Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 6 Issue 11, November - 2019

# Stator Driving Circuits and Mover's Free-falling Stopper in the Vertical Heavy Mass Energy Storage System

**Daming Zhang**
School of Electrical Engineering and Telecommunication
University of New South Wales
Australia, 2052
Email: daming.zhang@unsw.edu.au

***Abstract*— As safety of a system always prioritizes, a free-fall stopper for the mover in the vertical heavy mass energy storage system is indispensable. Besides massive springs installed at the bottom of the vertical passage, a free-fall stopper along the passage needs be adopted. In this paper two possible designs of such stopper are proposed. Furthermore a driving circuit for the stator circuit is presented, which has the features of 1) shortened charging time; 2) simple discharging circuit. With some modifications, it could be converted into bi-directional charging and discharging circuit which can produce currents flowing in either direction along the stator windings.**

***Keywords*— *Braking; energy storage; free fall; heavy mass***

## I. INTRODUCTION

With a worry of depletion of oil and possible high level of hostility and conflict among countries due to competition for limited and depleting oil, the author tried hard to come out a new method of energy storage. As it is a huge system which contains many aspects, the author has limited capability to complete all. In-completed parts are open for others to fill in. If eventually such design can be commercialized, companies which use this technology will benefit most, not only in the level of management but also ordinary employees. Furthermore it has potential to solve part of energy shortage problem many years after the oil depletion. For the system to work properly, mechanic strength of the system matters a lot. In [1-4], most parts of the heavy mass energy storage system have been addressed. But the driving circuits for the stator winding and free-falling stopper for the mover have not been investigated in detail yet.

Managing the stator current is very crucial as opening high-inductance inductor with high currents is catastrophic. Multiple parallel free-wheeling diodes and several folds of redundant protections are necessary to avoid it from happening. Along terminal connections of each stator winding circuit, multiple lightning arrester like devices in parallel need be installed to discharge the current when inadvertent sudden opening of the stator winding circuit happens.

Moreover high voltage can reduce the time for charging the stator inductor. Such high voltage can be produced by cascaded H-bridge converter.

The subsequent contents are organized as follows: In Section II driving circuit for stator winding is presented; Section III discusses emergency braking mechanism for free fall of the mover; Section IV concludes the paper.

## II. DRIVING CIRCUIT FOR STATOR WINDING

The stator winding inductance is calculated by following the steps below.

$$N_s I_s = \frac{B_1}{\mu_0} \cdot l_{gap1} + \frac{B_1}{\mu_r \mu_0} \cdot l_{core} \approx \frac{B_1}{\mu_0} \cdot l_{gap1} \tag{1}$$

$$N_s I_s = \frac{B_2}{\mu_0} \cdot l_{gap2} + \frac{B_2}{\mu_r \mu_0} \cdot l_{core} \approx \frac{B_2}{\mu_0} \cdot l_{gap2} \tag{2}$$

where $l_{gap1}$ is the air-gap without the mover in between while $l_{gap2}$ is the one with mover in between; for double-U shaped stator core, there are two air-gaps and two sets of stator windings, $N_s$ is the number of stator winding turns from each of two sets located at each of two sides and $l_{gap1}$ is the distance for one of two identical air-gaps.

