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Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems

Foad H. Gandoman[a], Abdollah Ahmadi[b,*], Adel M. Sharaf[c], Pierluigi Siano[d], Josep Pou[b], Branislav Hredzak[b], Vassilios G. Agelidis[e]

[a] Research group MOBI – Mobility, Logistics and Automotive Technology Research Centre, Vrije Universiteit Brussel, Pleinlaan 2, Brussels 1050, Belgium
[b] School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney 2052, NSW, Australia
[c] Energy Systems, Incorporated, Fredericton, NB, Canada
[d] Department of Industrial Engineering, University of Salerno, 84084 Salerno, Italy
[e] Department of Electrical Engineering, Technical University of Denmark, Lyngby, Denmark

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ABSTRACT

In the last two decades, emerging use of renewable and distributed energy sources in electricity grid has created new challenges for the utility regarding the power quality, voltage stabilization and efficient energy utilization. Power electronic converters are extensively utilized to interface the emerging energy systems (without and with energy storage) and smart buildings with the transmission and distribution systems. Flexible ac transmission systems (FACTSs) and voltage-source converters, with smart dynamic controllers, are emerging as a stabilization and power filtering equipment to improve the power quality. Also, distributed FACTSs play an important role in improving the power factor, energy utilization, enhancing the power quality, and ensuring efficient energy utilization and energy management in smart grids with renewable energy sources. This paper presents a literature survey of FACTS technology tools and applications for power quality and efficient renewable energy system utilization.

1. Introduction

In the last years, flexible ac transmission system (FACTS) technology has been used in efficient energy utilization, demand control, voltage stabilization, power quality enhancement, power factor correction and harmonic mitigation [1,2]. Additional applications include power flow control, voltage regulation, reactive power compensation, transient and steady state voltage stability enhancement, power loss reduction, power conditioning and quality improvement [3,4]. The emerging use of renewable and distributed generation (DG) has accelerated and expanded the role of power electronic devices for efficient electrical utilization and enhanced security and reliability of the electric utility grid [5]. Also, new applications have emerged for stand-alone microgrids with regards to renewable energy utilization using solar photovoltaic (PV) systems, micro-hydroelectric systems, the wind, biomass, waste-to-energy and hybrid ac-dc sources with battery energy storage for remote villages [6]. Renewable energy sources (RESs) are utilized at an accelerating rate and connected to both transmission and distribution/utilization systems using power electronic converters. This results in increased harmonics and deterioration of power quality at the point of common coupling. Power quality issues and mitigation have emerged as serious challenges and issues facing electric utilities and industrial/commercial/residential users [7].

Various FACTS devices and control strategies can help to mitigate power quality problems. For efficient use of power system resources the concept of FACTS was introduced in the late 1980's. The basic concept of FACTS devices was based upon the use of high-voltage power electronics to control real and reactive power flow and voltage in the transmission system [8].

Extensive research has focused on new topologies and architectures of voltage-source converters (VSCs) to improve the performance of FACTS devices in power systems and consequently enhance power system security [9,10]. Recently, FACTS devices and smart control strategies have been gaining a more prominent role in energy generation from renewable sources such as solar, wind, and waves [11]. Significant research has been focused on maximizing the energy extraction from RESs. The results of the implementation of FACTS devices in smart grids with renewable systems are encouraging [12,13].

The aim of this paper is to review and discuss applications of FACTS devices in smart grids with RESs. The paper focuses on the following

* Corresponding author.
E-mail address: Ahmadi.abdollah.janah@gmail.com (A. Ahmadi).

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issues:

- Impact of distributed-FACTS (D-FACTS) systems and emerging voltage source inverter (VSI) on modern electrical systems stabilization. Power quality harmonic reduction in AC-DC- AC interfaced renewable energy and battery storage devices.
- Role of FACTS devices and control strategies in electrical power system power quality and voltage regulation.
- Comprehensive study of history of application of FACTS devices in traditional and modern electrical networks.
- Different surveys, categorized by the type of published document, top researchers, top research centers and active countries, in terms of FACTS devices technology.

The paper is organized as follows. In Section 2, an overview of power quality in electrical networks is presented. FACTS devices are described in Section 3, while D-FACTS devices are presented in Section 4. FACTS/D-FACTS devices and power quality are explained in Section 5. In Section 6, the role of FACTS devices in enhancing power quality in future networks is explained. Finally, the conclusions are drawn in Section 7.

2. Overview of power quality and facts devices in electrical networks

Power quality issues are manifested as distorted voltage and current waveforms and/or frequency deviations that may cause failure or maloperation of customer equipment. Additionally, the power systems should provide their customers with a secure, reliable and uninterrupted flow of energy with sinusoidal voltages at the contracted magnitude level and frequency.

