Development of Arduino Based Power Conditioning Unit for Superconducting Magnetic Energy Storage (SMES) System used as UPS for Load Leveling during Charging of Electric Vehicles

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Abstract. With the advancements in Electric Vehicle (EV) technology, more and more EVs are entering into service and simultaneously the number of charging stations are also increasing. These charging stations are connected to the EVs for a small duration of time. Hence, as the number of EVs increases, the simultaneous charging of multiple EVs generates a peak active power demand for this duration. The available peak load compensation technologies such as flywheel storage, pumped hydro storage or Battery Energy Storage System (BESS) take a long time to respond and are not very efficient. With an operational efficiency exceeding 90 % and quick reaction time (< 1 second), a Superconducting Magnetic Energy Storage (SMES) system can be a viable solution for this scenario. A SMES system generally consists of a superconducting coil system being charged during the low load/no load period and discharged during the peak demand, with the help of a power conditioning unit (PCU). This paper describes the development of various sub-systems of the SMES-PCU, such as a three-phase rectifier, bidirectional chopper unit, three-phase inverter and the controllers with a description of various modes of operation and sizing of components. The paper also includes the simulation of overall SMES-PCU with suitable assumptions, to present the operational characteristics of the integrated system.

1. Introduction

Electric Vehicles (EVs) are the future of road transportation. Each year, more and more EVs are manufactured and adopted worldwide. This rise in EV population is adding to the concern of increased load on the electric power grid. The potential impact of EVs on global energy systems [1] reports a rise in the peak load by above 30% with even 25% electric vehicle penetration by 2050. This will create huge stress on the generators as they are designed to be operated at a constant maximum output power [2] [3]. This brings into consideration energy storage systems to provide power during peak loading periods.

Conventional grid level energy storage systems include pumped hydro power plants and Battery Energy Storage Systems (BESS) with a few applications of flywheel energy storage [4], super-capacitor energy storage and Compressed Air Energy Storage (CAES) [5] [6]. All these energy storage systems are having very high specific energy density (> 100kJ/kg). However,
during transient power fluctuations, huge power is required to be pumped into the grid or extracted from it, which is not possible with these conventional technologies in lieu of their large actuation time [6] [8] (typically more than 1 second). Another disadvantage with these energy storage systems is their low conversion efficiency (70-80 %, except for the BESS which have 90 % efficiency [4] [6]).

Also, the penetration of EVs is not bound to be uniform as stated in McKinsey’s Geospatial Analytics forecast considering Germany as an example with 10% national penetration [1]. Local pockets with significant EV populations will emerge ensuing the need to distribute the load leveling systems rather than a centralized load leveling operation. Most of the conventional energy storage systems are area specific and thus, cannot be distributed as per the EV population density.

Considering all these shortcomings, a Superconducting Magnetic Energy Storage (SMES) system is the best available option. A SMES system has a typical energy density of about 10 kJ/kg. However, it has high specific power density of (>100 kW/kg) with a power transfer efficiency of more than 95% [4] [7], making it the most suitable energy storage system for mitigating transient power fluctuations in the grid. Also, the SMES systems can be highly modular [9], adding to a distributed energy regulation capacity.

This paper describes a possible strategy for load-leveling operation of the SMES system through simulation and with suitable assumptions. Section 2 describes the overview of the proposed SMES-PCU system with its various components. Section 3 presents a theoretical approach to coil design with calculation for its various parameters, considering stacked solenoid configuration for the magnetostatic analysis using COMSOL. Section 4 describes the MATLAB Simulink model for observing the load leveling operation of the SMES system. This is followed by results and discussions on the magnetostatic analysis of stacked solenoid and the observations of the MATLAB simulation for load leveling operation of SMES system; finally ending with conclusions and bibliography.

2. Overview of SMES-PCU system
The SMES-UPS system, as shown in Figure 1 comprises of - (a) superconducting coil (b) persistent switch/action (c) type-D chopper (d) DC-link capacitor (e) bidirectional converter (f) filter circuit (g) 3-Phase transformer and circuit breakers (h) controllers for bidirectional converter and chopper circuits and (i) refrigeration system

The superconducting coil is responsible for storing the excess energy available during base load operation, from the grid in the form of magnetic flux density (B) produced due to the flow of persistent current. This trapped energy can be calculated using equation (1)

\[ E = \frac{1}{2} LI^2 = \frac{1}{2\mu_0} \int_V B^2(x, y, z) \, dx \, dy \, dz \]  

where \( L = \) inductance of superconducting coil (H), \( I = \) persistent current flowing through the coil (A), \( B = \) volumetric flux density produced by the coil (T) and \( \mu_0 = \) permeability of free space = \( 4\pi \times 10^{-7} \) H m\(^{-1}\) [10]. This trapped energy is fed back to the grid during peak load when the superconducting coil discharges.