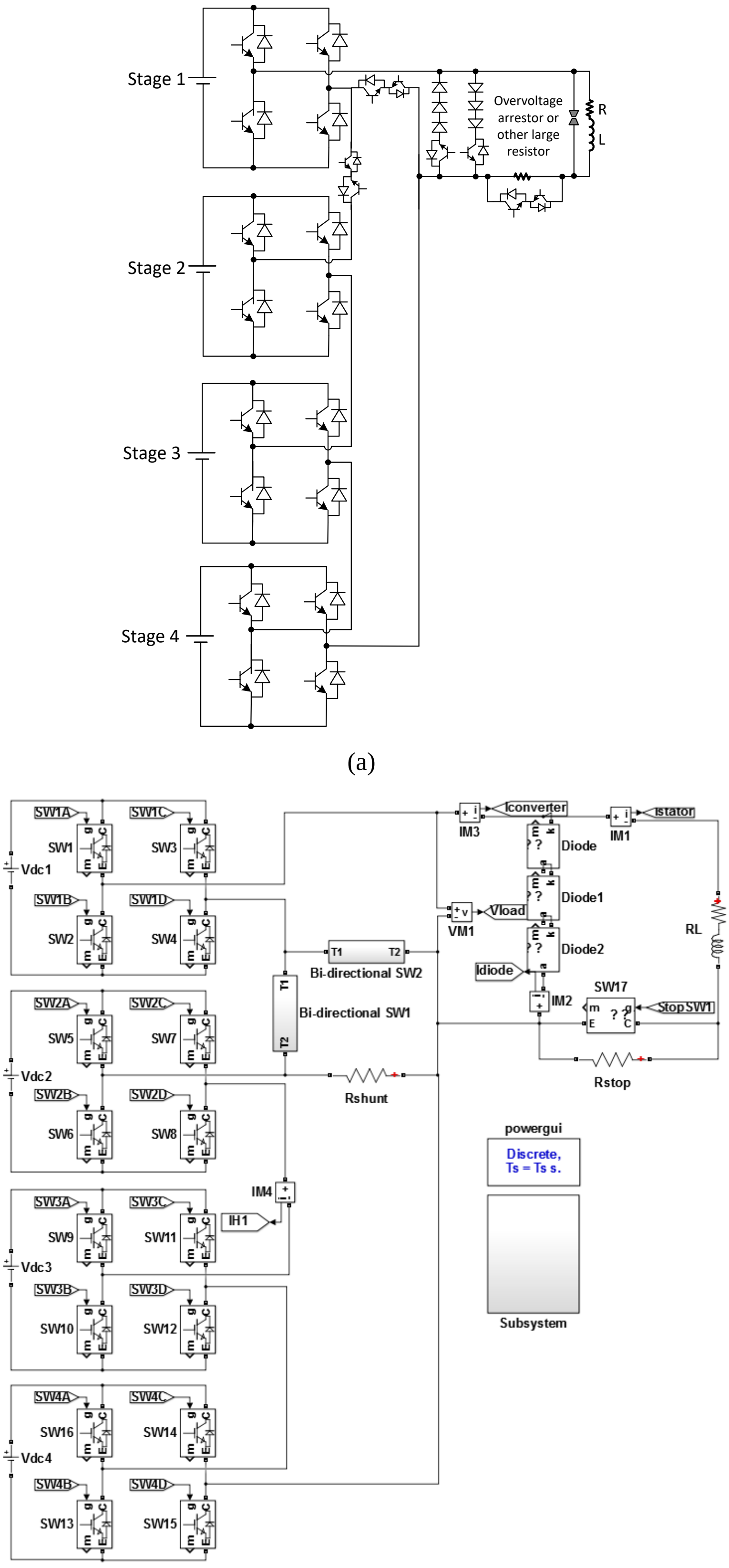
Above equations are equivalently for one air gap and one stator winding.

In the design shown in [4], air gap with mover is 0.32m. Here we assume $l_{gap2}$=0.40m, $B_2$=1.25T, $I_s$=500A. Then

$$N_s = \frac{B_2 \cdot l_{gap2}}{I_s \mu_0} = \frac{1.25 \times 0.40}{500 \times 4\pi \times 10^{-7}} \approx 800 \tag{3}$$

For an effective vertical height of 160m and a mover vertical span of 20m, a necessary parking span of 20m for the mover is necessary. By doing so, the mover is always enclosed inside the stator windings. Then the total vertical height of the interleaved stator is 180m high. Assume that the vertical height of each stator magnetic core is 1m. So is 1m for the interleaved vertical air gap in between neighboring stator magnetic core.

