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Energy Buffer and Other Issues in Heavy Mass Energy Storage with Vertical Movement by Linear Machine

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***Abstract*— Potentially heavy mass energy storage using linear machine to vertically move heavy masses stored in containers has a chance to be commercialized due to its environment friendliness, long life span and relatively lower ratio of cost to life span. In this paper some existing technical obstacles have been addressed and some possible solutions were worked out. The main ones include de-magnetization method to avoid saturation of the stator cores, buffer storage to make smooth energy and power exchange between the storage system and power grid. A brief comparison was made between solid or non-interleaved stator and plate structure and interleaved stator and plate structure.**

***Keywords*— Energy storage; heavy mass; linear machine; vertical movement**

I. Introduction

Massive or grid-scale energy storages which are high-efficient, environment-friendly, lower ratio of cost to life span are the long-pursued solutions for energy crisis[1-3]. Such pursues have been un-stopping from several decades ago and are being intensified in recent years.

So far quite many relatively good solutions have been worked out. Pumped hydro energy storage is a good solution where water and reservoirs are available. For those regions with no access to water, then heavy mass energy storage described in [4-8] is a plausible solution. Although heavy mass energy storage was adopted in [4-6], each method suffers from relatively low efficiency due to severe friction losses.

In [7-8], a linear machine has been proposed to convert potential energy of heavy mass to/from electricity. In order to minimize friction losses, it lifts the heavy mass vertically. Furthermore by using multiple parallel aluminium strands to form stator windings, the copper losses in them are reduced, leading to higher efficiency. Moreover, by using transitional pulse current, uplifting force could be increased. In some applications, such as wind energy storage, the wind may just last several hours during one day. It is necessary to complete the energy storage within that short time span. To solve this problem, a multiple rotor or mover structure could be adopted to improve the lifting efficacy and increase the storage capability[8,10].

In the structures shown in [7-8], the possibility of stator core excursion into saturation region has not been addressed. Furthermore, one system will suffer a large fluctuation of energy storage because upward movement and downward movement have different power levels exchanged with power grid. To overcome such problems, this paper proposes to have one pair or multiple pairs of the identical systems. By doing so, when half of the movers move upward, another half will move downward. Therefore, nearly constant power exchange with power grid can be achieved during the movement of the movers along the passages. Nevertheless such system also needs to have a buffer storage at their stoppage time when movers or rotors reach top or bottom for loading or unloading containers with heavy masses. By adopting a buffer storage unit like super-capacitors based energy storage etc, smooth or nearly constant power exchange between energy storage systems and power grid can be achieved.

This paper further proposes a new topology evolved from combining two identical systems. Such new system shares common central magnetic limb without wound stator windings. Instead each side has doubled ampere-turns for the stator windings.

To make the system commercialisable, the cost on heavy mass is a critical issue as it takes a majority part of overall cost. In view of the fact that cement or concrete is relatively expensive, fragmented stone could be used instead. Compared with using concrete or cement, the size of container with fragmented stones only needs be slightly larger as the mass densities of most stones are above $2\times10^{3} kg/m^{3}$.

Furthermore tracks along which the containers are moved to park on the high and low platforms could be shared and made moveable by mini-locomotives. The stainless steel framed and plastic-windowed containers are built to store the fragmented stones. The container holders integrated with rotors or movers hold the container with heavy masses.

The subsequent contents are organized as follows: in Section II, measures for preventing stator cores from excursion into saturation region are discussed; Section III addresses the issue on pairing systems for smooth power storage and release; Section IV discusses buffer storage for smooth power exchange between energy storage system and power grid; Conclusion is given Section V.

II. MEASURES FOR PREVENTING STATOR CORES FROM EXCURSION INTO SATURATION REGION

During the movement of the movers or rotors, each layer of magnetic cores in the stator experiences minor loop of magnetization in sequence. Such minor loop could be modelled by Jiles-Atherthon model governed by Eqns. (1)-(11) and is shown in the first quadrant in Fig. 1.

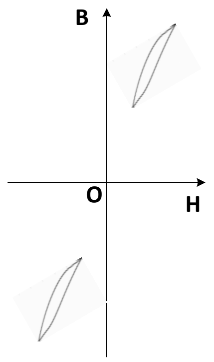

Fig. 1. Minor magnetization loops for the stator cores

After many rounds of movement of the movers, chances for stator core excursing into deep saturation region are possible. To avoid this from happening, one solution is to reverse the direction of the current in the stator winding and adjust accordingly the working currents in the mover windings after some rounds of operation. By doing so, excursion into saturation region for the stator cores could be avoided. By doing so, the magnetic cores in rotors or movers can also avoid deep saturation.

