The Role of Mathematical Model of Energy Storage by Power Systems Computer Aided Design / Electromagnetic Transients including DC in Power Energy Security Control

Haoning Yang *
North China Electric Power University, Baoding, China
*Corresponding author e-mail: 330242344@qq.com

Abstract. In order to discuss the application of energy storage system in power energy control, in this study, the energy storage system in small wind power generation system is taken as the research object, and the converter mathematical model in the energy storage system is built. Meanwhile, in the control state of grid-connected operation, the energy storage system is analyzed and a Power Systems Computer Aided Design / Electromagnetic Transients including Direct Current (PSCAD/EMTDC) simulation model based on Power Quality (PQ) control and Space Vector Pulse Width Modulation (SVPWM) mode is built. And when Insulated Gate Bipolar Transistor (IGBT) fails on the upper bridge arm of A-phase Alternating Current (AC) converter in the energy storage system, the changes of AC voltage, AC current, active power, and reactive power in the system and simulated. The results show that the simulation model of energy storage system established by PSCAD/EMTDC is feasible under the PQ control of grid-connected operation. In addition, fault analysis shows that the current conduction of A phase is delayed in the negative half wave, and there is a positive Direct Current (DC) bias, but the distortion of current of B phase and C phase is not significant. And the active power and reactive power remain within the set reference range. Therefore, it is possible to determine the failure of the converter IGBT of the energy storage system by whether or not the three-phase current on the AC side of the energy storage system has a DC offset. This study aims to provide theoretical basis for the follow-up fault diagnosis and system protection of the energy storage system.

Keywords: Energy storage system; Converter; Grid-connected operation; PQ control; PSCAD/EMTDC.

1. Introduction
Energy is an important means of production in today's industrial development and the cornerstone of social development [1]. In today's society, people's demand for electric energy is increasing, and there are new requirements for the quality and security of electric energy. Traditional power system uses fossil energy to generate electricity in a centralized way, which causes high carbon emissions and consumes a large amount of fossil energy, so as to result in serious problems such as environmental pollution and energy destruction. Therefore, the development of solar energy, wind energy, and other renewable
energy sources has great potential [2-4]. With the application of solar energy and other renewable
energies, the traditional centralized power grid is forced to transform to the intelligent power generation
mode of renewable energy and energy storage system [5]. Wind power generation system, as a kind of
renewable energy, can operate in two ways: grid-connected and off-grid. In the presence of public power
grid, grid-connected wind power generation can alleviate the contradiction of power supply demand in
this region [6]. But in cases where there is no continuous wind or the wind power is insufficient to drive
the blades of the wind system, other solutions need to be found.

Energy storage system can be applied in the production, transmission, and distribution of electric
ergy, which plays an important stabilizing role in the control of electric energy [7]. The energy storage
system can be used as the backup power supply for power system transmission, provide reactive power
compensation, and regulate the voltage of the power system in the process of power transmission.
Energy storage system is of great significance to improve the reliable operation of power system network.
The energy storage of the battery in the energy storage system is discharged by the redox reaction of the
positive and negative electrodes of the battery, which is widely applied in small distributed power
generation. The primary control methods of energy storage systems are PQ control, droop control, and
voltage Vf control, among which PQ control is the most widely applied.

In this study, the mathematical model of the converter in the energy storage system is introduced, a
small wind power model containing an energy storage system is built, the IGBT fault of the converter
in the energy storage system is analyzed qualitatively, the fault simulation model is constructed, and the
changes of AC voltage, AC current, active power, and reactive power when the converter fails in the
energy storage system are studied.

2. Method

2.1. Application of Energy Storage System in Electric Energy Control
Micro-grid is a small distribution system constructed by distributed power generation devices, energy
storage batteries, energy conversion devices, and other systems. Energy storage battery has nonlinear
capacity effect in the discharge process of micro grid, which is composed of positive pole, negative pole,
and electrolyte. As the discharge rate of some energy storage batteries increases, the concentration
gradient inside the battery would be more obvious, which would also accelerate the decrease of the
available capacity and voltage at both ends of the battery, as shown in figure 1. It can be concluded that
at the discharge rates of 0.5 C, 1.0 C, 1.5 C, and 2.5 C, the available capacity in the battery decreases
continuously, and the terminal voltage also decreases gradually.