Self-inductance of each of two sets of the stator windings is given by (4)



(a)

(b)

Fig.1. Driving circuit for the stator winding modelled in Matlab/Simulink

$$L = \frac{\lambda}{I_s} = \frac{N_s \cdot (m_1 B_1 A + m_2 B_2 A)}{I_s} \qquad (4)$$

where $m_1+m_2=180/2=90$, and $m_1$ is the number of stator core layer and $m_2$ is the number of stator core layer overlapping with the mover structure. With the mover vertical span being equal to 20m, $m_2=(20m/1m)/2=10$ and $m_1=80$.

$B_2=1.25T$. $B_1$ is nearly a half or 0.63T. $A=1m*1m=1m^2$. Then

$$L=\frac{\lambda}{I_s}=\frac{N_s\cdot(m_1B_1A+m_2B_2A)}{I_s}=\frac{800\times(80\times0.63\times1+10\times1.25\times1)}{500}=100.6H \quad (5)$$

As the charging/discharging of each set of two stator windings induces transient voltages in the other and influences its performance, it is good to connect two sets of stator windings in series.

Then

$$L=\frac{\lambda}{I_s}=\frac{2\left[N_s\cdot(m_1B_1A+m_2B_2A)+N_s\cdot(m_1B_1A+m_2B_2A)\right]}{I_s}=\frac{3200\times(80\times0.63\times1+10\times1.25\times1)}{500}=402.4H$$

(6)

where both self and mutual flux linkages are included.

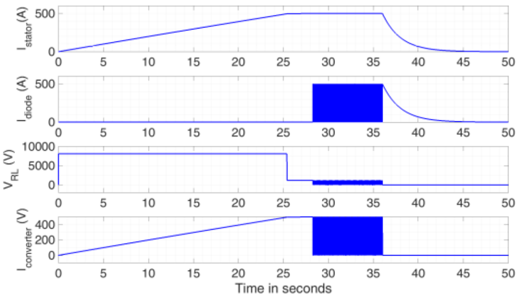


Fig. 2. (a) Stator current; (b) current in free-wheeling diodes in parallel with the stator winding; (c) Voltage across the stator winding; (d) Current from the converter

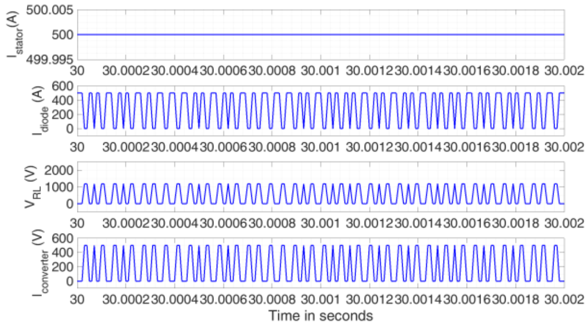


Fig. 3. Zoomed-in figures of those in Fig. 2

The fundamental inductor charging circuit can be found in [5]. A cascaded H-bridge converter as shown in Fig. 1 can be adopted for un-directional charging of the stator windings. Fig. 1a shows the bi-directional driving circuit for the stator winding while Fig. 1b shows its un-directional implementation in Matlab/Simulink. At the charging stage, bi-directional SW1 is closed while bi-directional SW2 is open and a high voltage is applied across the stator winding modelled by R-L. By doing so, charging time can be shortened. When the stator winding current reaches 99% of its rated value, bi-directional SW1 is turned off and SW2 is turned on. Then the first stage of the cascaded H-bridge converter is used to sustain the current in the stator around its rated value. When it is time to stop or reverse the stator current, one can turn off the bi-directional SW2 and also turn off the switch in parallel with Rstop. By doing so, the energy stored in the stator winding can be dissipated through resistors in the circuits.

Figs. 2 and 3 show the simulation results of inductor current, free-wheeling diode current and converter current, from which one can see that the inductor current can be charged gradually from zero to nearly 500A, then be maintained around 500A, finally discharged to zero through the free-wheeling diodes and dissipative resistor Rstop, when stop command is received.

