the increasing penetration of DG, several technical challenges may arise which include voltage control, power quality and protection issues, etc. Therefore, additional components need to be modelled together with conventional distribution system components in order to study the impact of DG on the distribution system. The first objective of this paper is to review the required models of system components, the impacts of DG on system operation, mitigation of challenges, associated standards and regulations for the successful operation of distribution systems. A number of commercial and open source tools are available for modelling and analysis of distribution systems. An ideal computational tool should include necessary functionalities to study the impacts of increased DG penetration as well as various options to overcome possible operational problems. Based on the first objective, the second objective is to make a summary of characteristics and features that an ideal computational tool should have to study increased DG penetration. A comparison study of two commonly used computational tools is also carried out in this paper.

1. Introduction

Distributed generation (DG) units are relatively small power generation sources that are connected to the distribution networks (DN) and close to the loads being served [1]. However, expansion of DN by integrating renewable based DG to electricity grid has attracted much attention worldwide due to their environmental benefits. This integration needs to provide a reliable and cost-effective service to customers while ensuring that voltage regulation, power quality and protection issues are within standard ranges.

Traditionally, DN are not designed considering the integration of a large number of DG units. High penetration of DG into DN affects the normal operation of the system in both positive and negative ways. Improved voltage profile, reliability, power loss reduction and support of ancillary services are major positive impacts [2], whereas negative ones include malfunction of the protection system, poor power quality, reverse power flow and islanding, etc [3,4]. Various technical restrictions are being adopted worldwide in order to mitigate these negative impacts [5].

Currently, available distribution system analysis tools are insufficient to study the impacts of increased DG penetration due to the lack of required models and functionalities. Therefore, simulation tools must combine modelling and analysis capabilities of all required components related to DG and storage technologies together with traditional distribution components. This study aims to provide a comprehensive review of the negative impacts that increased DG penetration has on system operation, necessary mitigation studies, associated standards, required models of system components and computational tools.

The paper is organised as follows: Section 2 presents an overview of components that need to be modelled for conducting a study of large-scale penetration of DG. Section 3 provides an overview of the negative impacts of increased DG penetration on DN, operation standards and mitigation techniques of these impacts. Characteristics and functionalities that an ideal computational tool should have to model and analyse distribution systems with high penetration of DG have been discussed in Section 4. This section also provides a comparison between two commonly used computational tools. Finally, Section 5 concludes the paper.

2. Basic components of distribution system with DG penetration

2.1. Distribution networks

In an electric power system, power is generated in generation station and then it is transmitted through the transmission line.

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http://dx.doi.org/10.1016/j.rser.2017.03.069
Received 7 December 2015; Received in revised form 15 February 2017; Accepted 10 March 2017
1364-0321/

Finally, the electric distribution network is designed to deliver the electricity to the end users. Electric power can be distributed by overhead lines or underground cables. A distribution line is modelled by a 3×3 series impedance matrix which is expressed in per unit based on the nominal phase-to-ground voltages [6]. In most of the cases, distribution lines are placed underground due to high population density. Depending on the feeder arrangement, a distribution system can be divided into two fundamental ways: radial and loop systems [7].

2.2. Loads

An electrical load is an electrical appliance that consumes electric power. Loads can be modelled based on two different approaches. Firstly, static loads are modelled by following the behaviour of their active (P) and reactive power (Q) changes at any instant of time with respect to bus voltage and frequency at the same instant. Commonly used such load models are constant impedance, constant current, constant power, frequency dependent model, ZIP (polynomial) and exponential load models [8]. Secondly, dynamic loads are modelled by studying the P and Q at any instant based on the instantaneous and past histories of bus voltage and frequency [9]. A composite load combines both static and dynamic load models. Based on the types of consumers, the loads can be modelled in four different ways: commercial, industrial, agricultural and residential [10]. Commercial loads are typically air conditioning units and discharge lighting. Industrial loads are mostly induction motors (up to 95%). Likewise agricultural loads basically include induction motors for pumps. The residential loads include domestic appliances (e.g. refrigerators, washing machines etc. as well as heating and air conditioning units). These types of load models are usually represented by hourly load behaviour which is termed as load duration curve (LDC) [11]. LDC can be modelled using stochastic theory representing the uncertainty of weather and consumers types.

