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Stability-based minimization of load shedding in weakly interconnected systems for real-time applications

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A R T I C L E I N F O

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A B S T R A C T

The transient stability of power systems is highly affected by the changes in the power generation and load levels. Due to the variability of the generating resources, the system stability can be provoked and the system stability limits can be reached as a result of certain sudden drop in the power generation. In these cases, the load shedding can act as an effective emergency corrective action for keeping system stability; however, over-shedding of loads results in severe economical as well as social security problems. Therefore, minimization of the load shedding required for the restoration of the system stability is one of the main objectives of this paper. Another critical issue related to successful load shedding is the fast assessment of the system stability, and the amount of the load shedding as well as the implementation of the load shedding corrective action. Therefore, this paper presents a fast method of stability assessment and load shedding requirements in the weakly interconnected power system. The method is an improved form of the extended equal area criterion (EEAC) where the required system equivalence is based on the availability of wide area monitoring (WAM) devices in modern power systems. The paper also investigates the impact of the implementation duration of the required load shedding. The results are verified through time domain simulations which confirm the accuracy of the presented method and its suitability for real-time applications.

Introduction

Generally, the electric power is produced through an energy conversion process in which a primary energy source is converted into electric power. The primary energy resources can be classified according their capability of replenishment into two broad categories; non-renewable (or conventional) and renewable energy resources [1,2]. The access to cheap energy and availability of energy resources for the future (or the energy security) is one of the major challenges in the energy sector [3]. Non-renewable energy resources are distributed in an uneven way throughout the world. On the other hand, many types of renewable energy resources such as wind and solar are available at all locations on the earth [4]. Therefore, renewable energy resources can contribute in enhancing the worldwide energy security, reducing the energy threat, and crisis. Due to their low pollution levels in comparison with conventional sources of energy as well as their natural availability, renewable energy resources are sustainable [5].

From grid integration point of view, the integration of large amounts of renewable energy sources causes a significant change in the classical energy mix and raises a number of major challenges [6–9]. These challenges are mainly associated with the grid stability, reliability, security, power quality and behavior during fault conditions. Elaboration of specific technical requirements or grid codes for the connection of large amounts of variable renewable energy has been constructed. The main conditions of these grid codes show that grid-connected renewable sources should contribute to the power system operation, control, reliability, and stability. In addition, these contributions should be as close as possible to those contributions provided by conventional sources [8,9].

Some major renewable energy resources such as wind and solar are inherently variable and intermittent [1,3,6,7]. Recently, the predictability of these renewable resources has been significantly enhanced; however, their natural variability and intermittency prevents their reliable large scale integration with power systems. Successful power system operation requires the capability of the system generating units to be included in operational programs such as dispatch, unit commitment, security, and reliability [7,10]. Given that it is not techno-economically feasible or may be impossible to store bulk amounts of electric energy, variable

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renewable energy sources may not provide the main operation requirements of power grids.

From the security point of view, the sudden significant changes in the power production (or power swings) from variable renewable can upset the stability of power systems especially when the amounts of variable generation are large. Variability in the power generation can be detected in conventional and renewable energy sources. The main reason of this variability is the lack of the required input primary resources such as non-renewable fuels or renewable resources. In addition, some of the generation variability is attributed to the forced outage of generating units due to failures. These failures can be internal (i.e. within the generating units) or external (i.e. in the power networks). This paper focuses on the real-time impact of the sudden changes in the power production on the stability of power systems.

Currently, wind energy is one of the most prevalent adopted renewable power sources [11,12]. Historically, there was an agreement that wind turbines do not engage in the electromechanical oscillations (EMOs) [13–15]. This was based on the facts that wind power sources were considered as current sources. For example, a DFIG was considered as a current source under the traditional power factor control operation [13–15]. In either a weak grid or a grid with large amounts of wind power, the ancillary voltage/frequency control of wind farms are required for stabilization of power systems [8,16]. Consequently, recent wind farms react as synchronous generators and engage in EMOs; however, there are already many grid-connected uncontrollable wind farms that made up with squirrel cage induction generators (SCIG) that are directly connected to the grid. These kinds of wind farms may significantly affect the stability of power systems as their power control capability is very limited.