Eqn. (1) shows the total magnetization.

$$M = M_{irr} + M_{rev} \quad (1)$$

where M is the total magnetization, M_{irr} is the irreversible magnetization, and M_{rev} is reversible magnetization, which is given in (2).

$$M_{rev} = c\left(M_{an} - M_{irr}\right) \quad (2)$$

where M_{an} is the anhysteretic magnetization, and c is the coefficient of proportionality.

The anhysteretic magnetization M_{an} is described using the Langevin function:

$$M_{an} = M_s\left(coth\frac{H_e}{\mathrm{a}} - \frac{\mathrm{a}}{H_e}\right) \quad (3)$$

where M_s is the saturation magnetic moment of the core material and a is a shape parameter.

$$\frac{\partial M_{an}}{\partial H_e} = \frac{M_s}{\mathrm{a}}\left[1 - coth^2\left(\frac{H_e}{\mathrm{a}}\right) + \left(\frac{\mathrm{a}}{H_e}\right)^2\right] \quad (4)$$

H_e in (3) is the effective magnetic field which is expressed as

$$H_e = H + \alpha \cdot M \quad (5)$$

where H is the magnetic field in the core, and α is the inter-domain coupling factor.

The flux density, B, is given by

$$B = \mu_0(H + M) \quad (6)$$

where H is the magnetic field or magnetizing field, and μ_0 is the permeability of free space.

$$\frac{dM}{dB} = \begin{cases} \dfrac{\xi}{\mu_0\left[1 + (1-\alpha)\xi\right]} & \text{if } \delta_M = 0 \\ \dfrac{\eta}{\mu_0\left[k\cdot\delta + (1-\alpha)\eta\right]} & \text{if } \delta_M = 1 \end{cases} \quad (7)$$

where

$$\delta_M = \begin{cases} 0 & \text{if } \operatorname{sign}(dH/dt)\cdot\operatorname{sign}(M_{an} - M) < 0 \\ 1 & \text{if } \operatorname{sign}(dH/dt)\cdot\operatorname{sign}(M_{an} - M) > 0 \end{cases}, \quad (8)$$

$$\xi = c\frac{dM_{an}}{dH_e}, \quad (9)$$

$$\eta = (M_{an} - M) + k\cdot c\cdot\delta\cdot\frac{dM_{an}}{dH_e} \quad (10)$$

and

$$\delta = \begin{cases} 1 & \text{if } \operatorname{sign}(dB/dt) > 0 \\ \text{-}1 & \text{if } \operatorname{sign}(dB/dt) < 0 \end{cases} \quad (11)$$

III. ONE PAIR OF SYSTEMS FOR SMOOTH POWER STORAGE AND RELEASE

Fig. 2 shows one possible arrangement of one pair of the system[7-8], where joining mechanic parts link two identical systems together.

Fig. 3 shows a new arrangement by combining two limbs together, one being from the first system and the other being from the second system. A common winding is adopted for the joint central limb. Such arrangement requires the magnetic flux in one magnetic path flowing in the clockwise direction while the other flowing in the opposite or anti-clockwise direction. The magnetic circuits for the stator structures as shown in Fig. 3 are given in Fig. 4. In order to establish the same level of magnetic flux in the stator magnetic paths as in Fig. 2, the ampere-turn for the central limb needs to be NI as well. Furthermore, as the flux passing through the central limb becomes doubled, its width is just a combination of two limbs or double of each limb.