Lightning-arrester like device in parallel with the stator winding needs be installed. By doing so, overvoltage can be avoided due to mal-operation or other incidents.

A bi-directional charging/discharging circuit is shown in Fig. 4. Its working mechanism is presented below:

*Procedure 1 - Positive direction charging*:

SW1 and SW4 are closed; SW2 and SW3 are open; air-gap is in charging mode with large air gap. Positive high voltage between terminals A and B are applied. Downward current flowing through the inductor coil is established gradually. After completing the charging, the air gap is reduced to protection mode with smaller air gap. SW1 and SW4 continue to stay closed. Chopper circuit in front of terminals AB is applied to sustain the current in the coil around its rated value. Magnetic flux is established in the air gaps where the mover is sandwiched for the system to work.

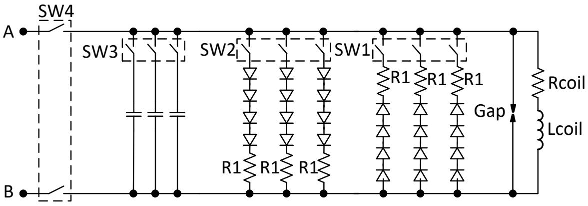


Fig. 4. Bidirectional charging/discharging circuit

*Procedure 2 - Stop mode1:*

When it is time to stop the system, one needs to turn off switch SW4 and air gap in the high voltage arrester needs be adjusted to have larger air gap to cope with potential high voltage. The inductor current will free wheel through the diodes in the path of SW1. After a short delay in the scale of tens of milliseconds, SW3 is turned on. After a further delay time in the scale of tens of milliseconds, SW1 is turned off. Inductor current will flow through the capacitor and charge it. When the capacitor voltage becomes slightly bottom positive and top negative, SW2 is turned on. When the current flowing through coil crosses zero and reverse its direction with small current, SW3 is turned off. The reversed small current will free wheel through the diodes with SW2 till zero. By doing so, the energy in the coil is converted and stored in the capacitor.

*Procedure 3 - Negative direction charging*:

For next round operation, SW3 is closed first with SW2 still remaining in the closed position. Current from bottom to top through the coil is established by the energy stored in the capacitor. When the voltage across the capacitor has very small higher voltage at the bottom terminal compared with the top terminal, SW3 is opened. The current flowing through coil will free wheel through the diodes with SW2. Then negative voltage between terminals AB or positive voltage between terminals BA is increased step by step to certain level for fast charging the current in the coil to its rated value. Then the voltage between BA provided by a DC/DC converter is reduced to a level which sustains the current in the coil around its rated value. Next the air gap in the overvoltage arrester is reduced to smaller one to take the role of safeguarding against inadvertent opening of the circuit. Reversed magnetic flux is established in the air gaps where the mover is sandwiched for the system to work.

*Procedure 4 - Stop mode2*:

When it is time to stop the system, one needs to turn off switch SW4 and air gap in the high voltage arrester needs be adjusted to have larger air gap to cope with potential high voltage. The inductor current will free wheel through the diodes in the path of SW2. After a short delay in the scale of tens of milliseconds, SW3 is turned on. After a further delay time in the scale of tens of milliseconds, SW2 is turned off. Inductor current will flow through the capacitor and charge it. When the capacitor voltage becomes slightly top positive and bottom negative, SW1 is turned on. When the current flowing through coil crosses zero and reverse its direction with small current, SW3 is turned off. The reversed small current will free wheel through the diodes with SW1 till zero. By doing so, the energy in the coil is converted and stored in the capacitor.