![Figure 1. Relationship between different discharge rates, available capacity, and terminal voltage of energy storage batteries](image-url)
2.2. Mathematical model of AC energy storage system

Energy storage technology is very limited in the practical application of electric power engineering. It is often operated in the form of small-scale storage battery or pumped energy storage power station. As an important electrical energy conversion device in the system, the energy storage converter is the key link connecting the DC energy storage part and the AC power grid part. The energy storage system usually adopts voltage source converters, as shown in figure 2.

![Figure 2. Structure of the converter of the battery energy storage system](image)

As shown in figure 2, on the AC side, $U_a$, $U_b$, and $U_c$ are three-phase symmetrical phase voltages, $I_a$, $I_b$, and $I_c$ are three-phase currents, $R$ is the equivalent resistance, and $L$ is the filter inductor. In the DC side, $C$ is the parallel capacitor, $E$ is the electromotive force, and $U_{dc}$ is the voltage. The DC voltage can be regarded as equal to the DC electromotive force, so the circuit equation of the energy storage system in the three-phase static coordinate system can be written as follows.

$$
\begin{align*}
U_{sa} &= L \frac{di_{sa}}{dt} + R \cdot I_{sa} + v_a \\
U_{sb} &= L \frac{di_{sb}}{dt} + R \cdot I_{sb} + v_b \\
U_{sc} &= L \frac{di_{sc}}{dt} + R \cdot I_{sc} + v_c
\end{align*}
$$

(1)

The existing three ways can control the energy storage system, but PQ control is often adopted in the grid-connected operation. PQ control can control the power of the energy storage output system, realize independent control of active and reactive power through the control between the outer power loop and the inner current loop, and keep consistent with the power value of the system. When the energy storage converter is connected to the grid, the instantaneous voltage and current at the outlet of the system can be converted to the instantaneous voltage and current in the three-phase static coordinate system, and then the active and reactive power can be controlled through the control of the outer power loop and the inner current loop.

Under the PQ control of the energy storage system, the PI control expression of the external power loop is as follows.

$$
\begin{align*}
\Delta P &= P_{ref} - P \\
\Delta Q &= Q_{ref} - Q \\
i_{dref} &= k_p \cdot \Delta P + k_i \int_0^t \Delta P dt \\
i_{qref} &= k_p \cdot \Delta Q + k_i \int_0^t \Delta Q dt
\end{align*}
$$

(2)
Among them, $\Delta P$ is the difference between the reference value of active power and the actual value, $\Delta Q$ is the difference between the reference value of reactive power and the actual value, $\text{Pref}$ is the reference value of active power, $\text{Qref}$ is the reference value of reactive power, $id_{ref}$ is the current reference value of active power controlled by PI, $iq_{ref}$ is the current reference value of the reactive power after PI control, and $k_p$ and $k_i$ are the control parameters of the power outer loop.

The PI control expression of the current inner loop is as follows.

$$
\begin{align*}
\Delta i_d &= i_{d,ref} - i_d \\
\Delta i_q &= i_{q,ref} - i_q \\
v_d &= U_d + \omega Li_d - \left(k_p' \cdot \Delta i_d + k_i' \cdot \int_0^t \Delta i_d dt \right) \\
v_q &= U_q - \omega Li_d - \left(k_p' \cdot \Delta i_q + k_i' \cdot \int_0^t \Delta i_i dq \right)
\end{align*}
$$

(3)

id and iq are components of direct axis and quadrature axis of three-phase AC current in the static coordinate system, $U_d$ and $U_q$ are voltages, $v_d$ and $v_q$ are the voltage at the outlet of the energy storage converter, and $k_p'$ and $k_i'$ are the control parameter of current inner loop.

The PQ control framework of active and reactive power in the complete energy storage system is shown in figure 3.

Figure 3. Frame diagram of PQ control of converter of battery energy storage system

2.3. Establishment of wind power generation system based on energy storage system

In the past, wind power plants were generally located in remote deserts or border areas, but now more and more wind power systems are applied in urban street lighting, weather stations, and other fields. However, the wind power is greatly affected by the weather. When there is no continuous wind or the wind speed is low, the wind power system will be cut off, which will affect the normal use of the system. This problem can be solved by installing energy storage devices to wind power generation system to achieve the purpose of continuous power supply. Small wind power systems that use a mixture of batteries and supercapacitors include wind turbines, generators, rectifiers, Boost converters, energy storage systems, and load shedding parts. The system adopts the DC bus structure, which is characterized by strong expansion. Supercapacitors can increase the output power of the system. When the load is pulsating, it is possible to provide corresponding power to increase the service life of the battery. The wind energy utilization factor can be expressed by the following formula:

$$
C_p = 0.22 \left( \frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{\frac{12.5}{\lambda}} \\
\lambda_i = \left( \frac{1}{\lambda + 0.08\beta} \right)^{-1}
$$

(4)
Among them, $C_p$ is the wind energy utilization coefficient, which is used to evaluate the energy conversion efficiency of wind turbines, $\beta$ is wind pitch angle, $\lambda$ is the tip velocity ratio, and $\lambda_i$ is the optimal tip velocity ratio.