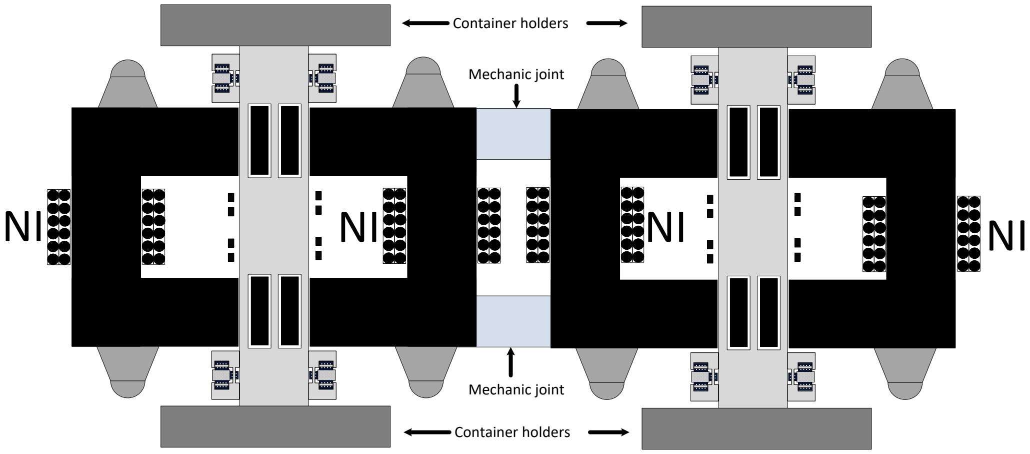

Fig. 2. Double systems for having smooth power storage and release

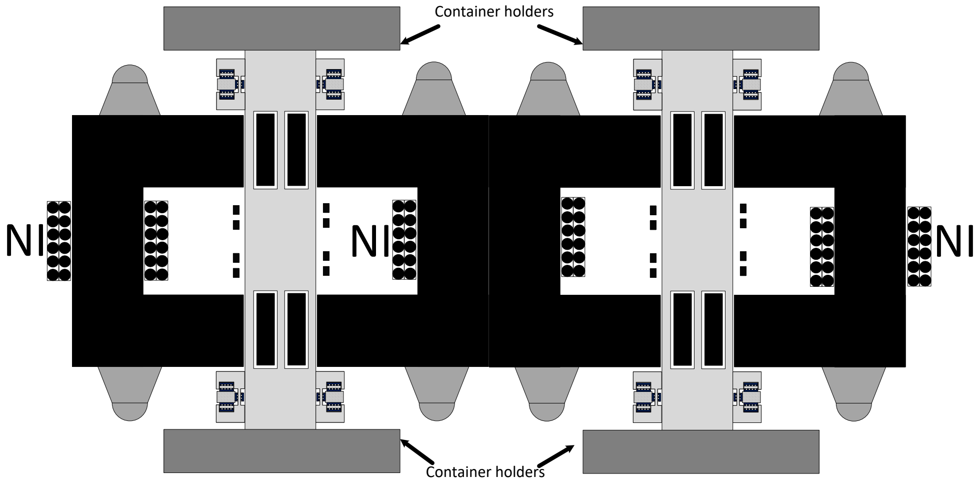

Fig. 3. Double systems with one shared limb and one set of winding

If the magnetic flux flowing through the stator magnetic paths are in the same direction both being clockwise or both being anti-clockwise, then such two systems cannot be combined. The explanation is given by the magnetic circuit as shown in Fig. 5, from which one can see that there is no value of x to make the flux in the combined system same as that in each of the two original systems.

Another possible solution is given in Fig. 6 and its stator magnetic circuit is shown in Fig. 7. The ampere-turns are placed at two sides of the combined structure. In order to produce the same amount of flux density, each ampere-turns need be doubled or y in Fig. 7 needs to be 200%. The central limb experiences very small magnetic flux flowing through it but it needs be there. Nevertheless its width can be reduced.

In some design, the containers and their holders may span long. Then stator supports are protrusive and block the extension of the container holders. The stator support could be placed inside the stator magnetic loop as shown in Fig. 8.

To increase the mechanic strength, the supporting poles, either for supporting the stator magnetic cores or for supporting bearings, can be joined together at the bottom and top of the passage and even along the passage wherever appropriate. Extra support for the supporting poles such as grounded skew support can be adopted.

IV. ONE PAIR OF SYSTEMS FOR SMOOTH POWER STORAGE AND RELEASE

When one pair of or double systems are adopted, one mover or rotor is at the top while the other is at the bottom. They move in the opposite directions in the same speed. During the movement, nearly constant power exchange can be achieved between the double systems and the power grid. When they reach their respective terminals, loading or unloading of the containers takes place. During this stoppage, the power exchange between the energy storage system and the power grid is stopped. To avoid such dis-continuousness of power exchange, a buffer storage unit as shown in Fig. 9 is necessary, where the power converter is adopted to link it to the power grid. One such unit can be super-capacitor based system as shown in Fig. 10.

The detailed storage and release of energy for the systems with buffer storage unit are shown in Tables I and II.

TABLE I. STATE OF EACH SYSTEM WHEN STORING ENERGY IN HEAVY MASSES

	State		
System 1	Up: Store	Down: Release	Stop: No exchange
System 2	Down: Release	Up: Store	Stop: No exchange
Buffer storage	Release at slow rate		Store at fast rate

TABLE II. STATE OF EACH SYSTEM WHEN RELEASING ENERGY IN HEAVY MASSES

	State		
System 1	Down: Release	Up: with no containers	Stop: No exchange
System 2	Up: with no containers	Down: Release	Stop: No exchange
Buffer storage	Store at slow rate		Release at fast rate

Assume that a passage spans 120m and movers or rotors move at a speed at 6m/s. Then it takes the movers or rotors 20s to complete movement along the passage. The stoppage time for the movers or rotors at the top and bottom should be controlled as short as possible, say 4s. When the whole system operates in the mode of energy storage in the heavy mass, during the up or down movement of the movers or rotors along the passage, the stored energy in the buffer storage unit can be released slowly into the power grid. At the moment when the movers or rotors reach the top or bottom of the passage, the energy stored in the buffer unit needs to be completely released. Then fast storing of the energy from the power grid into the buffer unit needs be done within the stoppage time and ready for the next round energy exchange. By doing so, nearly constant power exchange between the energy storage system and the power grid can be fulfilled. Such procedure is summarized and shown in Table I.

