A dynamic model of battery energy storage system based on the external characteristic equivalent

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Abstract. With the increasing application of battery energy storage in the power grid, there will be inevitably a large number of battery energy storage systems (BESS) in the future distribution network. It is very important to study the equivalent model of BESS which is suitable for comprehensive load modelling. In this paper, the battery group is established based on a type of general battery model, and then, a simulation platform of BESS based on MATLAB/Simulink is constructed, using a double closed loop control strategy with constant power as control object. Through the simulation analysis of grid-connected characteristics of BESS, a semi-mechanism dynamic model of BESS based on the external characteristic equivalent is proposed. This model represents the variation trend of the electrical variables of BESS during transient state, and considers the inertia characteristics of the BESS relative to power grid. By comparing the simulation results under different disturbance intensity, the proposed model can describe the transient characteristics of BESS, and can meet the performance requirements of the load modelling for the distribution network side.

1 Introduction

With the development of economy and society, on the one hand, the electricity demand is increasing continually and has obvious time characteristics, which make the peak-valley difference further expand. The application of energy storage technology in distribution network can effectively reduce peak-valley difference so as to realize peak load shifting, and then improve the comprehensive utilization ratio of distribution network assets [1]. On the other hand, small capacity and distributed intermittent renewable energy access will be widely distributed in the smart distribution network, and energy storage system (ESS) will be an essential device to smooth power fluctuation [2]. Battery energy storage is very suitable for smart distribution network because of its flexible configuration, fast response as well as no geographical environment restrictions [3]. Therefore, there will be a host of BESS in the future smart distribution network. Obviously, dynamic characteristics of BESS will affect the dynamic characteristics of the whole distribution network.

In the study of power system, load model has an important influence on the stability analysis of power system [4]. Since other models such as generator and transformer have been mature, the generalized load model considering the dynamic characteristics of BESS has become a key factor in the accuracy of power grid simulation results to the distribution network with BESS. Therefore, it is of engineering application value to study the dynamic model structure and parameter identification of BESS for generalized load model.

At present, many researches have been made on the modeling of energy storage batteries, and there are mainly two types of models: the electrochemical model [5], which has high precision but is extremely complex and is difficult to be applied to practical simulation [6]; the equivalent circuit model [7-9], which is widely used due to its simple modeling method, convenient parameter fitting as well as clear physical meaning.

The exiting researches on the modeling of energy storage system are mostly based on complex mathematical equations, or are simplified as a constant power source. Reference [10] establishes a detailed mathematical model of all parts of BESS for power system stability analysis, including battery group, inverter as well as controller. Reference [11] employs the general model of WECC that has complex model structure to verify the multiple application scenarios of BESS in power system. Reference [12] presents a generalized ESS model, using a set of linear differential algebraic equations describing (DAEs) the various types of ESS. Reference [13] proposes an electromechanical dynamic model based on wind-solar-storage hybrid simulation, but it is essentially a DC Thevenin equivalent model, without considering the influence of converter system. Reference [14] puts forward a general model of BESS taking account of grid-connected controller and converter that is equivalent to a first-order inertial link, but it is insufficient to describe the transient characteristics of BESS. Obviously, the above models are not applicable to describing the dynamic behavior of BESS in the generalized load model for the distribution network side, and now there is no dynamic model applicable to the generalized load modeling.

On the basis of the existing results, this paper studies the BESS dynamic model for the generalized load model for the distribution network side. Firstly, the simulation platform of BESS is built. Secondly, the dynamic behavior of grid-connected BESS is analyzed and its main features are extracted. On this basis, a dynamic model of BESS is proposed, which is suitable for generalized load modeling for the distribution network side. Then, the proposed dynamic model is verified and discussed. Finally, a summary of the whole paper is made.

2 Simulation platform of BESS

Battery monomer model generally include Thevenin model [7], PNGV model [8], and Run-time model [9] and so on. In this paper, the battery monomer model is based on the general model proposed in [15]. The battery group is usually composed of battery cells using series and parallel connection mode. This paper employs the equivalent circuit method to constitute the battery group for easily simulating [16].

