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Original article

Mitigating techniques for the operational challenges of a standalone hybrid system integrating renewable energy sources

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ABSTRACT

Renewable energy sources (RESs) combined with energy storage can significantly increase the resilience of standalone systems. However, the intermittent nature of renewable energy resources creates a number of operational challenges for standalone systems. In this paper, the potential challenges facing the operation of a standalone hybrid system with solar photovoltaic (PV) and wind turbine energy generation and battery energy storage are addressed. Control strategies for the system sources are developed to mitigate the potential challenges. A droop-based voltage and frequency control strategy is proposed for the battery energy storage to balance the mismatch between the renewable generation and the load and to maintain the system stability. An active and reactive power control strategy with maximum power point tracking (MPPT) is proposed for the PV and wind sources to maximize the generation when there is a lack of energy resources and to supply quality power from the sources. A simulation was completed to determine the viability of the proposed control strategies. Results show that the proposed control strategies are able to regulate the system voltage and frequency within the acceptable ranges irrespective of variations in the sources and the load-demand.

Introduction

The utilization of RESs has increased in recent years due to their significant environmental and economic benefits for the generation of electricity [1]. Integrating different types of RESs into a system that is not connected to the electrical grid forms a standalone hybrid renewable energy system (SHRES). SHRESs have the potential to supply continuous electricity similar to the electrical grid. However, the electricity generated by RESs, such as PV and wind turbine, is intermittent due to the uncertain and changing natures of these energy resources. The volatility of the electricity generated from these energy sources creates an imbalance between the renewable generation and the load. This imbalance causes deviations of the bus voltage and frequency [2,3] and eventually affects the system's stability and power quality [4]. Hence, some type of energy storage, such as fuel cells [5,6], supercapacitors [7], or batteries [8], must be integrated into the system to balance the mismatch between the renewable generation and the load by absorbing power during excess generation and supplying power during periods of low generation. However, the SHRES sources require suitable control strategies for the proper sharing of the load to synchronize the balance between the source power and the load-demand. The load-sharing control strategies based on a communication link and control interconnections increase the control complexity [9,10], reduce the reliability [11,12], and limit the flexibility and expandability [12] of the system. In addition, such control strategies require power electronic converters to regulate and convert the electricity supplied from the sources to the load. The electricity transferred using a number of power electronic converters increases the power transmission losses and consequently reduces the overall system's efficiency [13]. Maintaining a stable system, supplying electricity with high quality, load sharing, reliability, flexibility, expandability, and system efficiency are the challenges in providing a robust SHRES. These technical challenges can be mitigated by suitable control strategies and an appropriate interfacing configuration of the system sources.

The technical challenges of SHRESs and their mitigation techniques have been addressed in several articles. The stability and power quality issues of a DC and AC bus linked standalone system combining PV, wind turbine and energy storage are discussed in [14,15]. In [14], the proposed control strategy for the power electronic converters is to maintain a stable voltage and frequency of the three-phase AC bus under balanced and unbalanced load conditions by regulating the DC link voltage and the modulation index of the PWM inverter. A similar approach is presented in [15] for the

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stable operation of a system supplying power to single-phase AC loads. A filter circuit has been added at the inverter output to eliminate the presence of harmonics and improve the power quality. However, the DC and AC bus linked standalone hybrid system has the disadvantage of failing to produce power when the single inverter supplying the load fails. Through additional inverters, the reliability of the system can be significantly improved.

Hence, the authors in [16] proposed two inverters for interfacing the DC and AC bus of a standalone hybrid system. These two inverters are operated in parallel to share the load equally by using output impedance. The voltage control strategy based on the space vector pulse width modulation technique is proposed to regulate the output voltages of both inverters. However, the deviation in the amplitude or phase angle of the output voltage due to output impedance causes a circulating current between the inverters and affects the equal sharing of load. Furthermore, the deviation in output voltage of the parallel inverters leads to system instability. The main disadvantage of using output impedance for sharing the load is that it increases power losses and, as a result, reduces the overall efficiency of the system. Furthermore, the proposed control strategy for the parallel inverters does not include a current controller, and a large circulating current transient may cause the inverter to overload and damage the interfacing circuit. The large current transient also affects the power quality. In addition, the use of more inverters requires additional controllers and increases the complexity of the control algorithm.