Oppositely, when the whole system works in the mode of release of stored potential energy into the power grid, during the up or down movement of the movers or rotors along the passage, energy from the power grid is slowly stored or charged into the buffer unit. At the moment when the movers or rotors reach the top or bottom of the passage, the buffer unit needs to be fully charged. Then fast releasing of the energy from the buffer unit into the grid needs be done within the stoppage time and ready for the next round energy exchange. By doing so, nearly constant power exchange between the energy storage system and the power grid can be achieved. Such procedure is summarized and shown in Table II.

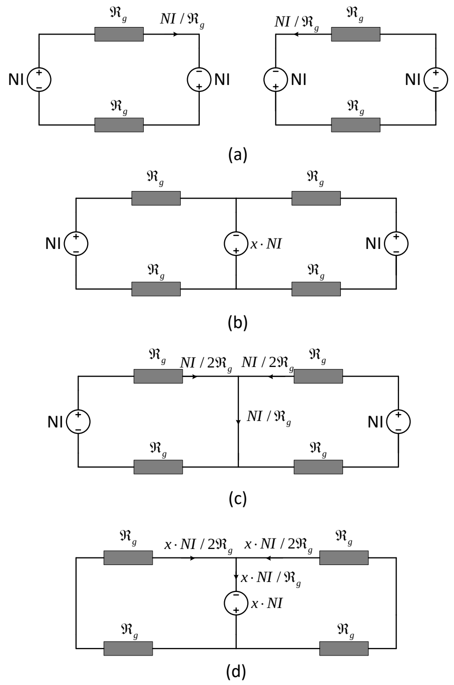

Fig. 4. Magnetic circuits for overall system shown in Fig. 3

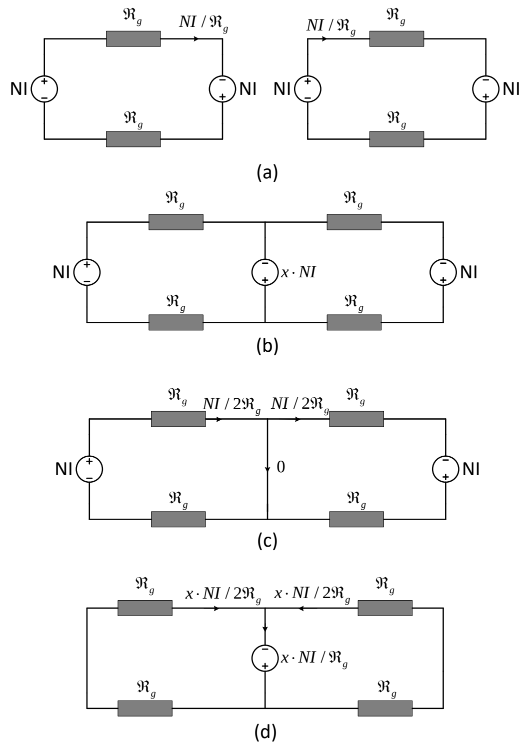

Fig. 5. Magnetic circuits for double systems with the stator flux flowing through them in the same directions

During the mover's stopping procedure, to reduce the moving mover's speed to standstill, braking operation is necessary. For upward movement, electromagnetic force can be stopped. Then the mover can stop moving naturally due to the action by the weight of mover or mover plus containers. But for

