

# A novel superconducting magnetic energy storage system design based on a three-level T-type converter and its energy-shaping control strategy

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## ABSTRACT

Superconducting magnetic energy storage (SMES) has been widely used to stabilize the power fluctuations of wind farms to achieve efficient grid connections. However, conventional converters can rarely satisfy the high power quality requirements of a power grid. Compared to other converters, a three-level T-type converter (3LT<sup>2</sup>C) can improve the output performance and operating efficiency of a system and reduce the voltage stress and conduction loss of power switches. Therefore, the 3LT<sup>2</sup>C has broad application prospects for electric power storage. A precise control strategy is also necessary for the practical application of an SMES system, which has significant nonlinear dynamic characteristics. Energy-shaping (ES) control is a nonlinear control method that is based on the theoretical design of interconnection and damping assignment (IDA), which considers both the nonlinear nature of a system and the energy perspective. This study proposes an ES control strategy for an SMES system based on a 3LT<sup>2</sup>C. Mathematical models and port-controlled Hamiltonian (PCH) models of the SMES system are established. The ES control strategy of the SMES system is designed based on a feedback interconnection structure through analysis of the novel SMES topology. Finally, the effectiveness of the control strategy and the proposed topology are verified through simulations.

## 1. Introduction

Superconducting magnetic energy storage (SMES) systems, which combine superconductor and power electronic devices, achieve fast energy conversion as power regulating systems. SMES systems have broad application prospects in future power systems because they have a more rapid power response and higher power density than conventional energy storage systems [1,2]. Because SMES systems are usually connected in the grid connection point of new energy power generators, the output current must meet the high power quality requirements of the power system. However, existing research can hardly solve the power quality problem of the SMES converter; therefore, it is necessary to perform SMES research based on its novel control strategy and topology.

SMES systems have the characteristics of multiple variables, nonlinearity and strong coupling during operation, and their control performance greatly impacts the system stability. The most common proportional-integral-derivative (PID) control [3,4] is a type of linear control, which does not require an accurate system model but is highly sensitive to parameter variations; therefore, PID control cannot be applied to complex nonlinear systems. Nonlinear control does not neglect

the system nonlinearity and, thus, can easily obtain global stability and better robustness. Dynamic feedback linearization requires the entire state of the system to be observable; it cannot effectively adapt to parameter variations or external interference [5–7]. Sliding mode variable structure control must solve the chattering problem near the sliding plane caused by the discontinuous control law [8,9]. The robustness of backstepping control is relatively poor, and the computational requirements are considerable [10,11]. Fuzzy logic control is highly robust; however, it lacks a systematic method for establishing the fuzzy rules and has low steady-state precision [12,13]. Model predictive (MP) control is an intuitive control approach that does not require linear controllers and modulators, and nonlinearities and restrictions can easily be included in the control law. However, research on MP control is still immature and requires further progress [14–16]. These nonlinear control methods do not consider the internal or external interconnection structure of the system. The passive control theory states that a passive system will eventually run to the lowest energy point due to its dissipation. Energy shaping (ES) is a control process used to stabilize the system at the expected equilibrium point by injecting external energy into the controlled system. Romeo Ortega and Arjan van der Schaft first proposed the interconnection and

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damping assignment passivity-based control (IDA-PBC) method [17–20], which preserves the advantage of state-modulated control method [17] and avoids introducing the Casimir function. In the IDA-PBC method, the port-controlled Hamiltonian (PCH) equations should be established first to describe the structure of the controlled system. Then, the control input can be easily obtained by solving the energy equation. Low control complexity is a significant advantage of the IDA-PBC method; therefore, it can conveniently provide energy shaping. By considering both the nonlinear nature of a system and the energy perspective, ES control can achieve better control performance than conventional linear and nonlinear control. ES control based on the PCH model has been widely used in robotics [21], PWM rectifiers [22], double-fed wind power systems [23–25], and battery energy storage systems (BESSs) [26]. Because SMES is a passive system, the converter and chopper can be regarded as energy conversion devices in the ES control strategy. The internal and external interconnected structures are studied to reveal the energy flow trends. There is currently a lack of research on using the ES control strategy for SMES systems; therefore, applying ES control to SMES systems has practical significance, based on the nature of nonlinear systems.

Multilevel converters, which overcome the many disadvantages of traditional two-level converters (e.g., the high voltage stress of the power switches and large harmonic output current), have been widely used in high voltage and high power situations [27,28]. In 2007, Knaup proposed the three-level T-type topology, which has fewer switching tubes, more uniform power dissipation and greater efficiency than the traditional neutral point clamping (NPC) three-level topology; therefore, the topology has become a focus of research for applications of three-level converters [29–32]. The three-level T-type topology is primarily used in grid-connected inverters; however, to date, no studies have used this topology to energy storage systems with bidirectional energy transmission. Therefore, there is practical significance to applying the three-level T-type topology to SMES systems with a high power density to improve the systems' output characteristics. However, NP potential is involved in the energy conversion process of the three-level converter, leading to imbalances in the DC-side capacitor voltage and reducing the operating reliability of the converter. Ref. [33] used a variable zero-sequence voltage to balance the NP potential. Modified space vector pulse-width modulation methods were presented in Refs. [34,35]. These methods may require complex calculations for SMES systems based on a three-level T-type converter (3LT<sup>2</sup>C). However, an improved space vector modulation method for a Z-source three-level T-type inverter, which simplifies the space vector diagram and effectively achieves NP potential balance, was proposed in Ref. [36]. A similar approach is used to maintain the NP voltage balance of the SMES system based on the three-level T-type topology.