2.3. Voltage regulators

Change of distribution voltage depends on load variation and number of DG units penetration into DN. Voltage regulators (VR) are used for maintaining the voltage within standard limits [12–15] and consumers receive the steady state voltage. In the distribution system, VR are installed at a substation or along distribution lines. Different types of regulators are used such as on-load tap changer (OLTC) transformer, shunt capacitor and reactor, and flexible alternating current transmission system (FACTS) devices.

2.3.1. On-load tap changer transformer

On-load tap changing mechanism in transformers is generally used to avoid a supply interruption during a tap change [16]. The OLTC transformer equipped with automatic voltage control (AVC) relay adjusts the transformer output to set the customer voltage within statutory limits [12]. OLTC voltage regulation is performed by changing the turn ratio of a transformer which is automatically controlled by AVC relay to increase or decrease the customer voltage level. Several voltage control techniques associated with OLTC are available such as line drop compensation (LDC), time grading between series operating OLTCs and circulating current compensation techniques for parallel operating OLTCs [17].

2.3.2. FACTS devices

FACTS devices are power electronic based systems that control power flow in the transmission and distribution networks for enhancing controllability and increasing power transfer capability of the network. The key benefits of using FACTS include improvement in system stability, voltage regulation, reactive power balance, load sharing between parallel lines, and reduction in transmission losses [18]. FACTS can be connected in series, shunt or both in series and shunt configurations.

(a) **Series compensation equipment**

In series compensation, FACTS works as a controllable voltage source. The series compensation equipment can be modelled through variable impedance [19]. The static synchronous series compensator (SSSC) [20] and dynamic voltage restorer (DVR) [21] are examples of series compensators.

(b) **Shunt compensation equipment**

In shunt compensation, FACTS works as a controllable current source. A reactive current is injected into the line to regulate voltage by varying shunt impedance. There are two methods of shunt compensations: shunt capacitive compensation and shunt inductive compensation [22]. The static VAR compensator (SVC) [23] and static synchronous compensator (STATCOM) [24] are examples of such compensators.

(c) **Series-shunt compensation equipment**

Series-shunt compensation equipment can control both secondary side voltage and input Q at the same time. The unified power flow controller (UPFC) is an example of such equipment [25].

2.4. DG types

DG covers a wide range of renewable and non-renewable technologies such as gas turbine, internal combustion engine, micro turbine, wind turbine, photovoltaic generator, solar thermal, biomass gasification, small and micro hydro turbines, fuel cell, geothermal, ocean energy and battery storage. Some of these are described below:

2.4.1. Internal combustion engine

Internal combustion (IC) engine converts chemical energy derived from liquid or gas fuels into mechanical energy. Then, it rotates a synchronous generator (SG) or an induction generator (IG) that is directly connected to the grid and converts mechanical energy into electrical form. Most often IC engines use diesel, gasoline and petroleum gas as fuels. IC engines include both intermittent (e.g., Reciprocating, Wankel and Bourkes engines) and continuous combustions (e.g., Jet engine, Rocket engine and Gas turbine) [26].

2.4.2. Gas turbine

A gas turbine consists of compressor, combustion chamber (or combustor) and turbine [27]. Different types of fuels, including natural gas, fuel oils, and synthetic fuels can be used in a gas turbine. The potential energy from fuels is first converted to hot gases that spin a turbine to generate electric power. The turbine is interfaced with the utility grid through a SG.

2.4.3. Microturbine generator

The microturbine generator system consists of a high-speed (up to 120-kilo revolutions per minute) gas turbine unit and a permanent magnet synchronous generator (PMSG) [28]. The turbine unit includes a compressor, a combustion chamber and a turbine. Microturbine works like a gas turbine. The only difference is that this is interfaced with the utility grid through a PMSG.

2.4.4. Fuel cell

A fuel cell (FC) is a device that generates electricity by chemical reaction of hydrogen (H_2) and oxygen (O_2). Typically, FC is composed of reformer, stack and inverter [29]. Based on the electrolytic material, FC(s) are classified into five types [30]: alkaline, proton exchange membrane, phosphoric acid, molten carbonate and solid oxide FC(s). FC is connected to the distribution grid via an inverter and transformer. The output DC power of fuel cell is converted via an inverter to grid-compatible AC power.

2.4.5. Micro hydroelectric generator

A micro hydro (MH) power system generates electricity using the