Electrical Power and Energy Systems 95 (2018) 275–286

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Implementing dynamic evolution control approach for DC-link voltage regulation of superconducting magnetic energy storage system

Trilochan Penthia [a,*], Anup Kumar Panda [a], Sunil Kumar Sarangi [b]

[a] Department of Electrical Engineering, National Institute of Technology Rourkela, India
[b] School of Mechanical Engineering, KIIT University, India

ARTICLE INFO

Article history:
Received 3 May 2017
Received in revised form 7 July 2017
Accepted 21 August 2017

Keywords:
Superconducting magnetic energy storage
Dynamic evolution control algorithm
Magnet voltage distribution
AC loss reduction
Power quality
System stability

ABSTRACT

A Dynamic Evolution Control (DEC) scheme for the Superconducting Magnetic Energy Storage (SMES) system is presented in this article. The DC-link voltage of Power Converter Unit (PCU) is strictly regulated by the proposed control scheme irrespective of load transients. In SMES system, the PCU interfaces the SMES magnet and the AC system in order to give an efficient power exchange, and high quality power flow in the grid. Especially, this paper focuses on power quality improvement, and homogeneous voltage distribution & AC loss reduction across the magnet by achieving excellent DC-link voltage regulation. The harmonic components of magnet current are analyzed which are responsible for AC losses. It has been observed that the 3rd, 4th, 5th, 6th and 7th order harmonic components of the magnet current are significantly reduced. Particularly, a homogeneous voltage profile and less distorted magnet current are attained using the control scheme. The system supply current is found almost balanced, and its Total Harmonic Distortion (THD) is found well below 5%. Moreover, the control performance of DEC scheme is compared with that of the Proportional-Integral (PI) control technique. The proposed system is validated both in MATLAB/SIMULINK and real-time environment using a digital signal processor (dSPACE1104).

1. Introduction

Nowadays, Superconducting Magnetic Energy Storage (SMES) field is a centre of attraction for many researchers because of its high efficiency, high energy density, excellent longevity ($>$ 30 years) and quick response to the power compensation [1,2]. Even there are many Energy Storage Systems (ESSs) available commercially, and they are being used for different applications [3,4]. The SMES and Super-Capacitor Energy Storage (SCES) device are the two alternatives for electrical ESSs. Often, the application of the SCES is restricted because of its high energy dissipation due to self-discharge loss, and other practical limitations [4]. Therefore, SMES is preferable for pulsed power, system stability, load leveling, and other large-scale applications [5,6]. Mainly, it ensures a stable operation, high quality power supply, and alleviates intermittency of Renewable Energy Sources (RES) in power systems [7,8]. Superconducting magnet (i.e. SMES magnet, preferably an HTS magnet is used) is the key component of SMES system. The magnet discharges its stored energy through Power Converter Unit (PCU) to the grid for the achievement of smooth and quality power flow at the Point of Common Coupling (PCC). However, the selection of suitable control algorithms for PCU is a tough job, because the performance of SMES system depends absolutely on its employed control techniques [9,10]. In addition to the point, the PCU involves high speed switching semiconductor devices which adversely affect the SMES magnet in terms of AC losses [11], and insulation failure between its windings [12].

AC losses occur in the SMES system as a result of variation in the operating current and magnetic field due to the charging or discharging of energy. The AC loss per unit time might be significantly higher than in normal conditions during a discharge process since a SMES is expected to react quickly in response to a grid incident, i.e., a quick discharge to maintain the grid stability. Hence, if the current is more distorted and rippled then the chances of AC losses across the magnet and PCU will be higher. A SMES magnet works in three modes of operation: charging, standby and discharging. Mostly, the magnetization loss occurs during charging and discharging mode whereas eddy current loss depends on some material structure and its thermal properties [13]. Specifically, presence of harmonic contents in the direct current (i.e. magnet current) cause AC losses in the magnet. It has been noticed that the presence of 5% second harmonic in the current increases loss by 1%

---

* Corresponding author at: Power Electronics Laboratory, Department of Electrical Engineering, National Institute of Technology Rourkela, Odisha 769008, India.

E-mail address: trilochankoraput@gmail.com (T. Penthia).

http://dx.doi.org/10.1016/j.ijepes.2017.08.022
0142-0615/

in normal metal, whereas this loss can increase to 20% in superconductors [14]. In this article, the PCU that handles the power flow between the magnet and the electrical grid is based on a Voltage Source Converter (VSC) and a DC-DC converter as illustrated in Fig. 1. Both the converters are coupled to a common DC-link capacitor. Variation of voltage across the capacitor (i.e. DC-link voltage) depends upon control strategy, switching modes, cooling plate designs and especially dynamic power exchange [13,15]. Presence of harmonic contents and oscillations in the DC-link voltage cause distortions in the direct current which circulates in the magnet windings. Consequently, AC losses take place not only in the magnet, but also across the converters. Furthermore, regulation of DC-link voltage is mandatory in order to get an excellent quality of power flow in the grid. The Proportional-Integral-Derivative (PID) controllers are the most widely used traditional control techniques ever. Many researchers choose the PI controller as their default plant error controller because of its price, ease of tuning, simplicity and user-friendly. Even the gain parameters of PI are auto-tuned with the help of heuristic optimization techniques to achieve a significant system response for mono-variable control tasks [16]. Further, adaptive control techniques are preferred over the traditional control techniques to enhance the performance of the system irrespective of system dynamics and complexity. Mostly, adaptive controllers are neuro-controller, and they are well known for their excellent adaptability, stability, high speed data processing and high convergence rate. Various traditional [16,17,10,9] and adaptive [11,18–21] control techniques have been implemented in the SMES system for the elimination of such ripple contents of direct current, and DC-link voltage regulation.

