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Harmonic voltage resonant compensation control of a three-phase inverter for battery energy storage systems applied in isolated microgrid

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ABSTRACT

The aim of this paper is to propose a sinusoidal voltage signals tracking control strategy, adaptive for frequency of a three-phase inverter for a battery energy storage system (BESS) applied to an isolated microgrid. To support the normal operation of distributed renewable energy and feed the critical loads under the isolated mode, the BESS generally works in voltage control mode (VCM). The proposed control strategy, which transforms the tracking control problem into a state feedback control problem, includes two terms, one of which is state feedback control used to stabilize system while another employs multiple resonant controllers applied to achieve harmonics compensation control. The optimal linear-quadratic (LQ) control approach in which the root locus method is used for optimization selection of weight matrix $\boldsymbol{Q}$ is adopted to tune the control parameters of multiple resonant controllers. The proposed control strategy performs outstanding voltage control performance to maintain an excellent voltage level such as zero steady-state error and low total harmonic distortion (THD) under the situation of sudden load changes, back power flow of renewable energy such as photovoltaic and nonlinear load in an isolated microgrid. Finally, the validity of the proposed approach is verified through simulations and a three-phase experiment prototype of BESS with TMS320F28335 DSP.

1. Introduction

Microgrids (MG), containing a large number of distributed renewable power sources (DRS) such as solar power, wind power and others, are devoted to the key technique of connecting distributed power to the grid [1]. To increase the stability of the system by making it more immune to perturbations such as changes in the loading conditions or changes in electric energy production due to environmental variability, energy storage devices are configured and used, which has become an extensive and common solution [2,3]. There are many possible technologies that can implement an energy storage system, but a battery is usually the most prevalent.

Within the battery energy storage system (BESS), a power electronics inverter interfaces with a single- or three-phase MG for the energy storage unit. Power converters generally operate in two modes, namely the grid-tied mode and off-grid mode, which are an important feature for improving the flexibility and feasibility of MGs. Under different patterns, the control techniques of the inverter, described in [4,5], are different from each other. In general, in the grid-connected mode, the control principle of the inverter is current-controlled or direct power-controlled. While in the island mode, the inverter switches to voltage control, which is analogous to an uninterruptible power supply (UPS) for its local loads [3,6]. However, in terms of BESS, there is another critical point wherein the inverter should support the backward flow of power when the output of distributed power sources is more than loads demand. Furthermore, the voltage controller should be adaptive with frequency in order to cater to the droop control or secondary control in microgrids. This paper will focus on the study of the output voltage control of the three-phase inverter for BESS under the isolated mode of microgrids.

In the last two decades, a large number of control techniques have been researched and developed for three-phase inverters in the context of output voltage control. The traditional proportional – integral (PI) controller [7], proportional – resonant (PR) regulator [8,9], and nonlinear control strategies such as the sliding mode and deadbeat controllers [10–12] are a few examples of popular control strategies. Most of these control strategies are based on the classical control theory; hence, they employ the control structure

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of connections in a series with the internal current control loop and external voltage control loop. Due to the approximation of the model, which is the foundation of the control structure, the satisfactory control parameters can be generally acquired by plenty of repetitive cut-and-try tuning, especially for the resonant regulator. Additionally, an acceptable compromise between transient responses and stability is very difficult to achieve.

Recently, various types of advanced control strategies have been applied to a three-phase inverter for voltage control [13–19]. Feedback linearization control techniques, which can achieve a high performance for the output voltage, are proposed in [13,14]. However, the nonlinear model established in [13,14], which is based on the power-balanced principle, is unsuitable for voltage control. Ref. [15] proposes a model predictive control with a load current observer. However, the total harmonic distortion (THD) of the output voltage is high. An adaptive control strategy of the three-phase inverter based on a rotating frame system (dq-frame) is proposed in [16,17]. Ref. [18] describes a combination of robust tracking control techniques designed by a linear matrix inequality (LMI)-based optimization. The control techniques yield fast tracking performance in the presence of parameter uncertainties, but the THD of the voltage on a nonlinear load is unacceptable. A single-phase voltage control algorithm employs multiple resonant (*R*) controllers and is proposed in [19]. The parameters for resonant (*R*) controllers in [19] are determined by means of a convex optimization problem subject to a set of linear-matrix-inequality constraints to solve the parameter uncertainties problem. However its model of the plant, short of generality, is not suitable for the situation of a microgrid with distributed power sources.

Theoretically, the best solutions to the tracking problem are the approaches based on the internal model principle (IMP) [20,21]. The principle states that if the closed-loop system is asymptotically stable and a certain signal must be tracked or rejected without steady-state error, the stable modes that describe the reference and/or disturbance signal must be imbedded in the control loop, in the controller, or in the plant itself. In the case of sinusoidal signals, the stable modes describing sinusoidal signals with resonance peaks in a specified frequency lead to the so-called resonant (*R*) controller. The resonant controller has been triumphantly and effectively employed in many applications involving power inverters [22–26]. However, several problems must be settled before utilization of resonant controllers, such as stability problems and tuning of controller parameters.

