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Autonomous operation and control of photovoltaic/solid oxide fuel cell/battery energy storage based microgrid using fuzzy logic controller

T. Vigneysh*, N. Kumarappan

Department of Electrical Engineering, FEAT, Annamalai University, 608 002, India

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ABSTRACT

In this paper, development and simulation of photovoltaic (PV), solid oxide fuel cell (SOFC) and battery energy storage system (BESS) based microgrid is presented. The microgrid system is operating in autonomous mode to serve the loads. To effectively control the microgrid voltage and frequency and to achieve smoother power flow control between the generation and consumption, voltage–frequency (V/F) control based on fuzzy logic controller (FLC) is proposed in this paper. Even though when there are sudden load variations in the system and fluctuations in PV output power, the microgrid voltage and frequency is effectively maintained within the limits by the proposed FLC. The main function of the BESS is to absorb/supply the excess/deficit power from the PV system and to keep the dc-link voltage of the voltage source converter (VSC) constant. SOFC is used as a backup generator and it is controlled to generate its rated power when the state of charge (SOC) of the BESS reaches its lower limit. The PV, SOFC and BESS are connected to a common dc bus through dc–dc power electronic converters. A three phase VSC is used to convert the dc to ac and to supply various ac loads. The PV, BESS and SOFC based microgrid system is simulated using Matlab/Simulink. To show the effectiveness of the proposed FLC over the conventional proportional-integral (PI) controller, the same system is simulated using PI controller and the necessary results are compared.
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Introduction

In present scenario, the centralized and regulated electric utilities are mainly dependent on fossil fuels such as coal, petroleum and natural gas to meet the energy needs. Conventional power plants are centralized and therefore electric power has to be transmitted over long distance which leads to energy losses and decrease in the efficiency of the overall system. Another major drawback of the conventional method of power generation from fossil fuel is the emission of millions of tons of pollutant gases to the atmosphere, which is believed to be the main cause of global warming [1]. Given the exhaustible nature of fossil fuels on the one hand and the ever increasing energy demand on the other, “renewable energy” based distributed generation (DG) systems have attracted a growing research interest. Therefore to meet the energy demand in an eco-friendly manner, it is necessary to generate

* Corresponding author.
E-mail addresses: vigneysh@live.com (T. Vigneysh), kumarappann@gmail.com (N. Kumarappan).
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electricity from various renewable energy resources such as wind, solar, biofuel, tidal, geothermal etc.

DG systems play a great role in addressing the aforesaid problems. DG systems can be powered by both conventional and renewable energy sources [2]. DG systems are decentralized and use more flexible and modular technologies to meet out the energy demand. DG systems are beneficial to consumers as well as to utilities. The connection of such small DG units to a low/medium voltage network potentially increases the reliability to the end users and utilities. From this point of view, a microgrid can be defined as a group of DG units such as photovoltaic (PV) system, fuel cell (FC), wind turbines, micro turbines and energy storage system together with power electronics converters and loads, which can operate either in grid-connected mode or in autonomous (islanded) mode [3]. In addition to various benefits provided by the microgrid, it has numerous technical challenges to be addressed. For example, power fluctuation due to intermittent nature of renewable energy resources, voltage and frequency control during islanded mode of operation etc. This can be achieved by proper control of interfacing power electronic converters and by careful selection of filter and controller parameters [4].

At present, PV power generation system is one of the most promising renewable energy technologies due to various reasons such as no incurring of fuel cost, pollution free power generation and less maintenance cost. Thus, it is considered as a good alternative when compared to rapidly decreasing reserves of fossil fuels [5]. Further, when compared to conventional power plants, fuel cells have many advantages such as higher efficiency, low maintenance cost with almost zero emission and are best suited for DG application. Among the various types of fuel cells, proton exchange membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) are identified to capture significant part of the market in the near future [6]. Among these two, SOFC is best suited for utility [7]. As solar power is sensitive to weather changes, it is not feasible to meet energy demands solely and completely by PV system and so an additional backup system is required. This backup system may be a power generator or energy storage system. In this work, battery energy storage system (BESS) is used as an energy storage unit and SOFC is used as backup power generator.

The main concern of the PV system is its efficiency. Despite the recent advancements in solar cell materials, the energy conversion efficiency of the PV system still remains poor [8]. This efficiency further deteriorates when there is no load matching between the PV array and load terminal. Generally, if a PV module is connected directly to a load, the operating point of the module will not lie on the maximum power point (MPP) of the module's power–voltage (P–V) curve. Further, the MPP varies with respect to the solar irradiance level and cell's operating temperature. Hence, it is essential to increase the module's power conversion efficiency by forcing the module to operate at the MPP, irrespective of varying weather conditions. This is achieved with the help of power electronic converter along with a maximum power point tracking (MPPT) algorithm [8]. In this work, perturb and observe (P&O) algorithm is used to perform this function due to its simplicity and ease of implementation. Like MPPT control for a PV system, the efficiency of a FC system can be improved by applying maximum efficiency point tracking (MEPT) control. At maximum efficiency point, the FC will reach its highest efficiency. MEPT works by controlling the fuel flow rate into the stack. In literature [9–11], various methods such as extreme seeking algorithm, numerical optimization techniques were proposed to improve the efficiency of FC's. Recently, in Ref. [11], improved version of extreme seeking algorithm with higher tracking speed and higher accuracy is proposed to improve the energy efficiency of FC. However in this work, simple model of SOFC system is considered without MEPT control.

In literature [12–20], different combinations of power sources are used to develop the microgrid operating in grid-connected or autonomous mode. In these literature, conventional controllers like proportional-integral (PI) controller are used to control the voltage source converter (VSC). The common problem in designing the conventional controllers for this kind of non-linear system is its dependency on the mathematical model of the plant. Most often, the power electronic systems are ill-defined. Even though the entire system parameters are known, there will be parameter variations during the operation of the system and hence the controller designing task is challenging and it is mostly tedious and time consuming too. Also, it provides no guarantee that it will performs well under sudden load changes or disturbances [21]. Recently advanced controllers like predictive controller [22], sliding mode controller [23], H-infinity controller [24] are used to improve the system steady state and transient performance. However, these methods require complex analytical calculations. To overcome these problems, intelligent techniques are generally used [21]. Recently, intelligent techniques are widely used for various power system problems with very good performance [25–29]. In Ref. [25], particle swarm optimization is used to tune the parameters of PI controller to improve the power quality of the autonomous microgrid. In Ref. [26], the application of neural network is used to tune the parameters of the PI controller of a SOFC and micro turbine based hybrid power system. Fuzzy logic control is another intelligent approach which does not require any mathematical model of the plant whose behavior is not well understood. It is easy to implement with good accuracy in control. On fine tuning, it even gives better performance than the conventional controllers. Fuzzy logic controller (FLC) is robust against the system parameter variations and during changes in operating conditions [27]. In Ref. [28], FLC is used for controlling the dc-link voltage of the VSC. In Ref. [29], maximum power point tracker based on FLC is proposed for a standalone PV system with battery storage.

In this paper, the proposed microgrid consists of PV system, SOFC system and a BESS as DG units and operating in autonomous mode to serve the critical industrial/commercial loads without any interruption. To control the three phase grid-forming VSC, primary control circuit consisting of power control loop, voltage control loop and current control loop is adopted. The power control loop adopts the droop characteristics to set the magnitude and frequency reference for the VSC output voltage. Different from the previous studies, in this work, a new approach based on FLC is

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