Improved Heavy Masses Potential Energy Storage Systems

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***Abstract*— This paper explains several more aspects of heavy masses potential energy storage system using a linear machine. Symmetry is one of the main features in such a system. To reduce induced pulse voltages in neighboring coils arranged in the configuration where more than one side of mover conductors is accommodated along one stator vertical layer, either magnetic or non-magnetic one, due to transition experienced by the side of one coil, one may have more air gaps along the circumferential stator magnetic path, each of which accommodates less turns of mover coils. Equivalent mover windings are grouped with each of them being connected in parallel driven by one driving circuit or each of the mover windings accommodated in each air gap is driven separately by a driving circuit to reduce the induced voltage. Furthermore greater cross sectional area of the individual mover conductors can be used to reduce the number of turns, thereby leading to smaller induced voltage. Moreover whole mover windings can be converted into more sets with less turns in each set, and be arranged to spread vertically with longer span to further reduce induced voltages in each of them. By doing so, armature reaction brought by mover currents can also be contained to an acceptable level.**

Alternatively, one may use one coil instead of several coils across one pair of interleaved stator magnetic structure, one being magnetic layer while the other being non-magnetic or air layer. For such an arrangement, vertical distance for each stator layer needs be reduced and more air gaps need be introduced as well along the circumference of the stator magnetic path to reduce the number of mover conductors in each of them.

This paper further proposes a new mover winding configuration which has two sets of coils in one pair of interleaved stator magnetic structure. Compared with one set of coil configuration, it is more compact.

Keywords—Armature reactance; Energy storage; Induced voltage; Linear machine

I. INTRODUCTION

Cost-effective, environment-friendly, and durable massive energy storage is pivotal for solving energy crisis. Many researchers worldwide are gearing up efforts to seek feasible solutions[1-2].

In author's previous work [3-6], quite many aspects of the heavy masses potential energy storage using a linear machine system have been addressed. As the system is a complicated one, more elaborations are still necessary, including how to reduce the induced voltages in neighboring mover coils when one coil experiences transition and how to effectively contain armature reactance by the currents in the mover windings. In this paper, several more possible configurations are also proposed. Nevertheless their working mechanism is still the same as published ones in [3-7].

The remaining contents of the paper are organized as follows: In Section II, the new and modified configurations of the machine system is described in detail; Section III concludes the paper.

II. NEW AND MODIFIED SYSTEMS

Fig. 1a shows a new configuration, in which there are two pairs of distributed movers, one of which is symbolized in the figure by 'One pair'. Although only three air gaps are shown at each location, for a practical application, more air gaps can be used. Same as other configurations proposed earlier in [3-7], such a configuration is also symmetrical. Distributed air gaps sandwiched by magnetic plates are filled with mover windings, their insulations, and reinforcement. Each mover set in each distributed air gap is framed by stainless steel structure and all the stainless structures at one location are joined together, through which uplifting electromagnetic forces are accumulated.

In the structure in Fig. 1a, stainless steel frames for holding mover sets at each location from the two pairs of the distributed movers are joined together. By doing so, all the electromagnetic forces are to balance overall weight of mover itself and containers.

Fig. 1b shows the integrated mover structure, which moves along support guide poles via bearings installed on it.

The stator windings should cover stator magnetic cores as much as they can in order to minimize leakage flux. The winding style in which the stator windings are around on each layer of stator magnetic cores and they are connected in series for all the magnetic layers could be adopted instead of overall straight winding style from top to bottom as shown in [3-5].

When necessary, the stator windings can be wound for the parts of magnetic stator cores from the widened interleaved stator magnetic plates.