2.4. Establishment of simulation model of energy storage system based on PSCAD/EMTDC

The energy storage system in the small wind power system is simulated with PSCAD/EMTDC software. PSCAD/EMTDC is a simulation tool for power system analysis, which can simulate the best instantaneous event. The tool has Matlab interface, real-time Plot curve display and user-defined functions, and can support subnet nesting and other features. In this study, PSCAD/EMTDC tool is used to build the simulation model of grid-connected operation of energy storage system including AC system, DC power supply, and converter bridge. The AC system in the energy storage system uses three-wire symmetric power source for simulation, while the DC energy storage system uses DC power source for simulation, and the VSC AC bridge is based on the commutator bridge. Moreover, the circuit control in the energy storage grid-connected operation system is composed of phase lock link, coordinate system conversion link, and PI control link, among which the PI control link model of double-loop decoupling is shown in figure 4.

Simulation parameters include AC power grid frequency of 50Hz, voltage of 10kV, rated capacity of transformer of 1MVA, the rated voltage of 380V at the outlet of the energy storage converter, the resistance of 0.01Ω per phase on the AC side, the inductance of 0.8mH, and the DC voltage of 750V. The reference value of the initial active power is 0.3 MW, and it changes to -0.2 MW at 0.5 s, and changes to 0.2 MW at 1.5 s. The initial reference value of reactive power is 0.1 Mvar, which changes to -0.1 Mvar at 1.0s. The total simulation time is 2.0 seconds and the step size is 25 μs.

![Figure 4. Double loop decoupling PI control model of battery energy storage system](image)

2.5. Fault diagnosis of converters for battery energy storage systems

When the battery energy storage system in the small wind power generation system fails, it may cause the operation obstacle of the whole system. However, the failure probability of converter IGBT in battery energy storage system is relatively high, which is mostly caused by such factors as poor wiring or system overheating and damage. The structure of common battery energy storage system converter is shown in figure 2. Taking IGBT valve VT1 as the research object, AC Isa can circulate VT1 valve when the converter of energy storage system works normally. Isa is greater than 0, but when the VT1 valve is broken, Isa will circulate the anti-parallel diode of the valve and the VT4 valve. If Isa is less than 0, the current will only pass through the anti-parallel diode of VT4 valve. At this time, the waveform of Isa will be changed, so that the waveform of AC current will be changed, and the A-phase current...
will show positive DC bias. Since the sum of the current of phase A, phase B, and phase C is 0, after the bias of phase A current, the current of phase B and phase C will also show negative DC bias.

When the converter IGBT valve VT1 fails, the A-phase current Isa is greater than 0 to circulate in the anti-parallel diode, resulting in the A phase passing only 1/2 cycle in one power frequency cycle.

2.6. Establishment of converter fault model of energy storage system based on PSCAD/EMTDC

According to the energy storage battery system, a simulation model of the battery energy storage system is built in PSCAD/EMTDC platform, and the failure of converter IGBT in the energy storage system is simulated and analyzed. The set simulation parameters are as follows: the rated power of the converter is 500kW; the energy storage system uses the SVPWM control strategy, in which the power uses the PQ control method; the phase resistance of each phase on the AC side is 0.01Ω, the inductance is 0.8mH, and the DC voltage is 750V, the external voltage of AC is 10.5kV, the total duration of the simulation experiment is 1.0s, the power is 0.2MW, the reactive power is 0, and IGBT fault occurs at 0.5s after the start of the simulation experiment.

3. Results and discussion

3.1. Verification of simulation model of energy storage system based on PSCAD/EMTDC

PSCAD/EMTDC platform is used to verify the simulation model of energy storage system established in the early stage. It can be observed from figure 5 that when the reference value of effective power or invalid power changes in the simulation of grid-connected operation of energy storage system, the actual power would also change correspondingly, but it would soon be consistent with the reference value and respond to the power. This shows that the PQ control of the energy storage system built in the early stage is very feasible.