In this paper, the BESS is incorporated into urban low voltage power grid, of which control strategy is double closed loop structure based on the d-q synchronous rotating coordinate system decoupling control method. The outer loop is the power loop, and the difference between the grid-connected power bus and the given power is used as reference current value of the d, q axis after passing through a PI controller. The inner loop is the current loop, and the difference between the grid-connected current and the reference current is used as reference voltage value of the d, q axis after passing through a PI controller as well as being decoupled; then, the PWM control signal of converter is obtained by anti-Parker transformation. The block diagram of the grid-connected control strategy is shown in Figure 1, where U_{dc} is the port voltage of battery group; i_d and i_q are the d and q axis components of the grid-connected current, respectively; u_{gd} and u_{gq} are the d and q axis components of the grid-connected voltage, respectively; u^*_d and u^*_q are the output voltage of the current inner loop, respectively; P^* and Q^* are the given active and reactive power, respectively; L is a filter inductance.

In the d-q coordinate system, the grid-connected active and reactive power can be expressed as

$$\begin{cases} P = 3/2(u_{gd} \times i_d + u_{gq} \times i_q) \\ Q = 3/2(u_{gq} \times i_d - u_{gd} \times i_q) \end{cases} \quad (1)$$

The BESS applied to distribution network generally absorbs or releases the active power, and the power factor is set as 1. When the direction of the d axis component of the voltage is in line with that of the resultant vector of the grid side voltage, namely u_{gq}=0, the formula (1) can be simplified as formula (2).

$$P = 3/2 \times u_{gd} \times i_d;\ Q = 0 \quad (2)$$

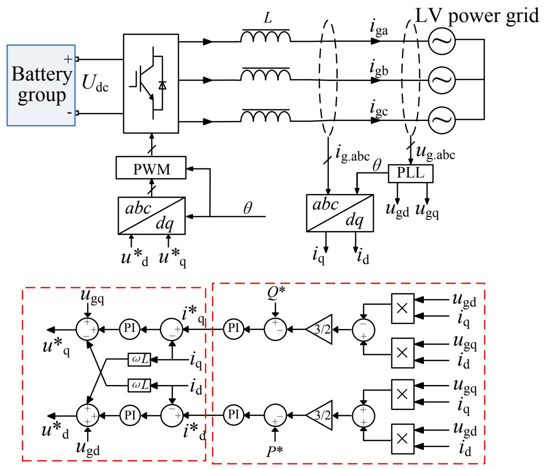

Figure 1. The control scheme of grid-connected converter.

3 Dynamic characteristics of BESS and its model

3.1 Dynamic characteristics of BESS

According to Figure 1 a simulation platform is constructed in MATLAB/Simulink to analyze the dynamic characteristics of BESS. When the voltage of power grid drops, through observing the change of the port voltage of battery group, grid-connected current, grid-connected power, the impact of the grid voltage on these variables is analyze, and thereby a mathematical model describing the relationship among them is established. Then the functional expression between grid voltage and grid connected power is got.

The power of battery group is set to 10kW, which is connected to the 0.4kV low-voltage power grid, and the power factor is 1. Supposing that a voltage drop with its duration being 0.1 seconds and its drop amplitude being 25% occurs, the curves of battery port voltage, grid-connected current and grid-connected power are recorded during 1 second before and after the voltage drop, which are shown in Figure 2.

Observing Figure 2, it can be found that BESS has the following characteristics during transient state: 1) In Figure 2 (a), the direct-current (DC) current of the battery group port increases about 5A, while the DC voltage of the battery group port decreases about 0.5V. 2) In Figure 2 (b), when the grid-voltage drops, the grid-connected current increases, but the increase magnitude is not proportional to the voltage drop amplitude. 3) In Figure 2 (c), similarly, when the grid voltage drops, the grid-connected power decreases, but the decrease magnitude is not proportional to the voltage drop amplitude, while the reactive power only fluctuates slightly at the moment when the voltage of the grid changes. 4) In Figure 2 (b) and 3 (c), during steady state and dynamic state, the grid-connected current and the grid voltage are in phase; when the grid voltage changes, the grid-connected power does not show step change, and there is a buffer process.