The control of parallel inverters for load sharing has also been addressed in the literature. A load sharing control strategy based on average current sharing control has been proposed for parallel inverters in [17,18]. The proposed control strategy provides good load sharing and reduces the circulating current between the parallel inverters. A master-slave control strategy is presented in [19] to uniformly distribute the currents among parallel-connected converters. In this strategy, the master source is responsible for supplying a reference current for the slave sources. The proposed master-slave current sharing control achieves good load sharing and eliminates the requirement of a phase locked loop (PLL) for synchronization. Although the average and master-slave controls have significant benefits, these control strategies require a communication link between the parallel inverters for current sharing. However, the load sharing control strategy based on droop concept avoids the requirement of a communication link and adds desirable features such as modularity, flexibility and reliability of the SHRES [20].

In [21], a control strategy based on model predictive control is proposed to regulate the voltage and frequency of a standalone hybrid wind-diesel energy system. To achieve the voltage and frequency regulation, the field voltage and the rotational speed of a generator fueled by diesel are controlled by computing the optimal excitation voltage and the diesel fuel rate. However, the proposed control strategy generally requires a significant computational effort. The authors in [22] proposed a control scheme employed with proportional-integral-derivative (PID) and proportional-derivative (PD) controllers to regulate the frequency of a standalone hybrid system combining wind turbine generator, diesel engine generator and energy storage. The proposed control scheme regulates the output power of the diesel engine generator to maintain active power-frequency balance. The PID and PD controllers eliminate the steady state error and damp out the oscillations in system frequency after disturbance. However, the system voltage may exceed the allowable range when the source delivers the active power. The system voltage can be regulated within the allowable range by balancing the reactive power. Regulating the voltage and frequency in proportion to the reactive and active power flows can be achieved by a control strategy based on droop control concept.

Hence, the authors in [23] proposed a droop control strategy with voltage control loop for the parallel operation of single-phase voltage source inverter (VSI). The power sharing and the voltage and frequency stability are achieved with the proposed control strategy. However, any phase delays caused by filter circuit at the inverter output will affect the power quality. The addition of a current control with the voltage control loop corrects the phase delays and provides fast compensation for transient disturbances [24]. In this paper, a control strategy based on droop with voltage control and current control loops is proposed for three-phase voltage source converter (VSC) to ensure the system stability and power quality. In order to reduce the computational requirement of the control circuit and achieve the desired control response, a proportional-integral (PI) controller is adopted in the control loops of the proposed control strategy.

This paper presents the concept of an experimental prototype of a SHRES integrating PV, wind turbine and battery energy storage. The objective of this paper is to design the control strategies for a three-phase VSI interfaced SHRES sources and investigate the performance of the proposed control strategies under various operating conditions. A modular approach to the interfacing configuration and control strategies is given to overcome the challenges in system flexibility, expandability and reliability. The voltage and frequency control strategy is designed using the well-known droop control method for the battery energy storage to regulate the system voltage and frequency. The proposed control strategy for the battery energy storage is capable of managing the power flow during the intermittency of RESs and minimizes the transients in the voltage and frequency. The active and reactive power control strategy is designed with MPPT control for the PV and wind turbine to regulate the power from the sources. The proposed control strategies are capable of mitigating the potential challenges and improving the performance of the SHRES significantly.

The remainder of the paper is organized as follows. In 2nd Section, the basic configuration of the SHRES for interfacing the sources with a common AC bus is discussed. The control strategies for the SHRES sources are discussed and explained in 3rd Section. Simulation results obtained for various operating conditions are presented and discussed in 4th Section. Finally, the conclusion of this work is given in 5th Section.

Basic configuration of the SHRES

The basic configuration of the SHRES considered in this research work is shown in Fig. 1.

This SHRES integrates PV, wind turbine and battery energy storage sources. These sources are connected separately to the three-phase common AC bus through appropriate power electronic converters to achieve the desired conversion. The PV is interfaced through a VSI to invert the DC output voltage generated by the PV panels. The wind turbine is equipped with a variable speed direct drive permanent magnet synchronous generator (PMSG). The PMSG is more suitable for standalone applications because it does not require an AC excitation source for initial operation [25]. However, the amplitude and frequency of the three-phase AC voltage generated by the PMSG fluctuates as the wind speed varies. Therefore, appropriate power electronic converters are required to connect the wind source. Connecting the wind source via a three-phase diode rectifier does not require any additional controllers to regulate the fluctuating frequency and significantly reduces the overall switching losses of the wind energy conversion system [26]. Hence, the wind turbine is interfaced through a three-phase diode rectifier to convert the fluctuating AC output voltage generated by the wind turbine into a DC voltage, and then, a VSI inverts the rectified DC voltage. The battery energy storage is