In general, the PCU adopts the Pulse Width Modulation (PWM) techniques with higher carrier frequencies (in order of Hz to kHz) to improve the dynamic performance of SMES system. Consequently, the output DC voltage of PCU contains high frequency with different steep edged pulse widths. The PWM voltage will be reflected and refracted due to mismatch of impedance between the converters and connecting cable when it propagates through the cable. High frequency and steep edged pulse width characteristic of the DC voltage cause undesirable oscillations at the magnet end and asymmetrical voltage distribution between magnet windings. The DC voltage with such unwanted characteristics devastates normal operation of magnet, magnet insulation and quench protection. Thus, the voltage profile of the SMES magnet should be considered during its insulation design. Moreover, the magnet voltage with oscillations and its asymmetrical distribution can be eradicated by considering appropriate control methods for PCU, cable properties and insulation design of magnet [1].

As from the above survey, the AC losses and voltage distribution of magnet windings are directly as well as indirectly related to the DC-link voltage profile of PCU. Therefore, reduction of AC losses and uniform voltage distribution of SMES magnet can be achieved by regulating the DC-link voltage. Specifically, this paper focuses on DC-link voltage regulation of PCU and its significant benefits to SMES system. In this work, a nonlinear control approach based on Dynamic Evolution Control (DEC) scheme [22,23] is proposed for tight DC-link voltage regulation. The main concern is the formulation of a control function for DC-DC converter to ensure the monitoring of direct current, and desired voltage distribution on and inside the magnet, even when the system is operating with inexact time varying load demands (i.e. load transients). On the other hand, the VSC adopts the popular Modified Synchronous Reference Frame (MSRF) method for its switching pulse generation as presented in the previous work [17]. Moreover, the DEC scheme is theoretically evaluated and validated with rigorous simulative and experimental analysis. It is performed thoroughly for tight regulation of DC-link voltage under load transients in order to achieve the AC losses reduction and uniform voltage distribution across the SMES magnet. Also, a high-quality power flow is attained by maintaining supply current balanced and harmonic free. Detailed modeling of SMES system and the DEC scheme are elaborated in Sections 2 and 3.

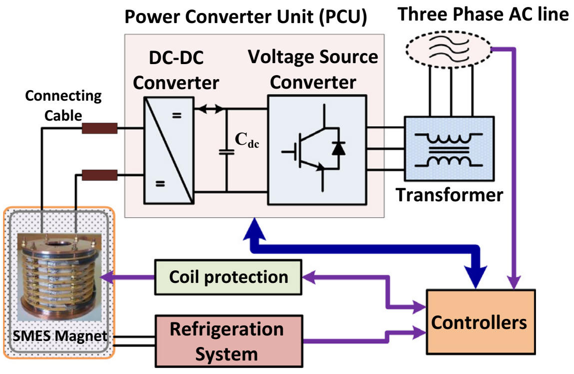

Fig. 1. Schematic block diagram of SMES system.

2. Modeling and design of SMES system

The configuration of the proposed PCU based SMES system, connected to the AC mains and parallel with the loading section as illustrated in Fig. 2. The PCU of the SMES system consists of a two-level VSC converter and a DC-DC converter. Both the converters are coupled with each other through a common DC-link capacitor. Insulated Gate Bipolar Transistor (IGBT) type switches are used in the converters because of its high efficiency and fast switching characteristics. Here, the source is assumed to be a balanced three-phase supply, connected to the loading unit. The loading unit is considered to be nonlinear loads.

The performance and feasibility of the SMES system depend on its circuit parameters. Therefore, the parameters of the system need to be designed carefully. The design of important parameters such as DC-link capacitor (C_{dc}), AC inductor (L_c), switching frequency of the IGBTs (f_{sw}) and equivalent inductance (L_{smes}) of the SMES magnet are already presented in the previous work [17]. Especially, prudent design of two crucial elements i.e. C_{dc} and L_{smes} of the system must be considered to ensure the AC loss minimization and uniform voltage distribution in the magnet irrespective of load transients. For a quick review, final expressions of the essential system design parameters are excerpted here. Suppose the SMES system is connected to an "X" kVA system and deals with a minimum of "$0.5X$" kVA and a maximum of "$2X$" kVA handling capability under dynamic loading condition for "n" cycles with a time period of "T". During such dynamic loading condition, with an increase in load demand, the voltage across the DC-link capacitor (V_{dc}) decreases and vice versa. Also, a maximum of 10% variation is allowed for DC-link voltage during such transient conditions, keeping in mind the voltage distribution and AC losses across the SMES magnet. The required mathematical expressions for the design of the parameters L_{smes} and C_{dc} are given as follows:

$$L_{smes} = \frac{\frac{8}{3}\left(2X - \frac{X}{2}\right)nT}{\left(i_{smes(\max)}\right)^2} \tag{1}$$

And,

$$C_{dc} = \frac{2\left(2X - \frac{X}{2}\right)nT}{\left[\{(1.05)V_{dc}\}^2 - \{(0.95)V_{dc}\}^2\right]} \tag{2}$$

Apart from the design of SMES system, the VSC and DC-DC converter need to be governed precisely in order to achieve a high-quality power flow at the PCC. Switching pulses (i_{g1}-i_{g6}) required