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An effective load shedding remedial action scheme considering wind farms generation

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ABSTRACT

In this paper, a fast load shedding remedial action scheme (RAS) is developed considering generation pattern of local wind farms using wide area monitoring framework. In the proposed RAS, the shedding candidates are selected and prioritized based on load types and their impacts on the voltage profile and transient performance of the system. The dynamics of wind farms are also included in the shedding requirements and formulas by defining effectiveness indices which are calculated based on the contribution of each generator to the dynamic performance of the system. This allows secure operation of the system after major contingencies while impacted customers are minimized. The proposed methodology, shedding formulas, and corresponding requirements are verified for the BC Hydro system using the PSS/E dynamic simulation package.

1. Introduction

Distributed generations (DGs) are extensively growing throughout the world as alternatives for congested central power plants (large power plants combined of multiple generating units with considerable active power output) [1] which reduce power losses in transmission lines [2]. Wind generation systems as the major part of sustainable energy sources reduce green-house emission [3]; however, their inevitable impact on the operation of power systems brings new challenges along with their increasing integration level to power grid [4]. In spite of supporting power system operation, wind generation is characterized by generation intermittency [3] due to high levels of uncertainty associated with wind speed/direction forecast [4], which makes the power system vulnerable to fluctuation and instability [5]. Their impact becomes more dramatic when power systems are designed to operate close to their stability margins due to economical considerations [6,7].

In order to utilize wind generation enormously without compromising power system stability, power transfer, voltage and frequency should be controlled within allowed operating ranges [2]. Either rotor angle, frequency or voltage instability may occur as a result of super-component-contingency (SCC) (i.e. losing a significant amount of active/reactive power transfer due to outage of major power generating/carrying components such as power plants, multiple-circuit transmission lines, etc.) [8], which have been the cause of several reported power system collapse and blackouts [9–11].

Power system transient stability control approaches can be categorized, namely, as preventive and corrective [6]. In the preventive control method, when a potential instability is detected, appropriate actions (such as changing generation pattern) are taken to steer the system toward more stable states, which has economical impacts due to generation/consumption reschedules. On the other hand, corrective control is aimed to preserve system stability when a contingency occurs in power system, which is challenging in the short amount of time before system breakdown [6]. Load shedding has been proven to be an economic and effective technique for avoiding voltage/frequency instability [12–14].

Under Voltage Load Shedding (UVLS) has been proposed in [15] and further developed in [16–18]. Under Frequency Load Shedding (UFLS) has also been developed as the last resort to maintain frequency stability [19]. In [2], a UFLS is proposed to minimize the amount of DG disconnections. A combined UFLS and UVLS scheme is also presented in [3] for power systems with high integration level of uncertain renewable sources. The possibility of substituting all diesel generations with photovoltaic and wind generations is investigated in [20] benefiting load shedding. The influence of different load types on UVLS and UFLS schemes along with power system dynamics has been studied in [21]. Conventional load

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Nomenclature

G_A, G_B, G_C, G_D	windfarm generators
L_A, L_B, L_D, L_E, L_F, L_G	loads at buses A, B, C, D, E, F, and G respectively
DTT	Direct Transfer Trip
RAS	Remedial Action Scheme
$1L1$	line number 1 at 130 kV
$1L2$	line number 2 at 130 kV
$1L3$	line number 3 at 130 kV
$1L4$	line number 4 at 130 kV
$2L1$	line number 1 at 230 kV
$2L2$	line number 2 at 230 kV
$2L3$	line number 3 at 230 kV
$2L4$	line number 4 at 230 kV
$2L5$	line number 5 at 230 kV
$2L6$	line number 6 at 230 kV
$2L7$	line number 7 at 230 kV

shedding schemes (i.e. UVLS and UFLS) suffer from malfunctioning when encountering SCCs, since they are slow and local protection approaches [22,15,23].

The importance of the application of Wide-Area Monitoring, Protection, Automation and Control (WAMPAC) frameworks for power systems has been intensified with increasing uncertainties in their operation states due to higher penetration of renewable energy sources to power grids [24,25]. WAMPAC framework consists of the so-called Special Protection Systems (SPSs), Emergency Control Systems (ECSs), Remedial Action Schemes (RASs) and Wide-Area Protection Systems (WAPSs) that all aim to preserve System Integrity Protection (SIP) [26].