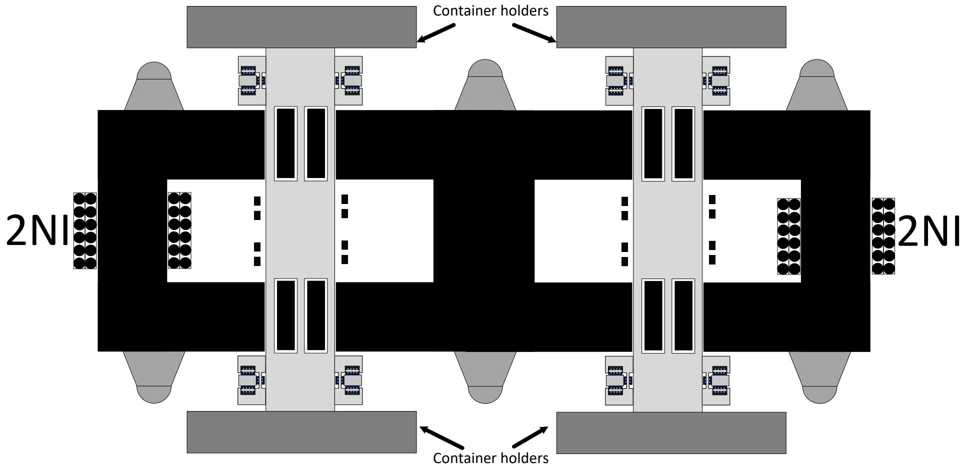

Fig. 6. A new arrangement of the system with combined limbs and side limb with doubled ampere-turns

the downward movement, when the mover with or without containers stops, to reduce its speed to zero, upward-pointing electromagnetic force needs be increased. Such extra power fed back to the power grid needs be addressed properly. When necessary, sizing of the super-capacitors can be increased to address such issues. Charging and discharging of the super-capacitors need be controlled to ensure smooth power exchange between the power grid and the system when transition occurs between stop/move and move/stop of the movers.

The extra cost from adopting the buffer energy storage is not high as the current cost of the super-capacitor is 20$/kW. For a 30MW level power storage, then the cost is $600,000. Such cost is several percent of the cost for the overall system.

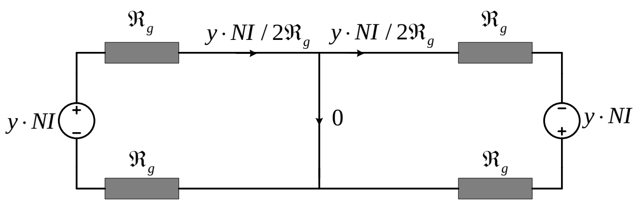

Fig. 7. Magnetic circuit in the structure shown in Fig. 6

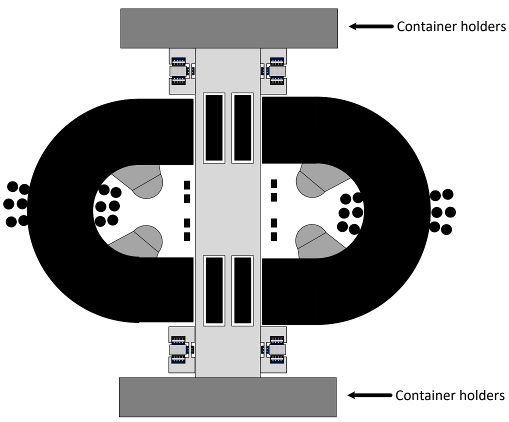

Fig. 8. A structure with support of the stator magnetic cores to be placed inside the stator magnetic path

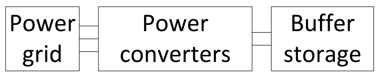

Fig. 9. Power converters for exchanging power between power grid and buffer storage

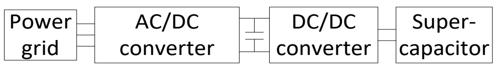

Fig. 10. Power converters for exchanging power between power grid and super-capacitor

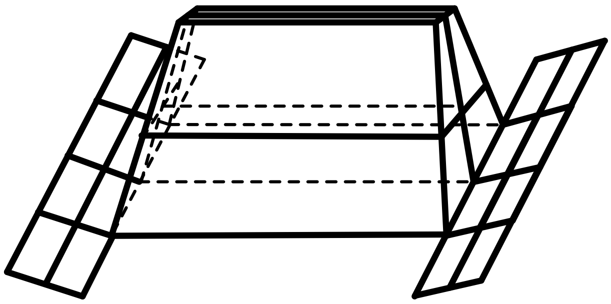

Fig. 11. Sketch of the container holders integrated with rotor or mover structure

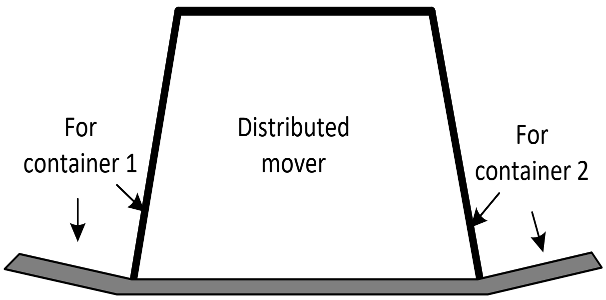

Fig. 12. Front view of the container holders integrated with the rotor or mover

One sample holder for holding the containers is shown in Figs. 11 and 12.

In the containers' holder structures shown in Figs. 11 and 12, a skew for the base is adopted to ensure side of the container can lean on the supports integrated with mover. By doing so, the base burden is alleviated.