By applying the *R* controller to the voltage control of the three-phase inverter to the BESS in a microgrid, a comprehensive and universal mathematical model was created that combines the plant and *R* controller based on the state space method. Through the proposed model, the problem of tracking control is translated into a problem of state feedback control that makes the determination of parameters for the *R* controller become the selection of a set of entries for the weight matrix. Consequently, a method of selection for entries of the weight matrix is proposed through the root locus which is very simple and convenient; furthermore, the parameters design becomes more convenient. Meanwhile a discrete-time state space model without any poles displacement for the *R* controller is set to implement the *R* controller to improve the stability. In contrast to the conventional tandem double loop proportional-resonant (PR) control needed to decouple by settling time between the loops, the proposed control algorithm, which is a concurrency control method, has high precision with no need for decoupling of loops. The proposed control strategy presents outstanding voltage control performance, such as fast transient response, tiny steady-state error, and harmonic rejection for low THD under various types of operation condition such as load jumps, backward power flows, and so on. To confirm the validity and feasibility of the proposed control approach, simulations and experiments are

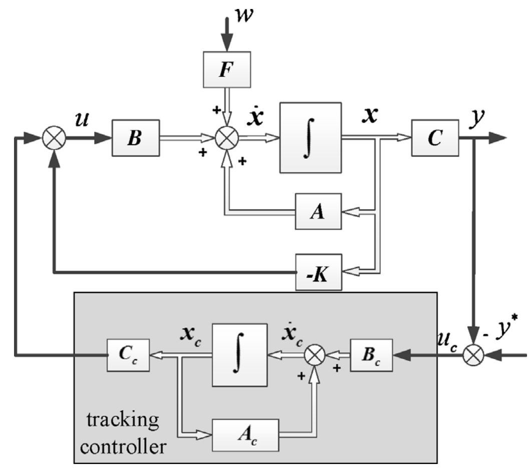

Fig. 1. Universal tracking control diagram.

performed through the MATLAB/Simulink software and an experimental platform with a TMS320F28335-based control board.

2. Control model

2.1. Universal model

It is well-known that the controlled object can be dynamically modeled as the form of state space [27]:

$$\begin{cases} \dot{x} = \boldsymbol{A}x + \boldsymbol{B}u + \boldsymbol{F}w \\ \quad y = \boldsymbol{C}x \end{cases} \tag{1}$$

where $\boldsymbol{x}$, $\boldsymbol{u}$, $\boldsymbol{w}$, $\boldsymbol{y}$ denote state variables, control input, disturbance input and controlled output, respectively. In classical control theory, the design for tracking control of output signal $\boldsymbol{y}$ usually adopts the series compensation approach by means of transfer function of $\boldsymbol{y}$ to control input $\boldsymbol{u}$ that can be derived from (1). It's obviously inconvenient for processing multiple input multiple output (MIMO) system. In addition, most applications in voltage control of power converter for DRS employ structure of dual-loop in series decoupled by the control speed [4]. Hence, this paper constructs a tracking control structure displayed in Fig. 1, which illustrates the tracking controller serving as an internal model as well as expressed in the form of state space. To conveniently determine the parameters of the tracking controller, the system, according to Fig. 1, is augmented into:

$$\begin{cases} \dot{x}_\Sigma = \boldsymbol{A}_\Sigma \boldsymbol{x}_\Sigma + \boldsymbol{B}_\Sigma u + \boldsymbol{F}_\Sigma w + R_\Sigma y^* \\ \qquad y = \boldsymbol{C}_\Sigma \boldsymbol{x}_\Sigma \end{cases} \tag{2}$$

where $\boldsymbol{x}_\Sigma = \begin{bmatrix} \boldsymbol{x} & \boldsymbol{x}_c \end{bmatrix}^T$ and

$$\boldsymbol{A}_\Sigma = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{0} \\ -\boldsymbol{B}_c\boldsymbol{C} & \boldsymbol{A}_c \end{bmatrix} \tag{3}$$

$$\boldsymbol{B}_\Sigma = \begin{bmatrix} \boldsymbol{B} \\ \boldsymbol{0} \end{bmatrix} \tag{4}$$

$$\boldsymbol{C}_\Sigma = \begin{bmatrix} \boldsymbol{C} & \boldsymbol{0} \end{bmatrix} \tag{5}$$

$$\boldsymbol{F}_\Sigma = \begin{bmatrix} \boldsymbol{F} \\ \boldsymbol{0} \end{bmatrix} \tag{6}$$

$$\boldsymbol{R}_\Sigma = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{B_c} \end{bmatrix} \tag{7}$$