Electrical Power and Energy Systems 104 (2019) 744–771

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Load flow balancing and transient stability analysis in renewable integrated power grids☆

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ARTICLE INFO

Keywords:
Load flow balancing
Transient stability
Single and multiple interval faults
Renewable integrated power grid

ABSTRACT

Due to random patterns of demand response from the consumer side and the unreliable nature of renewable energy resources, load flow balancing and transient stability become challenging issues in power systems. They are even more challenging in cases of multiple interval three phase (L-L-L) faults (MITPFs), which arise in power systems due to power quality disturbances. The intent of this work is to examine the influence of MITPFs on renewable energy resources (RERs) for load flow balancing and transient stability analysis. Wind turbine power dispatchability and uncertainty have a significant impact on load flow balancing and transient stability, especially in cases of occurrence of MITPFs. Probabilistic modeling is performed in this paper to formulate the complexity of randomness for load flow balancing through a smart node and transient stability analysis through a unified power flow controller. The proposed probabilistic algorithm is based on the deviations between generation and demand response patterns due to an MITPF. An autocorrelation expansion is applied to approximate the randomness of probabilistic variables between the forecast generation and actual response pattern. Future contingencies can be predicted before disruptive changes arise due to the occurrence of an MITPF using the above probabilistic analysis. Simulation results show that the proposed algorithm outperforms existing alternatives and can achieve near optimal performance for a wide range of load variations and power quality disturbances in renewable-integrated power grids.

1. Introduction

The economic prosperity of any country relies upon its electric power infrastructure. A stronger electric power infrastructure that incorporates advanced sensing, communication, security and control technologies in the form of a smart grid can provide a more reliable, efficient, sustainable and economical supply of electricity [1,2]. One of the key features of smart grids is to utilize renewable energy resources (RERs) within a renewable integrated power grid (RIPG), in order to meet consumer side load requirements for providing cheaper electricity [1]. However, there are also certain limitations involved with RIPGs, and the most important one is reliability, which must be resolved in order to provide a secure and sustainable form of electric energy to consumers [3]. Incorporating certain flexible AC transmission system (FACTS) devices into the RIPG, such as static compensators (STATCOMs), static synchronous series compensators (SSSCs) and unified power flow controllers (UPFCs), provides a promising way to address reliability issues in power systems. Among these, UPFCs are a versatile form of FACTS devices, which are capable of both shunt and series compensation in order to mitigate the effects of power quality disturbances in a power system [4]. Moreover, there are also various technical issues associated with RIPGs. One such issue is power quality disturbances and their adverse affects, which account for both load flow balancing and transient sta-

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☆ This work was supported in part by the U.S. National Science Foundation under Grants DMS-1736417 and ECCS-1824710.

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https://doi.org/10.1016/j.ijepes.2018.06.037
Received 13 March 2018; Received in revised form 10 May 2018; Accepted 18 June 2018

bility. These power quality disturbances occur in power systems due to the occurrence of different types of faults. An RIPG reacts adversely to power quality issues depending on the severity of the problem, i.e., type of fault. In this paper, an analysis of different line fault types is conducted based on their durations to clearly illustrate the difference between single interval three phase (L-L-L) faults (SITPFs) and multiple interval three phase (L-L-L) faults (MITPFs) and their impact on RIPGs for load flow balancing and transient stability. MITPFs occur in power systems due to, for example, lightning strikes on a transmission line over multiple time periods, resulting in closing and opening of a circuit breaker at multiple times. Such MITPFs have adverse effects on RIPGs in terms of multiple power dispatchability and transient stability issues.

Load flow balancing and transient stability are challenging tasks in cases of single interval faults in RIPGs. They are even more challenging in cases of multiple interval faults, where fault analysis patterns are more random and their adverse effects are more severe. Various strategies have been adopted and techniques have been developed for load flow balancing and transient stability using UPFCs in RIPGs. The techniques for load flow balancing can be divided into several categories. For example, some techniques address the problem of power balancing in a general RIPG with storage and flexible loads [5]. Alternatively, the development of a dynamic optimum power flow framework to model curtailment of renewable distributed generation, energy storage systems and flexible demand for multiple time periods, is discussed in [6]. The improvements made by using electric vehicle (EV) chargers and photo-voltaic (PV) inverters that can balance the network, are further considered in [7]. Another approach for load flow balancing is to control stored energy to balance power generation of renewable sources to optimize overall power consumption at the microgrid (MG) level [8]. Furthermore, several probabilistic approaches have also been proposed, in order to deal with the uncertainty involved with RERs. These include the design of novel probabilistic power flow and probabilistic optimal power flow algorithms to reduce uncertainties due to environmental impacts on PV and wind farm generation [9–11]. Addressing the problem of different charging and discharging behaviors of EVs with the integration of PV generation and wind power generation in terms of probabilistic load flow modeling is also proposed in [12,13].