3.2. Validation of converter fault model of energy storage system based on PSCAD/EMTDC

When the IGBT valve VT1 of the upper bridge arm of the A phase of the converter of the energy storage system fails, the AC voltage, the AC current, the active power, and the reactive power in the energy storage system may change accordingly. It can be observed from figure 6A that when IGBT valve VT1 of the upper bridge arm of the A phase of the converter in the energy storage system fails, the waveform of AC voltage remains stable and would not change. As can be observed from figure 6B, the waveform of the alternating current is changed. The conduction of the current in phase A is delayed in the negative half wave, and the average value of the current in A phase is positive within a period of waveform, indicating that the current in A phase has a positive DC bias at this time. The flow time of B phase and C phase currents in the negative half wave is longer than that before the fault, and the amplitude of the waveform also increases, but the distortion is not big.

Figure 5. Waveform diagram of active power and reactive power of energy storage system

Figure 6. Waveform diagram of AC voltage and current of energy storage system

3.2. Validation of converter fault model of energy storage system based on PSCAD/EMTDC

When the IGBT valve VT1 of the upper bridge arm of the A phase of the converter of the energy storage system fails, the AC voltage, the AC current, the active power, and the reactive power in the energy storage system may change accordingly. It can be observed from figure 6A that when IGBT valve VT1 of the upper bridge arm of the A phase of the converter in the energy storage system fails, the waveform of AC voltage remains stable and would not change. As can be observed from figure 6B, the waveform of the alternating current is changed. The conduction of the current in phase A is delayed in the negative half wave, and the average value of the current in A phase is positive within a period of waveform, indicating that the current in A phase has a positive DC bias at this time. The flow time of B phase and C phase currents in the negative half wave is longer than that before the fault, and the amplitude of the waveform also increases, but the distortion is not big.
It can be observed from figure 7A and 7B that when IGBT valve failure occurs in the converter of the energy storage system, the active power and reactive power in the system would show a corresponding but very small periodic fluctuation. It can be considered that the active power and reactive power are in a relatively stable state and remain within the range of the specified power value.

4. Conclusion
In this study, the energy storage system in the small wind power generation system is taken as the research object, the control strategy of the energy storage system under the grid-connected operation is discussed, and the control of the energy storage system is realized based on PQ control and SVPWM mode. The characteristics of the converter fault of the energy storage system are analyzed, and the simulation model of IGBT fault of AC of energy storage system is built by PSCAD/EMTDC software. The results show that the energy storage system is feasible, and the fault position of the converter IGBT of the energy storage system can be located through whether the three-phase current on the AC side of the system has DC bias. This study aims to provide a theoretical basis for the fault diagnosis of the subsequent energy storage system and the protection of the system.

References
[1] Wang Q, Kim M, Shi Y, et al. Predict brain MR image registration via sparse learning of appearance and transformation. Medical image analysis, 2015, 20(1), pp. 61-75.
[2] Verdugo C, Candela J I, Blaabjerg F, et al. Three-Phase Isolated Multi-Modular Converter in Renewable Energy Distribution Systems. IEEE Journal of Emerging and Selected Topics in
[3] Zhu Z, Hua L. Do subsidies improve the financial performance of renewable energy companies? Evidence from China. Natural Hazards, 2019, pp. 1-16.

[4] Kamran M. Current status and future success of renewable energy in Pakistan. Renewable & Sustainable Energy Reviews, 2018, 82, pp. 609-617.

[5] Rehmani M H, Reisslein M, Rachedi A, et al. Integrating Renewable Energy Resources Into the Smart Grid: Recent Developments in Information and Communication Technologies. IEEE Transactions on Industrial Informatics, 2018, (99), pp. 1-1.

[6] M’Zoughi F, Bouallégue S, Garrido A J, et al. Stalling-Free Control Strategies for Oscillating-Water-Column-Based Wave Power Generation Plants. IEEE Transactions on Energy Conversion, 2018, 33(1), pp. 209-222.

[7] Pradhan S, Murshid S, Singh B, et al. Performance Investigation of Multifunctional On-Grid Hybrid Wind-PV System with OASC and MAF Based Control. IEEE Transactions on Power Electronics, 2019, (99), pp. 1-1.