*Procedure 5 - Positive direction charging*:

For next round operation, SW3 is closed first with SW1 still remaining in the closed position. Current from top to bottom through the coil is established by the energy stored in the capacitor. When the voltage across the capacitor has very small higher voltage at the top terminal compared with the bottom terminal, SW3 is opened. The current flowing through coil will free wheel through the diodes with SW1. Then positive voltage between terminals AB is increased step by step to certain level for fast increasing the current in the coil to its rated value. Then the voltage between AB provided by a DC/DC converter is reduced to a level which sustains the current in the coil around its rated value. Next the air gap in the overvoltage arrester is reduced to smaller one to take the role of safeguarding against inadvertent opening of the circuit. Magnetic flux is established in the air gaps where the mover is sandwiched for the system to work.

Procedures 1 through 5 above form one cycle of the stator working steps.

Fig. 5 shows the inductor current, inductor voltage and capacitor voltage when adopting resonance discharging/charging method, where C=1F, Lcoil=402.4H, Rcoil=1ohm. With higher capacitance, the time for the energy transferring between inductor and capacitor is increased but with lower transient peak voltage across inductor or capacitor.

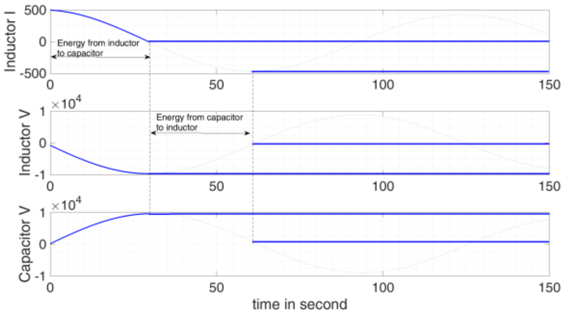


Fig. 5 Resonance discharging/charging

For safety, interlock between switches is indispensable. For example, in procedure 2, turn-off of SW1 needs be interlocked with turn-on of SW3. Only after SW3 is turned on, SW1 is allowed to turn off. The purpose of interlock is to ensure there is always path for the current in the inductor to flow.

As the energy stored in the stator winding is in the range of several kilowatts to tens of kilowatts, uni-directional charging and discharging circuit as shown in Fig. 1 can be used without compromising the overall energy efficiency much. Furthermore it is safer compared with resonance discharging/charging method as shown in Fig. 4. As mal-operation in the method shown in Fig. 4 can cause serious problems, extra care needs be exerted. The best approach is to buy such kind of system from well-established companies.

## III. EMERGENCY BRAKING FOR STOPPING FREE FALL

The touch-ground speed of the free-falling mover can be determined as follows:

