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Coordinated control of distributed energy resources to support load frequency control

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ABSTRACT

The control of generating resources to follow the unscheduled load changes is considered to be an essential process in the power system in order to maintain the frequency of power supply. This load frequency control (LFC) problem has been given more importance in the recent smart grid environment because of the impact from high penetration of distributed energy resources (DER) installed at the distribution level. The renewable sources are highly intermittent in nature, so it is required to coordinate and control the DER units to maintain the feeder power flow at substation bus bar which is seen by transmission system operator during the LFC process. This paper aims to identify the impact of distributed generation and its control method to reduce the deviation of feeder power flow from the scheduled value in real time operation. The error in feeder power flow with respect to scheduled value is utilized by the PI controller to estimate the change in power reference of all DER units. The power output of DER units are maintained to reference values by the individual PI controllers. The particle swarm optimization algorithm is employed to minimize the error in feeder power flow by optimally tuning the gain values of all PI controllers. The proposed method is examined on a small transmission system along with the feeder of IEEE 37 bus distribution system with balanced loading condition. The complete system along with DER units is implemented in the MATLAB based stability package named Power Analysis Toolbox (PAT) for performing time domain analysis. The impact on feeder flow and system frequency for the disturbance in load and weather condition without feeder control scheme (NFC) is compared with the feeder control scheme (WFC).

1. Introduction

Load Frequency Control (LFC) is one of the important control problems in electric power system design and operation to support automatic generation control, and is becoming more significant today because of the increasing size, changing structure, emerging new uncertainties, environmental constraints and the complexity of power systems [1]. In modern power systems the frequency has been given primary importance due to the ability to accurately estimate the parameter at virtually any voltage level in the point of interconnection [2]. This LFC problem is aimed to maintain the stability performance of power system following a disturbance from either a load or a generating unit.

There are several methods proposed for obtaining better solutions to the conventional LFC problem [3–11]. The recent survey on various control strategies used in solving LFC problem is described in [3]. The analysis and tuning of controllers in LFC problem for multi-area power system is described in [4]. The application of LFC in an area with small hydro power plant is analyzed in [5]. The multi-objective LFC control problem is formulated considering the effect of bilateral contracts [6,7]. In [8], the dynamical response of the LFC problem is improved with a state estimation and observability methods. The robust LFC design is proposed by considering MISO-PID controller [9], self-tuning fuzzy PID controller [10] and fractional order PID controller [11]. The use of intelligent algorithm in LFC design is proposed in [12]. The sequential quadratic programming (SQP) approach is proposed for designing a robust PID controller in LFC [13]. The design of LFC model using genetic algorithm based multi-agent approach is described in [14]. A particle swarm optimization (PSO) based multi-stage fuzzy controller is proposed for LFC problem [15]. The LFC design considering sliding mode control is proposed in [16] and model predictive control is proposed in [17]. However, the impact of renewable sources on the LFC problem is of great concern as a result of grid modernization.

The conventional LFC problem including various types of distributed energy resources to improve the system stability is

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presented in [18–24]. The conventional LFC considering coordination between conventional power plants and distributed energy resources is proposed to increase stability margin [18]. The automatic generation control structure is proposed to overcome the drawback of intermittency due to renewable energy resources by controlling pressure steam valves, storage units and load dynamic responses [19]. The modified calculation of area control error (ACE) in conventional LFC problem is proposed under the circumstance of large-scale DG penetration [20]. The energy management of fuel cells along with energy storage systems using load following control mode is described in [21]. A PSO based optimal PI controller design is proposed to achieve robust LFC operation in the smart grid with wind power, battery and electric vehicles [22]. The multi-objective optimization problem is formulated considering linear active disturbance rejection control approach for LFC problem and solved by hybrid PSO technique [23]. The impact of wind power plants in primary frequency control is analyzed by considering coordinated regulations of wind power plant with a flywheel-based storage systems [24].

Smart grid control strategies are expected to utilize distributed generations and controllable loads in the demand side. In order to achieve this, battery energy storage performs an important role for smoothing their natural intermittency and ensuring grid-wide frequency stability [25]. The advantages of using comprehensive demand response strategy in the presence of large renewable sources on LFC problem are discussed in [26,27]. 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.