This study proposes a new topology and control strategy for SMES systems to improve their output performance and control effect. The circuit configuration, mathematical model, control scheme, and computer simulation are presented.

## 2. Topology and model of the proposed SMES system

### 2.1. Mathematic models of SMES systems

The proposed SMES topology, based on the three-level T-type topology, is shown in Fig. 1. The converter of the SMES system consists of a 3LT<sup>2</sup>C and a chopper. The 3LT<sup>2</sup>C is used to transfer the energy between the AC side and the DC side of SMES. The superconducting magnet charges and discharges through the bidirectional chopper to maintain a stable DC-link voltage.

The three-phase voltages of the grid are expressed as  $e_a$ ,  $e_b$  and  $e_c$ ; the three-phase currents of the converter are expressed as  $i_a$ ,  $i_b$  and  $i_c$ ; the DC-side capacitor voltages are expressed as  $U_{dc1}$  and  $U_{dc2}$ ;  $L_{sc}$  represents the inductance value of the magnet;  $i_{sc}$  represents the current of the magnet; and  $C_1$  and  $C_2$  are the values of the two DC-side

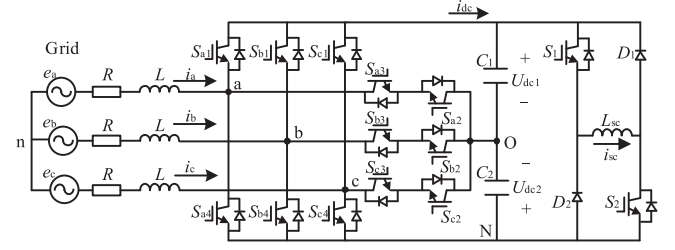


Fig. 1. Topological structure of the proposed SMES system.

capacitors.

In this research, the ES control method used in the current loop of the SMES system is proposed to contain both AC-side 3LT<sup>2</sup>C and DC-side chopper for robust improvements. The establishment of the mathematical model for the 3LT<sup>2</sup>C-based SMES system is the basis of the design of the ES control method; therefore, the mathematical model of SMES will be described in detail, as follows.

Each phase bridge arm of the 3LT<sup>2</sup>C contains four switching tubes. The status of the switching tubes can be expressed as  $S_{xn}$ , ( $x = a, b, c$ ;  $n = 1-4$ ). The insulated gate bipolar transistors (IGBTs) on the bridge circuit of each phase,  $S_{x1}$  and  $S_{x3}$ , as well as  $S_{x2}$  and  $S_{x4}$ , are complementary to one another.  $S_{x1}$  and  $S_{x4}$  cannot be turned on simultaneously. The switch state can be expressed as

$$S_x = \begin{cases} 2, U_{xO} = U_{dc}/2, (S_{x1}, S_{x2}, S_{x3}, S_{x4}) = (1, 1, 0, 0) \\ 1, U_{xO} = 0, (S_{x1}, S_{x2}, S_{x3}, S_{x4}) = (0, 1, 1, 0) \\ 0, U_{xO} = -U_{dc}/2, (S_{x1}, S_{x2}, S_{x3}, S_{x4}) = (0, 0, 1, 1) \end{cases}, \quad (1)$$

where  $U_{dc}$  is the DC-side voltage of the converter.

Then, the voltage between the point  $x$  and the DC negative can be represented as

$$U_{xO} = (S_x - 1)U_{dc}/2. \quad (2)$$

By applying Kirchhoff's law, the mathematical model of the AC-side 3LT<sup>2</sup>C in abc reference frame can be expressed as

$$\begin{cases} L(di_a)/dt + Ri_a = e_a - (U_{aO} + U_{On}) \\ = e_a - \frac{U_{dc}}{2} \left( S_a - 1 - \frac{1}{3} \sum_{x=a,b,c} (S_x - 1) \right) \\ L(di_b)/dt + Ri_b = e_b - (U_{bO} + U_{On}) \\ = e_b - \frac{U_{dc}}{2} \left( S_b - 1 - \frac{1}{3} \sum_{x=a,b,c} (S_x - 1) \right) \\ L(di_c)/dt + Ri_c = e_c - (U_{cO} + U_{On}) \\ = e_c - \frac{U_{dc}}{2} \left( S_c - 1 - \frac{1}{3} \sum_{x=a,b,c} (S_x - 1) \right) \end{cases}, \quad (3)$$

where  $R$  and  $L$  represent the value of AC-side resistance and inductor, respectively; and the voltage between DC neutral and grid neutral  $U_{On} = -U_{dc} \sum_{x=a,b,c} (S_x - 1)/6$ .

In Refs. [37–39], the most common modelling method for the voltage source converters (VSC) uses Park's transformation to eliminate the time-variant dependence of the dynamical system. The relevant transformation matrices can be expressed as

$$T_{abc/\alpha\beta} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}, T_{\alpha\beta/dq} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}, \quad (4)$$

where  $\theta$  is the angle between the d axis of the dq reference frame and the a axis of the abc reference frame, and the zero sequence has been neglected.

The following park transformation (5) can be applied to the abc

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