The chopper circuit is responsible to maintain a steady voltage across the DC-link capacitor by charging or discharging the coil. This is achieved by the chopper controller which accepts the DC-link voltage as feedback and accordingly switches on or off the chopper’s controlled switches to maintain this voltage at a steady value [11]. The bidirectional converter converts 3-phase AC voltage from the grid to DC, charging the DC-link capacitor in rectifier mode, during the base load period. On other hand, during peak load, bidirectional converter converts the DC voltage from the DC-link capacitor and feeds back 3-phase AC voltage into the grid in inverter/regeneration mode [12]. The converter controller performs the phase synchronization
and Sinusoidal Pulse Width Modulation (SPWM) generation to trigger the converter switches at specified times to obtain 3-phase AC Pulse Width Modulated (PWM) voltages [13]. The 3-phase AC PWM voltages are then passed through a 3-phase filter to remove the harmonics from the output and a sinusoidal output is fed to the grid [14].

The 3-phase transformer is responsible for stepping down the high voltage on the grid side to the low voltage on the converter side for rectification and stepping up the low voltage on the converter side to high voltage on the grid side during regeneration. The circuit breaker isolates the SMES system from the grid in case of occurrence of any fault within the SMES system. The refrigeration system maintains the temperature of the superconducting coil at the required level to ensure the rated current flowing through the coil without quenching it.

3. Parameter estimation for a stacked solenoid coil geometry

A solenoid made up of stacks of single HTS pancake coils is considered. The coil parameters are estimated assuming each stack is made up of concentric ampere turns with incremental circumference. The input parameters are the stack’s inner diameter ($\phi_i$), length of HTS tape available ($L$), tape thickness ($t$), tape width ($w$), insulation thickness ($t_i$), distance between two stacks ($d$) and number of stacks ($N_s$), as shown in figure 2.
Arithmetic progression is applied to the incremental circumference with common difference \((t+2ti)\) and the sum of the incremental circumferences equal to \((L)\), to obtain the number of turns \((N)\) using equation (2)

\[
N = \frac{(t + 2ti) - \left(\frac{\phi_i}{2}\right) + \sqrt{\left(\frac{\phi_i}{2}\right) - (t + 2ti)^2 - 4(t + 2ti)\left(\frac{\phi_i}{2}\right)}}{2(t + 2ti)}
\]

The outer diameter \((\phi_o)\) is calculated using equation (3)

\[
\phi_o = 2\left[\frac{\phi_i}{2} + N(t + 2ti)\right]
\]

and the height of the coil \((H)\) is given by equation (4)

\[
H = \left(N_s - 1\right)\frac{d}{2} + N_s(t + 2ti)
\]

The difference between \(\phi_o\) and \(\phi_i\) gives the span of the coil \((S)\).

4. MATLAB Simulink model for SMES-PCU

A MATLAB simulation was carried out to observe the load leveling operation of the SMES system when the grid is under overload. The Simulink model is shown in figure 3. In this, a 15 kW resistive load is connected and disconnected to the grid (3-phase 400V L-L, 50 Hz, 10 kW), between 0.02 to 0.12 seconds using timed switching of an ideal switch component, to simulate overload. The corresponding 3-phase grid voltage and current are observed under loaded as well as unloaded conditions.

![Image of the simulation model for SMES-UPS](image_url)

Figure 3. Image of the simulation model for SMES-UPS

The SMES system model consists of a superconducting coil modeled as an inductance \((L)\) of 282 mH, in series with a resistance \((r)\) of 0.01 Ω to represent the current lead and joint resistances. The coil current and voltage are measured. The type-D chopper circuit is modeled as per the schematic shown in figure 4, with \(S_1\) and \(S_2\) taken as IGBTs with on-state resistance \((R_{on})\) of 0.16 Ω and forward voltage \((V_f)\) of 2.3 V. The diodes have on-state resistance of \((R_D)\) of
0.03 Ω and forward voltage ($V_D$) of 1.19 V. The parallel RC snubber circuit for each diode has a resistance of 500 Ω and a capacitance of 250 nF. The DC-link voltage is fed back as a reference to the hysteresis band-type chopper controller where it is compared with a fixed reference voltage. If the difference between the actual voltage and the reference voltage is more than the upper threshold voltage, the IGBTs are turned on and current flows from the DC-link capacitor to the superconducting coil to charge it. Similarly, if the difference is below the lower threshold, the IGBTs are turned off and the coil discharges to charge the DC-link capacitor, provided $D_1$ and $D_2$ are forward biased. This way, the DC-link voltage is held at a steady value with a suitable tolerance for the ripple voltage.