Generally, poor power quality may result in increased power losses, undesirable behavior of equipment, and interference with nearby communication lines. Widespread use of power electronics further burdens the power systems by generating harmonics in the voltages and currents along with increased reactive current [14].

Currently, quality problems have become more complex at all levels of electrical power systems. Therefore, power quality issues have received increasing attention by both the end users and utilities [15]. Maintaining the electric power quality within acceptable limits is a significant challenge [16]. The adverse effects of poor power quality are well discussed in [17].

Various sources use the term power quality indistinctively with different meanings such as supply reliability, current quality, voltage quality, service quality, quality of supply and quality of consumption [18]. Table 1 illustrates the most common problems from the standpoints of consequences, causes and explanation of the power quality phenomena in power systems. Among these phenomena, voltage sags account for the highest percentage, almost 31%, whereas the lowest percentage is voltage transients by 8%. Because of the increased use of sensitive loads, PV systems and power electronic equipment produce harmonic and asymmetrical voltages accounting for 20% and 18%, respectively.

We searched ‘Flexible ac transmission systems (FACTSs)’ keyword in the SCOPUS database and found 3264 articles, ranging from 1987 to July 2017. Figs. 1–5 sort the published articles by different categories. Fig. 1 shows the number of articles published worldwide from 1987 to July 2017. The line chart illustrates that, from 1987, the need to use FACTS devices to overcome power quality problems in power system has been increasing. As a result, research in this field has grown dramatically. Fig. 2 shows the distribution number of FACT-related articles.

Over the last three decades, many countries have performed studies on FACTS devices and their application to enhance the power quality in traditional and modern electrical networks. Among them, India ranked the first, and the United States, China and Iran ranked second to fourth, respectively, as shown in Fig. 3. Furthermore, the most famous researchers and research centers, in all parts of the world, together with number of publications are illustrated in Fig. 4 and Fig. 5, respectively.

3. FACTS devices

FACTS devices and integrated power electronic converters with flexible fast acting control strategies are used in emerging smart grids and integrated ac-dc renewable energy systems. They are based on the concepts of:

1) Modulating apparent admittance (Y) and impedance at the point of common coupling and key common ac bus.
2) Injecting ac components in series or parallel with the electric network nodes to create current flows or superimposed voltages.
3) Supplying localized reactive or capacitive current at the bus for reactive power flow control.
4) Modulating or switching the equivalent-driving point impedance (Z) at the interface bus by controlled switching.

The control strategies are based on voltage, power, angle or reactive power flow control using classical proportional-integral-derivative (PID) controllers, optimal control, heuristic soft computing control strategies and/or a multi-objective control performance index (J).

The converter topologies can be classified into:

a) Voltage source-converter fed
b) Dc-current source injection interface
c) Switched/modulated inductors or capacitors
d) Active power filter topologies

The resulting voltage and current waveforms are usually distorted and contain harmonics due to switching nature of power electronics converters, and additional interface filters are usually required.

In recent decades, due to the increasing demand of electricity in different countries, the need to build new transmission lines, electricity posts and increase the capacity of transmission lines has greatly increased. But the construction of new electricity transmission lines requires a huge capital investment. As a result, finding effective solutions to reduce the costs for electric companies has been a great challenge. The main objectives of FACTS devices are to increase the useable transmission capacity of lines and to control the power flow over designated transmission routes [37]. FACTS devices are also used to improve the power quality. There are different types of FACTS devices such as static VAR compensator (SVC); dynamic flow controller (DFC); thyristor controlled series compensator (TCSC); HVDC back to back (HVDC B2B); unified power flow controller (UPFC); static synchronous series compensator (SSSC); static synchronous compensator (STATCOM); and dynamic power flow controller (DPFC) [38,39]. According to their connection, they are classified as shunt-connected controllers, series-connected and combined series- and shunt-connected controllers. The main benefits and applications of basic FACTS devices in the electrical network are introduced in Table 2.

3.1. Static VAR compensator (SVC)

In the 1970s, the first generation of FACTS devices, known as Static VAR Compensator (SVC), was introduced. A SVC is a shunt-connected absorber capable of exchanging capacitive/inductive power to control specific parameters of the electrical power system [40]. In 1974, the first SVC was installed in Nebraska by General Electric. More than 800 SVCs with power ratings ranging from 60 to 600 MVAR have been installed by electrical utilities until now. ABB has provided about 55% of the SVC market, with 3% in Asian countries.

SVC may improve transient stability by dynamically supporting the voltage at key points and steady state stability by helping to increase