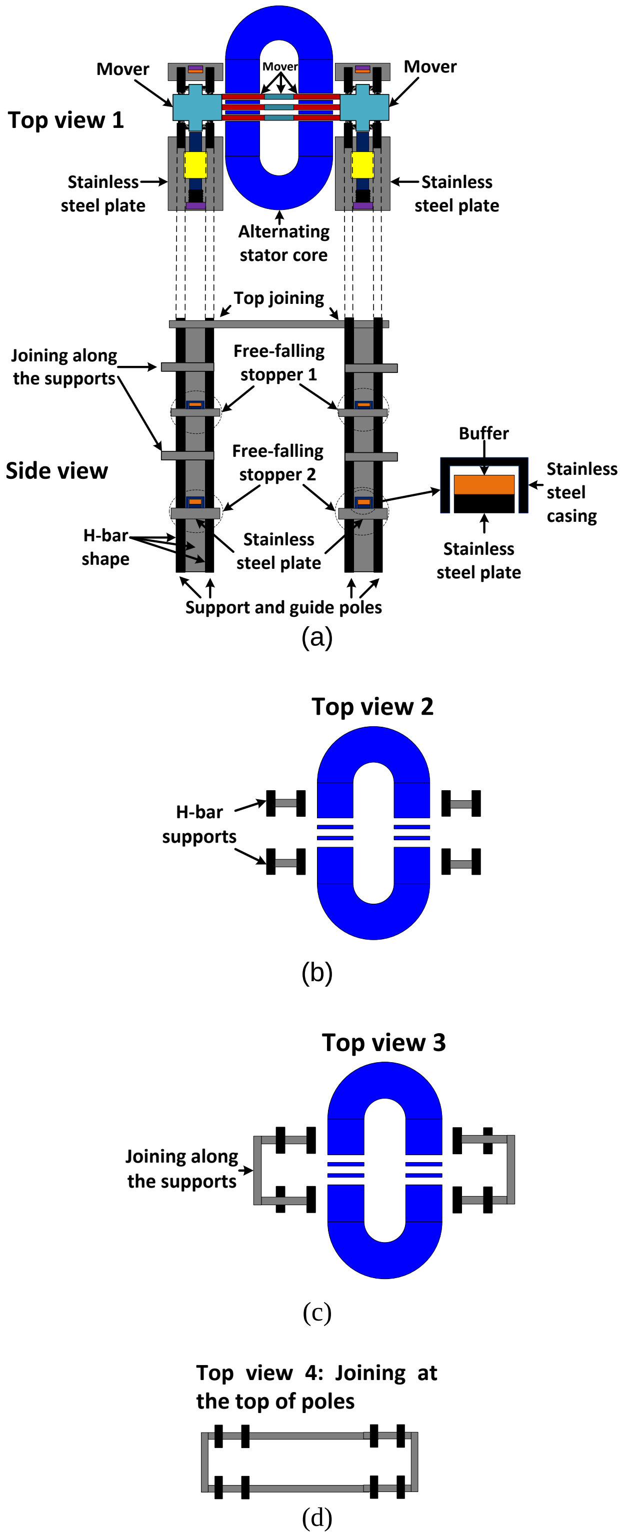
$$F = mg = m\frac{dv}{dt} \tag{7}$$

$$v(t) = gt \tag{8}$$

$$s = \int v(t)dt = \frac{1}{2}gt^2 \tag{9}$$

For a vertical length of 160m, when free-falling of the mover happens, its touch-ground speed could be as high as

$$v_{final} = g\times\sqrt{\frac{2s}{g}} = \sqrt{2g\cdot s} = \sqrt{2\times 9.81\times 160} = 56.0m/s \quad (10)$$

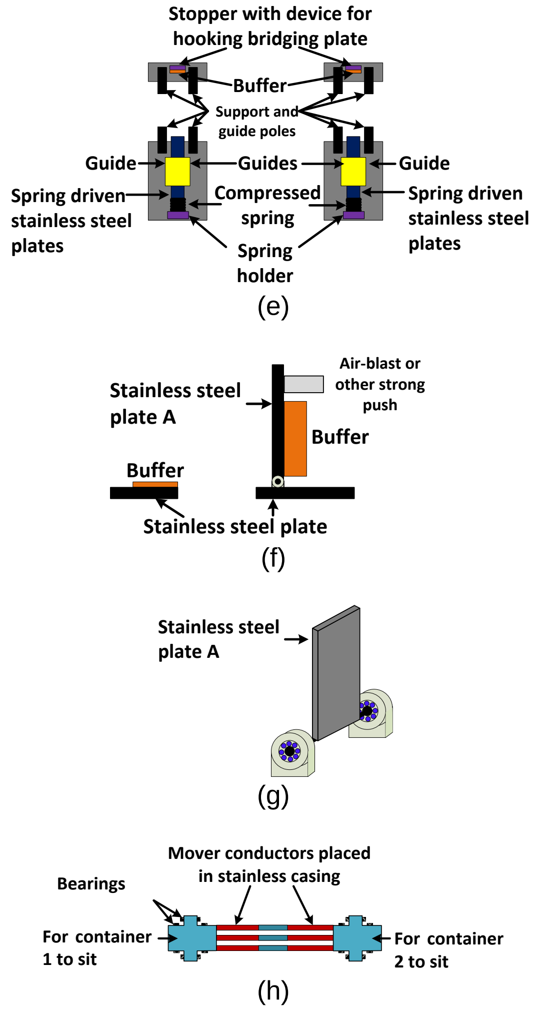


(a)

(b)

(c)

(d)



(e)

(f)

(g)

(h)

Fig. 6. Emergency stopper for the free-falling mover and mover's H-bar supports

As the mover with containers is very heavy, overall impact of the mover on support ground is huge if free fall happens. Hence the emergency stop for the free falling mover or rotor is indispensable.