Figure 4. Schematic of type-D chopper circuit

Figure 5. Schematic of Bidirectional converter circuit

A DC-link capacitance of 4700 µF with an ESR of 0.1 Ω is considered for the simulation. The bidirectional converter is modeled using IGBTs with reverse conduction diodes as shown in figure 5 and having a on-state resistance of 0.001 Ω. The controller for the bidirectional converter accepts 3-phase ac voltage from the grid. It is then passed through a Phase Locked Loop (PLL) to obtain the phase angle of the grid voltage. The phase angle from the PLL block is then sent to a MATLAB function generation block which generates 3 reference sine waves of unit amplitude each and a phase difference of 120° between any two signals. The reference waves are then passed through a modulator which essentially multiplies a gain value to the signals to produce 3-phase modulated reference signals. These modulated signals are then compared with a high frequency triangular carrier wave to produce the SPWM signals which are fed to the gate driver circuit. The output of the gate driver is fed to the upper and lower half switches of the bidirectional converter to generate 3-phase AC PWM voltage. The filter circuit is simply an L-type with an inductance of 100 mH and a series resistance of 0.1 Ω. The transformers are not considered in the simulation to reduce time.

5. Results and discussions

Stacked solenoid geometry with parameters as shown in table 1 are considered for magnetostatic analysis using COMSOL Multiphysics® v.5.3a, for two cases as shown in figure 6. It was observed that for the same geometrical parameters of solenoid, the inductance in the configuration with soft iron core and shielding was around 282 mH which is 47 times higher than 6 mH with air core. This allows for a linear increase in energy storage from 67 J to almost 3.2 kJ in the soft iron cored coil. Also, a decrease in magnetic flux penetration through the coil stacks was observed in the soft iron based configuration. This allows for an increase in the
operating current of the solenoid due to enhanced $J_c-B_c$ characteristics of the coil, which will further increase the energy storage capacity quadratically.

### Table 1. Coil parameters for Magnetostatic analysis using COMSOL Multiphysics

| Core Type | $\mu_r$  | ID (mm) | N  | $d$ (mm) | H (mm) | I (A) | Shielding | L (mH) | E (J) |
|-----------|----------|---------|----|----------|--------|-------|-----------|--------|-------|
| Air       | 1        | 50      | 383| 8        | 112.3  | 150   | absent    | 6      | 67.3  |
| Soft iron | 1000     | 50      | 383| 8        | 112.3  | 150   | present   | 282    | 3169.5|

**Figure 6.** Magnetostatic analysis of stacked solenoid-(a) with air core (b) with soft iron core, shielding and air gaps

Further, from the MATLAB simulation of the SMES-PCU circuit, it was observed that the chopper current and voltage are following the gate pulses in the correct order for the charging and discharging cycles of the superconducting coil (figure 7). Also, a drooping characteristic of the coil current is observed, maintaining the dc link voltage at a steady level even under load.

**Figure 7.** Charging discharging characteristics of type-D chopper and coil current
However, there is an absence of effective dynamic regulation of DC-link voltage due to sluggish nature of hysteresis band controller for chopper control in this application. This results in limited voltage regulation as is clear from figure 9 showing load characteristics of the grid with and without SMES system. However, a decrease in the current amplitude from 45 A without SMES system to around 40 A with SMES system connected to the grid is observed. This established the reduced dependence of the load on the grid. Thus, the SMES system is participating in the load leveling operation of the loaded grid, the effectiveness of which can be improvised by inclusion of a current control algorithm in parallel with the hysteresis band controller based voltage control of the chopper circuit.

Added to this, the grid voltage contains harmonics which motivates the optimization of output filter and development of a persistent switch/action to prevent the coil from discharging when the grid is not loaded.
6. Conclusions
Magneto-static analysis of stacked HTS solenoid using COMSOL shows an enhancement in the inductance and energy storage of the solenoid by 47 times with soft iron core and shielding. Also, the reduced flux penetration with this configuration further allows for more current to be passed through the superconducting coil.