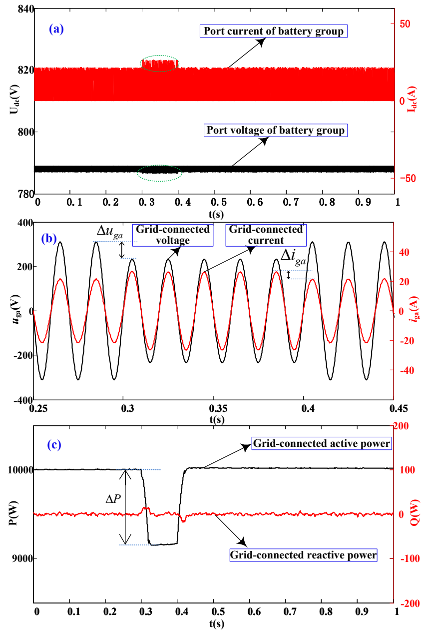

Figure 2. The transient characteristics of the BESS.

In term of the aforementioned analysis on dynamic characteristics of BESS, the following conclusions can be drawn: 1) During the grid voltage drop, although the port voltage of the battery group and the grid-connected power decrease, the port current of the battery increasing, while the total output power decreases. Therefore, it is not appropriate to take BESS as a constant power source. 2) During the dynamic period, the grid-connected voltage is determined by power grid, and the grid-connected current is determined by BESS and grid voltage, while the change of output power is determined by the combined effects of above all variables.

3.2 Dynamic model of BESS and its mathematical description

Concerning load modeling, the load model refers to the functional expression between the output power response and the input excitation voltage, which requires the model to be as simple as possible and the parameters as few as possible. Therefore, the dynamic model of BESS for distribution network generalized load modeling needs to meet the general requirements of load modeling and can describe the dynamic characteristics of BESS at grid-connected. In order to get the dynamic model of BESS, we will analyze and derive the model for load modeling based on the dynamic characteristics elaborated in Section 3.1.

The port voltage of the battery group is approximately constant (Figure 2 (a)) for the SOC can be considered unchanged in the microsecond and second time-scales, which determines the port voltage of the battery group almost unchanged. For converter system, its function is to convert DC to three-phase AC, so the port voltage can be equivalent to a three-phase voltage source from the perspective of functional equivalence. The equivalent three-phase voltage source is in phase with the grid voltage for the grid voltage and grid-connected current are the same phase (Figure 2 (b)). When the grid voltage drops, the grid-connected current increases (Figure 2 (b)). Thus, the equivalent three-phase voltage source can be connected with the power grid via a resistor. Furthermore, when the grid voltage has a step change, the power change has a buffer process, and from the point of view of the simplified model, a unity- gain inertia link can be used to represent.

Based on the above analysis, we can draw the dynamic model of BESS, of which equivalent structure is shown in Figure 3 and which is named as URT model in this paper. In Figure 3, $u_{b.abc}$ is the equivalent three-phase voltage source, which is in phase with the grid voltage $u_{g.abc}$; R is the resistance between the voltage source and the grid voltage; T is the inertial time constant; $i_{g.abc}$ is the gird-connected current.

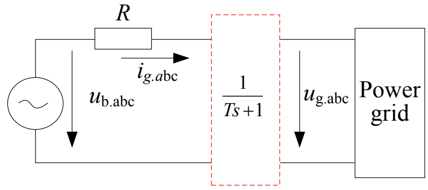

Figure 3. The dynamic model of the BESS.

It is important to point out that the inertial link in the red dashed frame is only used for the grid-connected power, but not for the voltage and current, and both sides of the inertial link can be understood as the grid voltage.

According to the equivalent model shown in Figure 3, the mathematical description such as formula (3)-(5) is given, where $i^*_{g.ab}$ is the conjugate of $i_{g.abc}$; P' is the intermediate value of grid-connected power.

$$i_{g.abc} = \frac{u_{b.abc} - u_{g.abc}}{R} \tag{3}$$

$$P' = u_{g.abc} \times i^*_{g.abc} \tag{4}$$

$$\frac{dP}{dt} = -\frac{1}{T}P + \frac{1}{T}P' \tag{5}$$

4 Model parameters and initialization

4.1 Model parameters

Known the structure of a model and its corresponding equations, the model parameters are obtained usually using system identification method. The first step of parameter identification is to determine the number of independent parameters and the identification initialization method.