Fig. 6a shows the top view of the stator core and part of the mover structure, free-fall stopper and also side view of the mover's guide/support poles and free-fall stopper, joint along the supports, joint at the top. On each side of the double-U stator cores, there are four guide/support poles for the mover, along which the bearings installed on the mover slide and rotate. Such poles are made of stainless steel. Sufficient size and dimensions of each pole are necessary to have high rigidity. Instead of using four poles at each side of the stator magnetic core, one can use two stainless steel H-bar supports at each side of the stator core as shown in Figs. 6a, 6b and 6c. Fig. 6b shows the top view of two H-bars at each side of stator core while Fig. 6c further shows the top view of two H-bars and their mechanical joints at each side of stator core. At the top of the mover's support, H-bars from each side can be mechanically joined together as shown in Fig. 6d. Along the passage, when necessary, H-bar mover supports can be joined with the stator cores' support poles mechanically. On the ground, all the poles for both stator core and mover are installed on the same large stainless steel base with sufficient dimensions, which is surrounded by even large stainless steel reinforced concreate foundation.

Fig. 6e shows one braking mechanism which is for stopping free-fall of the mover. In such brake, bridging stainless steel plate with cushion is sprung out to bridge the gap along which the mover moves, when free-fall happens. In the figure, pressed spring is adopted to force the bridging plate to quickly bridge the gap. The bridging plate could slide through two horizontal supports. One may also use high-pressure air-blast push to achieve this. Fig.s 6f and 6g illustrate a second possible bridging mechanism, in which the vertical standing bridge is pushed by the air-blast to quickly bridge the gap when the free-fall happens. Fig. 6g is a 3-D illustration of the bridging stainless steel plate which can rotate along an axis installed with bearings at two ends. Multiple such braking mechanisms are installed along the mover support H-bar poles on the two sides as shown in Fig. 6a. Furthermore one may install a spring at each side of the bottom of the mover. Fig. 6h is part of the mover with bearings installed, which is also shown in Fig. 6a.

## IV. CONCLUSION

In this paper, a driving circuit for providing magnetizing current in the stator winding in the heavy mass energy system is modelled in Matlab/Simulink. In order to shorten the charging time, one may use cascaded H-bridge converter to increase the voltage across the stator winding. When the current in the stator winding reaches 99% of its rated value, one may disconnect other stage, leaving only first stage to charge the stator winding. A proper controller can keep the stator current around its value. Furthermore this paper presents two possible braking mechanisms to stop the mover when its free-fall happens.

## REFERENCES

[1] Daming Zhang, “Review on Heavy Mass Energy Storage and a New Such a System Using Interleaved Magnetic Structure”, AUPEC 2018, Auckland, New Zealand, pp. 1-8.
[2] Daming Zhang, “Issues on Series-Parallel Circuits and their Drives in the Linear Machine for Heavy Mass Energy Storage System”, ACPEE, Hangzhou, China, pp. 1-11, March 2019.
[3] Daming Zhang, “A Massive Energy Storage System with distributed rotor or mover structure and transitional pulse current”, USA patent, filed in March 2019.
[4] Daming Zhang, Journal of Multidisciplinary Engineering Science and Technology, on-line link: http://www.jmest.org/vol-6-issue-1-january-2019/, pp. 9361-9371, 2019.
[5] A. Pokryvailo, M. Kanter, and N. Shaked, “Two-Stage Opening Switch for Inductive Energy Storage Systems”, IEEE TRANSACTIONS ON MAGNETICS, VOL. 34, NO. 3, pp. 655-663, 1998.