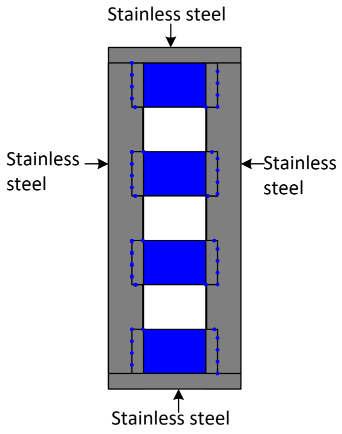

Fig. 13. Mechanic reinforcement for supporting the interleaved stator magnetic plates sandwiching distributed rotor or mover structures

Fig. 13 shows the mechanic reinforcement for supporting the interleaved stator magnetic plates sandwiching mover structures. Such reinforcement could be stainless steel or other materials. Along the direction of the magnetic flux established by the stator winding currents, perpendicular width of the reinforcement is the same as that of the magnetic material. Both ends of each layer of magnetic block forming interleaved stator plates shown in Fig. 14 are sharply tapered off and inserted into the stainless steel reinforcement in Fig. 13.

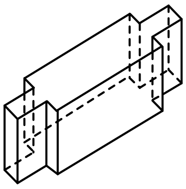

Fig. 14. Magnetic plate in Fig. 13 with tapered-off ends

As discussed in [10] on the interleaved stator structure, reluctance force could make movement of the mover or rotor un-stable. One possible solution was given [10] already. Another solution is given in Fig. 15. In group 1 of Fig 15a, CR1-CR3 form two sides in one coil experiencing electromagnetic-force alternatingly; CR2-CR4 form two sides in one coil experiencing electromagnetic-force alternatingly. In the group 2 shown in Fig. 15a, CR5-CR7 form two sides in one coil experiencing electromagnetic-force alternatingly; CR6-CR8 form two sides in one coil experiencing electromagnetic-force alternatingly. In Fig. 15b, in the group 1, CR1-CR3 form two sides in one coil experiencing electromagnetic-force alternatingly; CR2-CR4 form two sides in one coil experiencing electromagnetic-force alternatingly; CR5-CR7 form two sides in one coil experiencing electromagnetic-force alternatingly; CR6-CR8 form two sides in one coil experiencing electromagnetic-force alternatingly. In group 2 as shown in Fig. 15b, CR9-CR11 form two sides in one coil experiencing electromagnetic-force alternatingly; CR10-CR12 form two sides in one coil experiencing electromagnetic-force alternatingly; CR13-CR15 form two sides in one coil experiencing electromagnetic-force alternatingly; CR14-CR16 form two sides in one coil experiencing electromagnetic-force alternatingly. Such arrangement of the rotor or mover is very similar to that in [7-8, 10]. But vertical shift or separation by an odd number times the one stator layer height h between group 1 and group 2 of mover conductors is necessary. For example, the arrangement in Fig. 15a has 3h separation distance between side CR1 in group 1 and side CR5 in group 2 while the arrangement in Fig. 15b has 5h separation distance between side CR1 in group 1 and side CR9 in group 2. There is no overlapping between two groups. By doing so, the reluctance force from group 1 is significantly cancelled or balanced by that from group 2. The rotor or mover can move smoother.

In Fig. 15b, when necessary coil CR1-CR3 can be connected in series with the coil CR5-CR7; coil CR2-CR4 in series with the coil CR6-CR8; coil CR9-CR11 in series with the coil CR13-CR15; coil CR10-CR12 in series with the coil CR14-CR16.