The URT model has in total of 3 parameters: $u_{b.abc}$, R and T. When R or $u_{b.abc}$ is known, the $u_{b.abc}$ or R can be uniquely determined by combining the input voltage and the output power, and in other words, only one of R and $u_{b.abc}$ is an independent variable. In this paper, R is defined as independent variable, and then $u_{b.abc}$ is non-independent variable. Thus, the URT model has two independent variables, R and T.

4.2 Initialization

The initialization process of parameter identification is to determine the initial values of the non-independent and state variable. In URT model, the non-independent variable is $u_{b.abc}$, and the state variable is the model output response P_{mx}. Since the orders of magnitude corresponding to different variables may vary greatly, in order to improve the efficiency of identification, the per-unit system is generally adopted. We set U_b as per-unit value of $u_{b.abc}$, U_g as per-unit value of $u_{g.abc}$, and I as per-unit value of $i_{g.abc}$; the per-unit values of P_{mx} and R are still expressed with their actual value symbols.

Taking the grid voltage as the reference vector and passing through the Parker transformation, the d axis component of the grid voltage is equal to the resultant vector. Furthermore, the equivalent voltage source is in phase with the gird voltage. Therefore, U_b ,U_g and I can represent gird voltage, equivalent voltage source and grid-connected current, respectively, and then, the initialization process of model parameter identification is as follows.

1) Based on the steady-state grid voltage $U_g(0)$ as well as power $P(0)$, the initial value of grid-connected current is obtained by the formula (6).

$$I(0) = \frac{3}{2} \times \frac{P(0)}{U_g(0)} \tag{6}$$

2) The three-phase equivalent voltage source U_b is calculated by formula (7).

$$U_b = U_g(0) + I(0) \times R \tag{7}$$

3)The initial value $P_{mx}'(0)$ of the intermediate power P_{mx} is obtained by formula (8).

$$P_{mx}'(0) = \frac{3}{2} U_g(0) \times I(0) \tag{8}$$

4) Make the left end of the formula (5) be equal to zero, the initial value $P_{mx}(0)$ of the state variable (P_{mx}) is obtained.

$$P_{mx}(0) = P_{mx}'(0) \tag{9}$$

5 Simulation study

5.1 Description performance of URT model

In order to verify whether the URT model can describe the dynamic characteristics of BESS, taking the simulation platform of BESS introduced in Section 2 as the object and setting the voltage drops between 10% and 30% at grid-connected bus, a total of 3 sets of disturbance data as shown in Table 1, including the voltage and power, are collected to model BESS. Figure 4 is the tested power and model response power curves when the voltage drops are 15% and 25%, respectively.

Table 1. Sample instructions

Sample name	No .1	No .2	No .3
Voltage drop	15%	20%	25%

As shown in Figure 4, the model can well fit the sample data, which shows that the proposed URT model can effectively describe the dynamic characteristics of BESS and has good self-description ability. In addition, compared with Figure 4 (a) and (b), it can be found that the fitting effect is better than that of 20% when the voltage drop is 15%. The reason is that greater the voltage drop, the more obvious the transient power recovery process, and the power will go through a relatively long time to restore to the rated power state. Thus, the proposed URT model can well represent the dynamic characteristics of BESS.

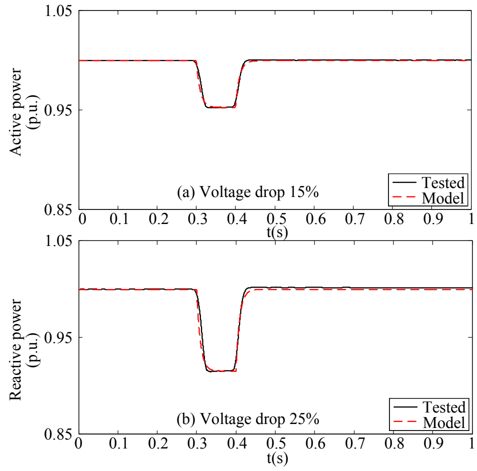

Figure 4. Power response curves of the model.