MATLAB simulation of SMES system shows that coil current and voltage follow the operating modes of the type-D chopper. Drooping characteristics of the coil current was observed indicating the discharging of coil to maintain the dc link voltage. Regulation of the grid voltage under load with and without SMES system has been established with limited effectiveness. Nevertheless, a reduction in the load current amplitude by around 11.11 % is observed with SMES system integrated with the grid. This indicates that the SMES system is participating in the load leveling operation. However, it couldn’t be captured effectively due to sluggish nature of the Hysteresis band controller alone. A parallel current control algorithm may enhance the performance of system, which must be taken up as a future work.

Nevertheless, grid voltage synchronization algorithm is working as per requirement. But the appearance of harmonics in grid voltage necessitates the design of a better input/output filter for the bi-directional converter and a persistent switch for the superconducting coil.

7. References
[1] www.mckinsey.com, “The potential impact of electric vehicles on global energy systems”, (2018). [Online]. Available: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-potential-impact-of-electric-vehicles-on-global-energy-systems.
[2] T.Nitta, Y.Shirai and T.Okada (1985), “Power charging and discharging characteristics of SMES connected to artificial transmission line”, IEEE Transactions On Magnetics, Vol. Mag-21, Nn. 2
[3] M. H. Ali, B. Wu and R. A. Dougal (2010), “An Overview of SMES Applications in Power and Energy Systems”, in IEEE Transactions on Sustainable Energy, vol. 1, no. 1, pp. 38-47.
[4] C.K. Das, O. Bass, G. Kothapalli, T.S. Mahmoud, D. Habibi (2018), “Overview of energy storage systems in distribution networks: placement, sizing, operation, and power quality”, Renew Sustain Energy Rev, 91 , pp. 1205-123. doi: 10.1016/j.rser.2018.03.068
[5] Chapter-9, “Emergency supply equipment”,[Electrical Systems and Equipment (Third Edition)], (1992).
[6] Moller, Kasper & Jensen, Torben & Akiba, Etsuo & Hai-Wen, Li. (2017). “Hydrogen - A sustainable energy carrier”, Progress in Natural Science: Materials International. 27. doi: 10.1016/j.pnsc.2016.12.014.
[7] K. E. Nielsen and M. Molinas (2010), “Superconducting Magnetic Energy Storage (SMES) in power systems with renewable energy sources”, IEEE International Symposium on Industrial Electronics, 2010, pp. 2487-2492. doi: 10.1109/ISIE.2010.5637892.
[8] McKerracher, R.D.Ponce de Leon, C. Wills, R.G.A. Shah, A.A. and Walsh, F.C., (2015) “A Review of the Iron-Air Secondary Battery for Energy Storage”, ChemPlusChem, 80: 323-335. doi: 10.1002/cplu.201402238
[9] J. Zheng, S S Peng, W Y Li, Y J Dai. (2019) “Magnet design of 10 MJ multiple solenoids SMES”, IOP Conference Series: Earth and Environmental Science, Volume 233, Issue 3, pp. 032026.
[10] Tixador, P. (2012), “Superconducting magnetic energy storage (SMES) systems”. High temperature superconductors (HTS) for energy applications, Woodhead Publishing Series in Energy, pp. 294-319, doi:10.1533/9780857095299.2.294.
[11] P. Mukherjee and V. V. Rao (2018), “Fuzzy Logic Controlled Superconducting Magnetic Energy Storage for Leveling Power Fluctuation of Grid Connected Wind Generator”, Int. Conf. on Power Energy, Environment and Intelligent Control (PEEIC), Greater Noida, India, pp. 665-669, doi:10.1109/PEEIC.2018.8665563.
[12] M. Steurer, C. A. Luongo, P. R. Ribeiro and S. Eckroad (2003),“Interaction between a superconducting coil and the power electronics interface on a 100 MJ SMES system”, in IEEE Transactions on Applied Superconductivity, vol. 13, no. 2, pp. 1806-1809, doi: 10.1109/TASC.2003.812895.
[13] Gour, Abhay. (2016). “Design and Development of Linear Moving Magnet Synchronous Motor based Twin PTC and HTS Level Sensor for LOX Recondenser”, Ph.D dissertation, Indian Institute of Science, Bengaluru, Karnataka - 560012, India.
[14] M.H. Rashid (2010), “Power Electronics Handbook”, 3rd edition, Butterworth-Heinemann, pp 183-196.