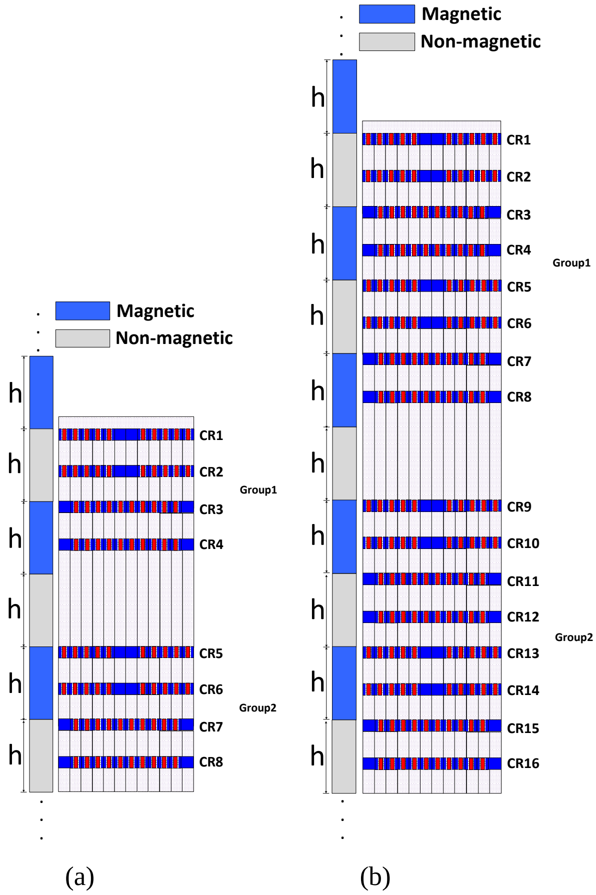

Fig. 15. Arrangement to balance reluctance force

Most parts of the stator structure and distributed rotor or mover structures as shown in Figs. 2, 3, 6 and 8 are also suitable for non-interleaved or solid stator magnetic structure as described in [9]. The top view of one of structures with solid or non-interleaved stator structure and plates is shown in Fig. 16. It is very similar to that shown in Fig. 6 which is for interleaved

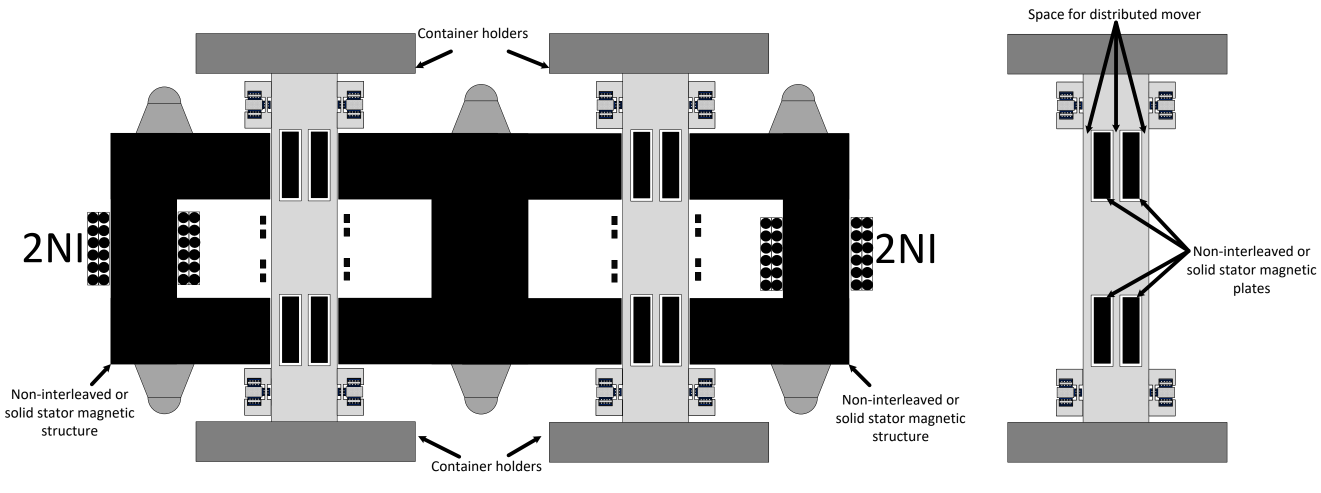

Fig. 16. Structure with solid or non-interleaved stator and plate structure

stator and plate structure. Besides having solid stator and plate structure, it is also necessary to modify rotor or mover in the non-interleaved stator structure. Figure 17 shows the stator non-interleaved magnetic plates spreading from the bottom to the top of the passage. Such stator plates sandwich the distributed rotors or movers.

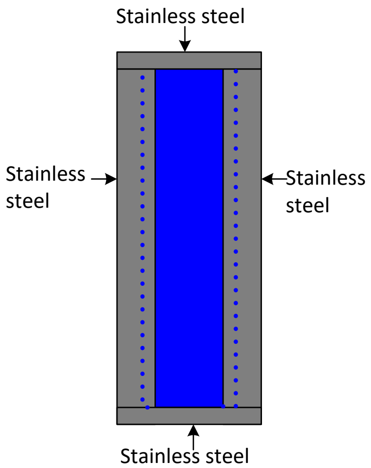

Fig. 17. Solid magnetic plate in Fig. 16(b)