The purpose of SPSs and more specifically RASs is to detect the emergency and abnormal power system states by taking fast predefined corrective/remedial actions (such as load shedding, generation shedding, capacitor and reactor switching, transformer tap blocking and etc.) [7,27] to avoid rotor angle, voltage or frequency instability and preserve power system integrity [6,8,28–30]. Despite the conventional load shedding schemes, fast load shedding that is a remedial action scheme can prevent power system collapse due to fast initiating of shedding before rotor angles/voltage/frequency move toward instability margins [31]. According to Western Electricity Coordinating Council (WECC) definition, the appropriate design approach for a RAS is that all system performance criteria must be met, even after a single component failure occurrence within the RAS. Similar to other protection systems, this design objective is mostly met using a fully redundant system design. This fully redundant design minmizes the possibility of a single component failure to jeopardize successful RAS operation [32]. Remedial Action Schemes can be categorized as response-based RASs or event-based RASs [27,29].

The response-based RASs are initiated by a response from electrical measurements indicating abnormal conditions (e. g. abnormal voltage or frequency), while event-based RASs are activated via specific events which are faster and more effective [8]. A remedial action scheme is proposed in [33] to prevent power system blackout due to contingencies at major EHVs transmission lines. The proposed methodology is using based-line equal area criterion for an OMIB (One-Machine-Infinite-Bus) power system with phasor measurement units (PMUs) utilized for monitoring power flow and applying load shedding and fast valve control of turbines. The presented RAS in [33] computes the timing and order of the required corrective actions using a line-based equal area criterion. Therein, all the critical machines are assumed to be clustered and are modeled as a single machine connected to the infinite bus. The approximations assumed in [33] make it applicable only to system tie-lines.

Although RAS schemes are basically established by carrying out extensive iterative offline studies for various possible contingencies [6,7], the subject RAS scheme can be calculated utilizing appropriate online stability analysis methods [34,35]. A generation-shedding remedial action is proposed in [7] in which online stability and generation cost functions are calculated to trip the required number of generators for minimizing costs. An event-based RAS has been proposed in [8] to avoid instability and system collapse against SCCs. The developed RAS in [8] neglects exciter and machine dynamic responses and considers the largest time constant for the governor simplified models based on system-frequency-response (SFR) methodology [8]. The presented RAS can cover only long-term voltage collapse and slow frequency deviations. Recently, a load shedding RAS has been developed based on real-time data from wide-area monitoring system in [36] which minimizes the amount of load to be shed by selecting the most effective load shedding candidates. However, it ignores the local generation pattern which leads to over load shedding.

In this paper, a load shedding RAS is developed based on [36] including the dynamics of wind farms in the shedding formulas by defining effectiveness indices which are calculated based on the contribution of each generator to the dynamic performance of the system. The developed RAS considers all the turbine-generator model details (i.e. machine, exciter, automatic voltage regulator (AVR), governor and turbine). In subsequent sections, the proposed RAS is presented and verified by simulations in PSS/E simulation package [37] for the power system of a region (P-region) of British Columbia province of Canada as depicted in Fig. 1, in the course of a system reinforcement project, while constructing new substation and transmission lines in the region. P-region is located in the north east of British Columbia and originally was supplied by 138 kV lines. Due to future load growth, it is necessary to supply the region with additional 230 kV circuits. In Fig. 1, substations are demonstrated using circles, generating stations and windfarms are represented using rectangular shape and named as G_K which $K \in \{A, B, C, D, E\}$. Lines are named as mLn in which $m \times 100$ kV represents the voltage level (for e.g. 1 represents 138 kV) and n represents the line number.

2. Load shedding methodology

In general, developing a load shedding formula and its requirements has two major steps. First, a boundary should be defined representing system conditions for which shedding is required. The boundary is calculated and developed based on several system variables (e.g. line flows, generator outputs, system reinforcements, etc.) which are selected mostly using engineering judgment and understanding of the system and sensitivity analysis. Then the shedding formula is developed based on the selected system variables. Herein, the shedding amount is determined based on the area load in a defined cut-plane (hypothetical cutting through the circuits connecting the studied area to the energy system). The cut-plane load is calculated using line flows to the area and local generation as expressed in,

$$L_{sh} = g\left(\sum_{1}^{n} P_{Li} + \sum_{1}^{m} P_{Gj}\right), \quad (1)$$