A common drawback of the above works is that all of these techniques require sophisticated storage, flexible loads and control mechanisms in order to provide effective load flow balancing on the receiving side of power grid stations. Moreover, these proposed approaches are computationally expensive and the optimal solutions in terms of load flow balancing are not guaranteed, considering larger deviations between loads, i.e., from KW to MW. To cover this gap, this work introduces a new solution method to this problem: a smart node transmission network topology that integrates different RERs with one another in order to accommodate load flow balancing in an RIPG, keeping variable heavy loads in mind. To the best of the authors' knowledge, this is the first work that addresses design of a customized smart node in order to stabilize the power system for load flow balancing on the receiving side, even in cases of occurrence of either SITPFs or MITPFs. The smart node is basically an intelligent interconnection of the transmission network that takes into account uncertainties in loads and renewable energy resources due to SITPFs or MITPFs and improvises the load flow balancing on the receiving side, based on the potential vulnerability of an RIPG.

Similarly, in order to address transient stability issues in power systems, various solutions have been proposed in [14–29].

Transient behavior is quantified with the inclusion of UPFCs, incorporating dynamic control strategies for power flow and voltage profile on different buses in [14,15]. A pattern recognition based solution for fault analysis, fault-type identification and fault-zone detection in a transmission line with the inclusion of UPFCs is proposed in [16]. Another approach for transient stability analysis is based on the design of a generic algorithm for simulating system transient stability for any type of fault for three and six phase systems [17].

In recent years, various approaches have been considered for transient stability enhancement in RIPGs using UPFCs. In [18,19], the authors considered UPFCs for simultaneous power flow control, and transient stability enhancement of hybrid power systems, i.e., for large interconnections, and correspondingly addressed the complexity of such power systems. Similarly, analyzing power quality disturbances for transient stabilities due to single line to ground (SLG), double line to ground (DLG) and triple line to ground (TLG) faults, i.e., SITPFs, and their compensation using FACTS devices was discussed in [20]. Also, characterizing UPFC energy functions in terms of Lyapunov energy functions, in order to determine the effect of UPFCs on transient stability enhancement, considering the occurrence of three phase short circuit faults in power systems during a single interval has been investigated in [21]. Addressing an issue of how to control UPFC parameters in order to achieve the maximal desired effect in solving the first swing stability problem in case of occurrence of an SITPF was proposed in [22,23]. Moreover, in order to control the entire flow of load and voltage sags/flickers, while eliminating harmonics simultaneously in cases of occurrence of different grid faults based on single intervals, [24] proposed an inventive systematic approach based on operating the UPFC in an optimal control mode to efficiently manage these power quality disturbances. Similarly, the stability assessment for the occurrence of SITPFs without FACTS controllers in the power network and then with the FACTS controllers was proposed in [25] to clarify the impact of SITPFs on the performance of wind turbines and transient rating of the FACTS controllers for enhancement of transient stability issues. Another approach is to consider multiple modes of oscillations due to the occurrence of a three phase to ground fault during a single interval and its compensation using a UPFC as was proposed in [26]. Similarly, tuning the gains of a UPFC controller with a simple Genetic Algorithm (GA) to address transient stability issues in cases of the occurrence of SITPFs was proposed in [27]. Furthermore, damping of the low frequency oscillations of multi-machine multi-UPFC power systems based on an adaptive input-output feedback linearization control (AIFLC) approach, considering an SITPF, was proposed in [28]. The same scenario of damping low frequency oscillations using a particle swarm optimization based output feedback UPFC damping controller, considering a 6 cycle SITPF, was investigated in [29]. All of these techniques were applied to RIPGs for compensating power quality disturbances using FACTS devices, by incorporating small delays that occurred due to SITPFs. However, the