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Adaptive coordinated feeder flow control in distribution system with the support of distributed energy resources

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ABSTRACT

This paper aims to minimize the feeder power flow deviation from scheduled value by balancing generation and load demand within the distribution system under various local disturbances. The available distributed energy resources (DER) can be properly utilized to control the feeder flow which gains significant advantages (i) to support load frequency control (LFC) problem at transmission level (ii) reduces unscheduled interchange in feeder which is priced higher (iii) increased reliability of the grid. The deviation in feeder flow is reduced by properly coordinating the power output from DER such as fuel cell, battery storage system and responsive loads (demand response) through an adaptive fuzzy controller with optimally tuned gains using particle swarm optimization. The level of participation from each DER units are decided using fuzzy inference system based on the availability of resources and level of disturbance. The photovoltaic array and wind turbine are also considered in the system and always operated at the maximum power point. The proposed method is examined on IEEE 37 bus system implemented in the MATLAB based Power Analysis Toolbox (PAT) for performing time-domain dynamic analysis. It is shown that the proposed adaptive controller exhibits better performance for various disturbance conditions.

1. Introduction

Distribution systems are being changed rapidly to accommodate the demand growth, reliability concerns and environmental policies. The key factor driving this change is the increase in penetration of Distributed Energy Resources (DER). This penetration level is limited by the feeder capacity, protection issues, intermittency of renewable sources, reverse power flow and voltage rise [1]. In spite of the above issues, the integration of DER units offers various benefits for the smooth operation of distribution systems, such as mitigation of peak demand, grid support, improved reliability and power quality and market liberalizations [2]. The focus of this paper is given to the grid support provided by DER units with the sophisticated control schemes.

There are many technical issues related to the penetration of distributed generation (DG) which mainly act as the driving force for the utility to conduct proper planning studies. The DG impact on steady state operations are analyzed in [3] and the impact on system fault levels are analyzed in [4]. The optimal sizing and allocation of DG units are optimally determined by considering power loss minimization [5], voltage fluctuations [6] and harmonic limits [7]. Thus the determination of penetration level was given importance based on steady state operational limits.

On the other hand, the management and control of DG units have been considered for the stability operation in order to support the grid for load frequency control (LFC) problem following a disturbance. An overview of the issues concerning the integration of DERs into the power system frequency regulation is given in [8]. In [9], the automatic generation control analysis is given to show the importance of frequency control. The robust control using genetic algorithm is proposed and compared with the conventional LFC problem in [10]. The conventional LFC problem including various types of DER units is analyzed for improving the system stability margin [11], enhancing frequency stability using energy storage [12], calculation of frequency support by wind turbine using neural network with sliding mode controller [13], control of wind farms and energy capacitors using adaptive neural network [14] and using PSO based fuzzy approach in an AC micro-grid environment [15].

Smart grid control strategies are expected to utilize distributed generations and controllable loads both at transmission and distribution level. The optimal day-ahead scheduling considering

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economical operations of DER units are presented in [16,17]. The active voltage control method, at distribution substation, is proposed in connection with demand response (DR) for aiding system frequency regulation support in the Netherlands [18]. The use of various controlled loads to obtain frequency regulation in smart grid environment is tested in [19]. The increase in stability margin of system is achieved by introducing DR control strategy in classical single area LFC problem as shown in [20]. Thus, the study of distributed generation impacts on load frequency regulation problem is necessary and needs more analysis in terms of time domain implementations using more accurate models.

1.1. Motivation

The DER units can be operated either in (i) grid-following mode when connected to grid and (ii) grid-forming mode or droop mode when islanded. The power reference values can be set by a supervisory power management unit or locally calculated according to a pre-specified power profile to optimize power export from the DER unit. Other commonly applied methods are based on compensating variations in the local load, peak shaving profiles, and/or smoothing out fluctuations in the substation feeder flow [21]. The PI controller scheme is introduced to provide conventional LFC considering the aggregated model of PV generation, energy storage and electric vehicles [22]. Similarly, the superconducting magnetic energy storage output power is controlled to maintain the tie-line power in presence of wind turbine for enhancing system stability in [23]. Hence, by properly utilizing the available DER units in a local distribution system helps to reduce the control effort on larger thermal generators.