One arrangement of a distributed rotor or mover sandwiched by stator magnetic plates is shown in Fig. 18, where only the conductors under the stator magnetic path are shown, and only one stator magnetic plate at one side of the one distributed rotor or mover is shown. Terminal connections of the rotor or mover conductors out of the magnetic path for the conductors shown in Fig. 18 are as follows: terminal B1' joins with terminal A1'; terminal A1 joins with terminal B2; terminal B2' joins with A2'; terminal A2 joins with terminal B3; terminal B3' joins with A3'; until terminal A5 joins with terminal B6; terminal B6' joins with A6'. In the same way, terminal D1' joins with terminal C1'; terminal C1 joins with terminal D2; terminal D2' joins with C2'; terminal C2 joins with terminal D3; terminal D3' joins with C3'; until terminal C5 joins with terminal D6; terminal D6' joins with C6'. By doing so, there are two coils, one starting from terminal B1 and ending at terminal A6 while the other starting from terminal D1 and ending at terminal C6. When necessary, these two coils can be connected in series. Then each terminal is to contact with the passage-long vertical conductors through carbon brushes.

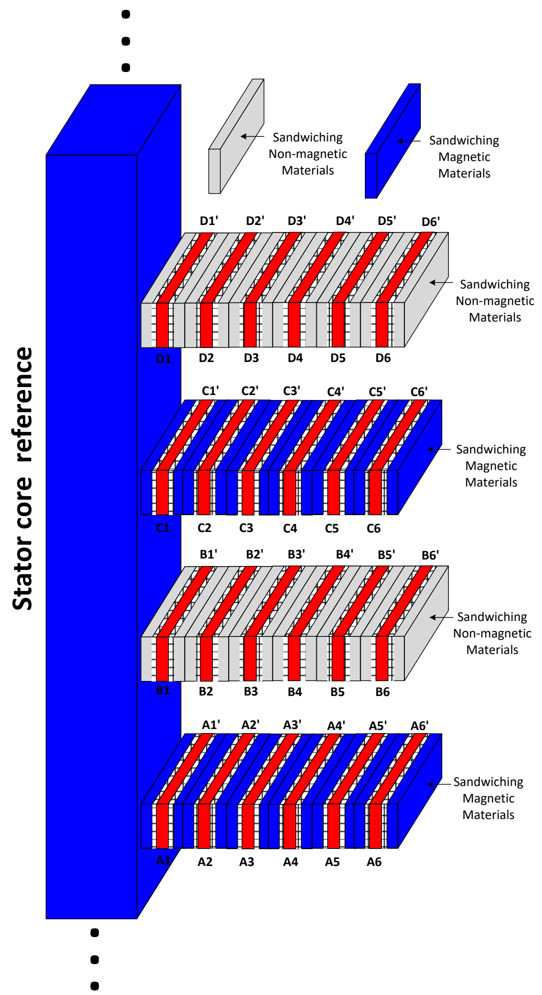

Fig. 18. Arrangement of rotor or mover conductors

The terminal connections for the rotor or mover conductors in one coil are outside the stator magnetic path and in the same way shown in [10].

In Fig. 18, there are alternating magnetic materials sandwiched layers and non-magnetic sandwiched layers. In the magnetic materials sandwiched layer, the mover or rotor conductors are sandwiched by magnetic materials and separated by insulators while in the non-magnetic materials sandwiched layer, the mover or rotor conductors are sandwiched by the non-magnetic layers. To reduce the weight, the non-magnetic sandwiching layers can be chosen from light materials with enough mechanic strength. The same metal casings or other reinforcing casings should be used to accommodate each of the non-magnetic and magnetic materials sandwiched layers as in [8]. Furthermore between different layers, stainless steels or other mechanic reinforcement links as described in [8] should be adopted. Other joining parts and container holders are also the same as that in [8,10] where the interleaved stator and plates are adopted.

When the non-interleaved or solid stator structure is adopted, the same pair structure and energy storage buffer as described above need be adopted to ensure smooth power exchange between the system and power grid.

Compared with interleaved stator and plate structure, solid or non-interleaved structure produces less uplifting force, has higher cost on the stator magnetic cores and less power produced during the movement. Nevertheless its mover or rotor can be made slightly lighter, power converters can be simplified. Detailed comparison will be conducted in the near future.

V. CONCLUSION

In this paper several issues have been addressed for making the heavy mass energy storage with vertical movement a feasible solution. Such issues include avoiding stator's and mover's cores from excursion into deep saturation regions by changing the stator winding currents in two opposite directions; introduction of buffer storage unit to have continuous power exchange when the containers reach top or bottom of the passage and stop for loading and/or uploading containers with heavy masses. Such buffer storage unit could be super-capacitors interfaced with power grid through power converters. To make the power exchange smooth between power grid and energy storage system, two identical systems are combined. This paper further proposes a new topology evolved from the combination of two identical systems. Such new system shares common central limb without wound stator windings. Instead each side has doubled ampere-turns for the stator windings. Furthermore to reduce the cost, fragmented stone is suggested to be the heavy masses.

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