Unlike conventional power sources, the placement renewable power sources are mainly dependent on the availability of the renewable resources. Usually, the feasible locations for renewable energy projects are remotely located with respect to the power grid [17–19]. Therefore, renewable sources are usually connected to the grid via long transmission systems that presents weak links. Generally, a transmission link (or tie-line) interconnecting two systems or two areas is said to be weak if its power capacity is smaller than the capacity of the smaller system by about 15–20% [20].

Traditional generation loss contingency analysis considers forced outage of generating units caused by internal or external failures [10]; however, integration of variable renewable sources adds additional power production contingencies [6,7]. These new contingencies are due to the resource-based power production loss. The intense variability and intermittency of a renewable resources cause significant sudden changes in the power production and stability harassment.

Following a large generation loss, the system frequency may drop quickly if the remaining generation no longer matches the load demand. Without adequate system response, loss of generation can produce extreme frequency excursions outside the acceptable range of power plants, degradation of the load response, overloading transmission lines, and may lead to system collapse [21,22]. Therefore, real-time assessment of the impact of sudden generation loss on the stability should be provided. In addition, fast and effective emergency corrective actions should be taken to prevent cascaded outage of generating units, instability and islanding of the system, and even system blackout.

Depending on the size of the frequency deviation caused by a disturbance, emergency control and protection schemes may be required for maintaining the system frequency and stability. Normal operation frequency deviations are small enough to be controlled by the governor natural autonomous response (i.e. primary control) and load frequency control (LFC). With large frequency deviations that may be caused by the outage of components or faults, emergency control and protection schemes must be used to restore the system frequency and stability [22]. Under frequency load shedding (UFLS) is an effective and fast emergency corrective action. UFLS shows success in preventing probable system instability due to large disturbances [10,22]. The main objective of an UFLS strategy is rapidly balancing the demand with the available supply. For weakly interconnected systems, this paper presents a simple and fast method for real-time estimation of the necessary load shedding in generation drop situations. The method is based on extended equal area criterion (EEAC) approach which extended the application of the traditional equal area criterion (EAC) [20,21] to multimachine systems [23–28].

The first step in the EEAC is reducing the system to a single machine infinite bus (SMIB) system. To do so, the machines are *decomposed* into two clusters or groups. The first group contains the critical machine(s) while the second group contains the rest of the machines. Each group is then *aggregated* into one equivalent machine and these two machines are *further aggregated* into one equivalent machine. Therefore, the multimachine system is reduced finally to a SMIB system on which the EAC can be easily applied. It is found that the EEAC system reduction method and the resulting equivalent will not accurately represent the dynamics of the original power system unless the machines comprising each group are coherent [25,29,30].

The impact of sudden changes in the power production considering weakly interconnected systems is presented in this paper. In addition, transient stability-based minimization of load shedding is determined. The equivalence of power systems required for the use of EEAC is improved by determination of its parameters from power system measurements available from WAMs. In addition, the presented equivalency method is not only applicable for standard conventional synchronous generators, but also covers any electric power sources. In addition, the method can be applied at any bus in a power system if the required measurements are available. The EEAC approach is utilized for providing fast analysis and decision making for real-time applications. The impact of the delay in the implementation of the load shedding corrective action is investigated. In addition, the presented method and results are verified through time domain simulation.

Study system and modeling

Fig. 1 shows the study system and its equivalent. It consists, as shown in Fig. 1(a), of two weakly interconnected areas or systems. It is assumed that the generators in area 2 are highly variable while area 1 comprises less variable power sources. In both areas sudden drop in the power generation may be attributed to forced outage of generators, or faults, or unavailability of the primary energy resources. In area 2, the variability of the power sources causes sudden changes in the output power of the generators. These sudden changes may cause emergency stability problems if the drop in the power sources is intense and rapid. In such situations, load shedding is implemented to ensure system stability by curtailing sufficient system loads for matching the available generation with the remaining loads and keeping the system stability.

Typically, load shedding is implemented to protect the system against the decline of either the frequency or the voltage or both of them. In this analysis, the load shedding is implemented to protect the system interconnection against frequency declines that cause system instability. Due to the delay in the propagation of frequency changes in weakly interconnected systems, there is a tendency to localize the power adjustments following large contingencies [22,31,32]. In addition, the localized power adjustments have a significant improvement on the system stability [31]. Therefore, drop of generation in a specific area will be pri-