The transmission system operator is responsible for economically scheduling all generation units at transmission level based on the forecasted value of aggregated demand in each distribution area for the considered time period in 15 min block. In modern power systems with distributed generations and LFC using conventional PID controllers, it is difficult to obtain desired performance and it might end up with complicated control design. Moreover, the unscheduled interchange in tie-line is usually priced high as compared to the power purchased based on scheduled values. Thus the tie-line flow has to be maintained as scheduled by transmission utility in each time block [24].

This paper aims to solve this issue by smoothing out fluctuations in the substation feeder flow to a distribution network so that the internal area fluctuations are not seen at the transmission level. This brings significant advantages such as (i) to support LFC problem at transmission level (ii) reduces unscheduled interchange in feeder which is priced high (iii) increased reliability of grid. The consideration of objective to minimize the substation feeder flow deviation through adaptive fuzzy based DER coordination is adding a novelty in this work which has not been reported in previous literatures. The fuzzy based adaptive PI controller has tuneable gains so that the unique structure proposed can be easily applied to other distribution network. The amount of power shared between DER units are also obtained by another fuzzy controller. The integral square error (ISE) of feeder flow with respect to scheduled value is minimized using the particle swarm optimization by tuning gain values of proposed controllers. The proposed controller is tested on the IEEE 37 bus system using the Power Analysis Toolbox (PAT) [25].

1.2. Modeling of DER in PAT

In this work, the machines and DERs are modeled in MATLAB/Simulink environment using Power Analysis Toolbox (PAT) library [25]. The PAT analysis has two stages (i) Steady state analysis by conducting load flow as first stage (ii) dynamic analysis by time domain simulation as second stage. In first stage of PAT toolbox, the network data and machine data are entered in a data file and the load flow is executed to obtain the steady state values and also calculate the initial conditions of various power components to perform dynamic analysis in the next stage. As mentioned earlier the scheduled values of all the DER units are obtained at each 15 min time block by conducting this steady state analysis and hence this scheduled values in feeder flow has to be maintained during dynamic analysis. In second stage of PAT toolbox, the electrical network is modeled using reduced admittance matrix with those buses corresponding to the generation units and dynamic buses (responsive loads–RL & DER units) are considered to be retained for time-domain simulation. The model of induction generator, variable load and solid-oxide fuel cell are already implemented and tested in PAT [26–29]. The variable load available in PAT library is used to implement the demand response (DR) characteristics. The Nickel-Metal-Hydride battery model is implemented in PAT as a DC voltage source as given in [30]. The photovoltaic array (PV) is modeled in PAT and stacked in both series and parallel combination using the characteristics of Kyocera 135 W PV panel [31,32]. The maximum power point tracking algorithm (MPPT) is used for extracting maximum possible power generation from the PV array. The wind turbine is modeled based on the steady state power characteristics along with pitch angle controller and coupled with squirrel cage induction generator [33]. These DER units are considered as fixed power injections in the load flow program to obtain the initial steady state condition of the system.

2. The proposed adaptive control scheme

The distribution network is considered with one substation at the main feeder and several distributed energy resources (DER) installed at downstream buses. The substation is connected with the transmission system through feeder and can supply power required to the local distribution system while a part of the load is met by DER units. In real time, the system could operate at different point from scheduled values because of load variation and intermittent nature of renewable energy sources. This internal fluctuation in local area can cause the changes in substation power flow from upstream system, which in turn needs to be controlled by load frequency controller in a larger scale. In order to support the grid stability in solving LFC problem with ease at the transmission level, the local disturbances should be smoothened so that the internal fluctuations in the distribution area are not seen at upstream part of the system.

One way of smoothing out internal fluctuation is by using conventional PI controller, which takes the error in feeder flow as input and provide change in reference power of DER units. The conventional PI controllers has advantage in controlling the distribution feeder adequately by simple design and without full information. But it used to be tuned for the particular operating region and level of disturbance. In modern power system, the distribution network exhibits highly complex nonlinear characteristics due to the penetration of DER units. The conventional PI controllers designed for one system condition may not be robust for a wide range of operating regions and hence unable to provide satisfactory performance.

2.1. Adaptive control scheme

In this work, a fuzzy logic control based dynamic analysis is proposed to reduce the feeder flow fluctuations as shown in Fig. 1. Fuzzy logic controller has been widely used in the complex control problems [15,22]. The difference in substation actual real power flow (Ps_act) from the reference value (Ps_ref, scheduled