5.2 Generalization performance of URT model

The three samples in Table 1 correspond to that the grid voltage drops are 15%, 20% and 25% respectively. The No. 2 is chosen as the training sample to obtain the mode parameters via system identification. Then, the obtained parameters are used to fit the other two samples, and the fitting effect means the generalization performance of the URT model. To fit the No .1 and No. 3 using the No .2’s parameters are called interpolation and extrapolation performance, respectively. The interpolation and extrapolation performance of URT model is shown in Figure 5.

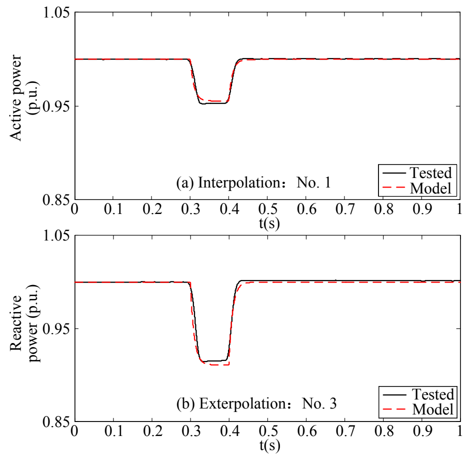

Figure 5. Generalization performance of the model.

As shown in Figure 5, the No.2’ parameters can well fit the No. 1 and No. 2. The average fitting errors of interpolation and extrapolation performance are 0.000846 and 0.0016, respectively, which can be acceptable for load modeling. Therefore, the model has good generalization performance.

5.3 Discussion

1) Adaptability of model. At present, the application of BES focuses on the active power regulation of power grid or wind/PV station, such as energy storage frequency modulation, peak load shifting, and stabilizing the power fluctuation of distributed power supply. For power system load modeling, when considering the distribution network with BESS, BESS is generally regarded as a part of the generalized load, of which model is combined with the traditional load model to form a generalized composite load model. Thus, the BESS model studied in this paper is based on the scenario when the grid power factor equals 1. Besides, although the proposed mode is based on load modeling, it can be applied to other power system transient simulation.

2) Physical meaning of model parameters. This model contains three parameters, in which U represents the equivalent voltage source with the same phase as the grid voltage; R represents the impedance between the equivalent voltage and the grid voltage; T is not a general conceptual electrical parameter, but a time constant, which simulates the inertia characteristics of the whole BESS. Therefore, the UTR model is a semi-mechanism dynamic model.

3) Influence of control objects on model performance. In this paper, the modeling BESS is based on the given power, while the given variable is current, the BESS has different dynamic characteristics, of which external performance is a constant current source. Therefore, the URT model is not applicable to the BESS whose the given is current.

6 Conclusions

Energy storage battery plays an important role in smart grid. It is very important for accurate simulation of power system to study the dynamic model of BESS which is suitable for the generalized load modeling for the distribution network side. In view of the need of generalized load modeling, the simulation platform of BESS is constructed based on MATABLE/Simulink. From the perspective of generalized load, a dynamic model of BESS based on the external characteristics equivalent is proposed, and thereby the following three conclusions are drawn.

1) Under the constant power as the given condition, on the one hand, the dynamic characteristics of BESS do not conform to the constant power characteristic, and the output is nonlinear; on the other hand, it does not conform to the characteristics of the constant voltage source, and has inertia from the point of view of the grid.

2) When the grid voltage drop occurs at the grid-connected bus, the change of the port voltage of the battery group is very small, which can be considered basically unchanged, while the port current increases slightly, and the output power decreases but the internal loss of battery group increasing.

3) The URT model is simple in structure and less in parameters. The variation trend of grid-connected current caused by the change of the grid voltage is simulated from the power grid standpoint, and the inertia characteristic of BESS relative to power grid is also considered. Therefore, the model can well describe the dynamic behavior of BESS and can be applied to the load modeling for the distribution network side.

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