The DER units can be operated either in (1) grid-following control mode or power dispatch control mode in the grid connected scenario and (2) grid-forming control mode or droop mode in the islanded microgrid scenario. The real and reactive power reference values can be set by a supervisory power management unit or locally calculated according to a pre-specified power profile to optimize real/reactive power export from the unit [28]. Other commonly applied methods are based on compensating variations in the local load, peak shaving profiles, and/or smoothing out fluctuations in the feeder power flow. In order to reduce the feeder flow deviations, the coordinated control of DER units could be very useful and hence the reference of power output values for each DER units has to be calculated by energy management unit. The fuzzy based strategy is introduced to provide frequency control and to reduce tie-line power fluctuations considering the aggregated model of PV generation, energy storage and electric vehicles [29]. The power sharing of DG units in a microgrid are analyzed considering two operating modes (1) unit output power control (UPC) and (2) feeder flow control (FFC) [30]. The frequency deviation and feeder deviation at immediate connection point of DG unit are considered to design the droop characteristics. Hence there is a possibility of deviation seen at main feeder for the load changes in local feeder without coordination among the DER units. By properly utilizing the available DER units in local distribution systems helps the LFC problem at transmission level to reduce the control effort on larger thermal generators.

The transmission system operator is responsible for scheduling all generation units based on the forecasted value of load demand in each area for the considered time period. These reference values must be maintained to match the power generations with load demand within each distribution area so that the feeder power flow is possible to maintain as scheduled by utility [19]. The disturbance in terms of load change or generation change within a distribution area will affect the feeder power flow which is further need to be controlled using the automatic generation control method (AGC) at transmission level. The price of unscheduled interchange in feeder power flow is usually charged higher as compared to the power purchased based on scheduled values. Moreover, in case of large scale power systems with conventional LFC using PID controllers, it is difficult to obtain desired performance and it might end up with complicated control design.

This paper aims to solve the above issue by smoothing out fluctuations in the feeder power flow to a distribution network by properly coordinating the available distributed energy resources installed in the same area, so that the internal area fluctuations are not seen at the transmission level. The DER units such as wind power, solar photovoltaic modules, fuel cell and battery storage system are considered along with the responsive loads/controllable loads (demand response). The integral square error (ISE) of feeder power flow with respect to scheduled value is minimized using the particle swarm optimization [31] by tuning gain values of all the PI controllers. The proposed control strategy is tested on a 3 bus transmission system along with the feeder of IEEE-37 bus distribution system with balanced loading conditions and the complete system is implemented in the MATLAB based simulation package called Power Analysis Toolbox (PAT) [32]. The model for DER units are developed and integrated with PAT. This is important because at the distribution level voltage and frequency loops cannot be decoupled as is the case at high voltage levels. The impact on feeder flow and system frequency for the disturbance in load and weather condition without feeder control scheme (NFC) is compared with the feeder control scheme (WFC).

The rest of the paper is structured as follows: The following Section 2 gives the modeling effort of all DER units considered in this work. In Section 3, the proposed coordinated control scheme is discussed. In Section 4, the description of test system and its implementation are given. The simulation results and related discussions are provided in Section 5 followed by a conclusion drawn in Section 6.

2. Modeling of distributed energy resources

In order to simulate the considered problem of reducing the feeder power flow deviations, the distributed energy resources (DER) are initially modeled as a dynamic model in MATLAB/Simulink environment using Power Analysis Toolbox (PAT) library. The PAT toolbox is very flexible and modular tool for load flow, transient, and small-signal analysis of electric power systems along with various FACTS and distributed generation devices [32]. In PAT, the transmission network is modeled using reduced Ybus matrix with those buses corresponding to the generation units and dynamic buses (FACTS & DG units) are considered to be retained. PAT model will consider the voltage and current signals in the form of per unit values or rms values, so it does not use the instantaneous values such as from SimPower voltage and current blocks.

The model of induction generator, variable load and solid-oxide fuel cell are already implemented and tested in the PAT [33–35]. The variable load model block which is already available in PAT library is used to implement the responsive load characteristics. The battery storage system, photovoltaic array, wind turbine are newly modeled and added to the existing PAT library after the proper validation of individual units performance with single machine infinite bus bar (SMIB) connected system in MATLAB/SimPower toolbox. The details of newly added DER models in PAT library are described in the following sub-sections.

2.1. Battery storage system

In the smart grid environment, the battery storage system is considered to be the most important device. Batteries can smooth the intermittent power output effect of renewable energy