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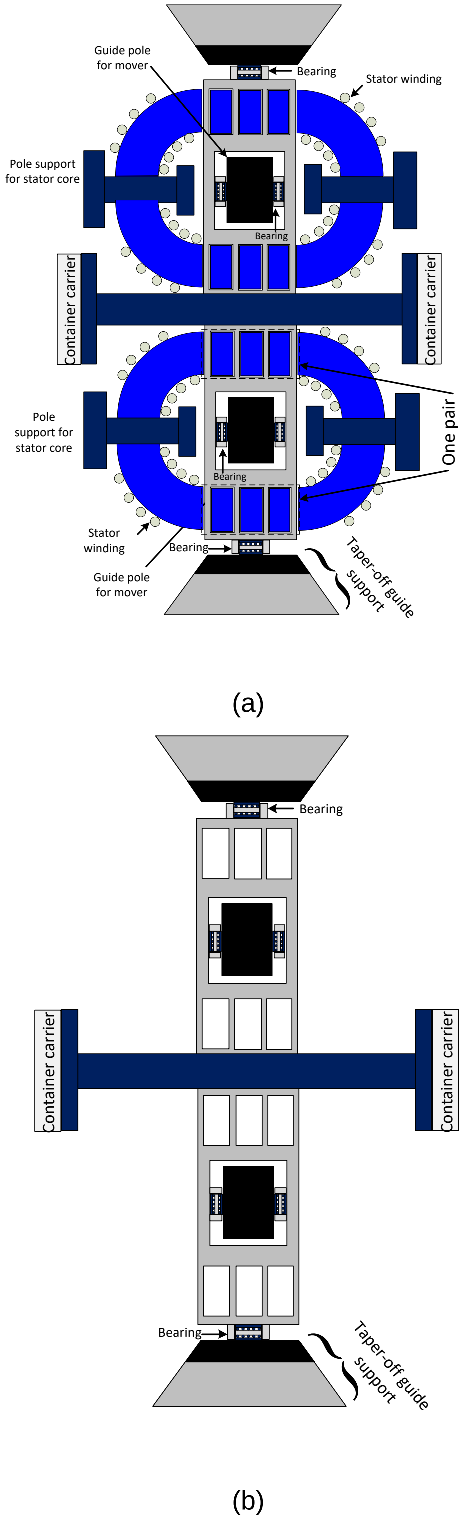


Fig. 1 New configuration 1

One vertical cut-cross section along the mover winding of the mover windings located at two sides of support pole, indicated by 'One pair' in Fig. 1a, their casings, their other reinforcement, also their attachment to central support is shown in Fig. 2, in which the cut cross section of one pair of distributed movers are shown. One side of the windings are A1A1', B1B1', A2A2', B2B2', U1U1', V1V1', U2U2', V2V2', while the other side is D1D1', E1E1', D2D2', E2E2', X1X1', Y1Y1', X2X2', Y2Y2'. Each of them should come with necessary insulations, though not shown in the figure.

A1A1' are two terminals of several turns in series and their cross sections are shown in Fig. 3. So are B1B1', A2A2', B2B2'. Others also have exactly the same number of turns in series.

To reduce the number of driving circuits, coils A1A1', A2A2' can be connected in series by joining A1' with A2. In the same way, coils D1D1', D2D2' can be connected in series by joining D1' with D2. As described below, there is a serious induced voltage issue in neighboring windings when one set of windings experiences transition between stator magnetic layer and non-magnetic layer. Hence it is recommended that they should be driven by separate driving circuits. That is to say, each of A1-A1', A2-A2', D1-D1' and D2-D2' coils or windings is driven by a separate driving circuit or all of them are grouped and each group is connected in parallel and driven by one driving circuit. Special attention needs be paid to the induced voltage polarities when joining the terminals to form parallel connections.

Sufficient number of turns of mover windings in series is necessary. This is because when those in equivalent physical positons relative to stator interleaved magnetic structure such as coils A1A1' and A2A2' in Fig. 2 is connected in parallel, nearly equal current sharing needs be guaranteed for stable operation by having sufficiently high circuit impedances. The best solution is still to use one individual driving circuit to drive each coil or winding accommodated in each air gap.

B1B1', B2B2', E1E1', E2E2' are handled in the same way as for A1-A1', A2-A2', D1-D1' and D2-D2' as described above.

To remove the reluctance force influence, U1U1', V1V1', U2U2', V2V2', and X1X1', Y1Y1', X2X2', Y2Y2' are adopted. They are connected in the same way as described for A1A1', B1B1', A2A2', B2B2', and D1D1', E1E1', D2D2', E2E2'.

Each driving circuit is positioned at either top or low parking platform and its connection with mover windings is done via vertical conductors spreading from the bottom to the top, against which carbon brush at the terminal of the mover windings contacts and conducts currents.

In the configuration as shown in Fig. 1, there are four guide supports against which the bearings touch and the movers move along vertically. The whole mover structure is installed with six sets of bearing systems installed on the mover, each of which contains multiple bearings along the vertical direction. Two of them are installed at each end of the mover structure while each two of another four of them are installed on the mover and move against one support pole in the middle. The precision requirement is very high for each component in the system. It could be good to use several layers in the vertical supports. Taper-off support poles can be used to increase strength of overall system. The stator support poles, mover guide poles are joined together at the top of the system. They are further joined with the interleaved

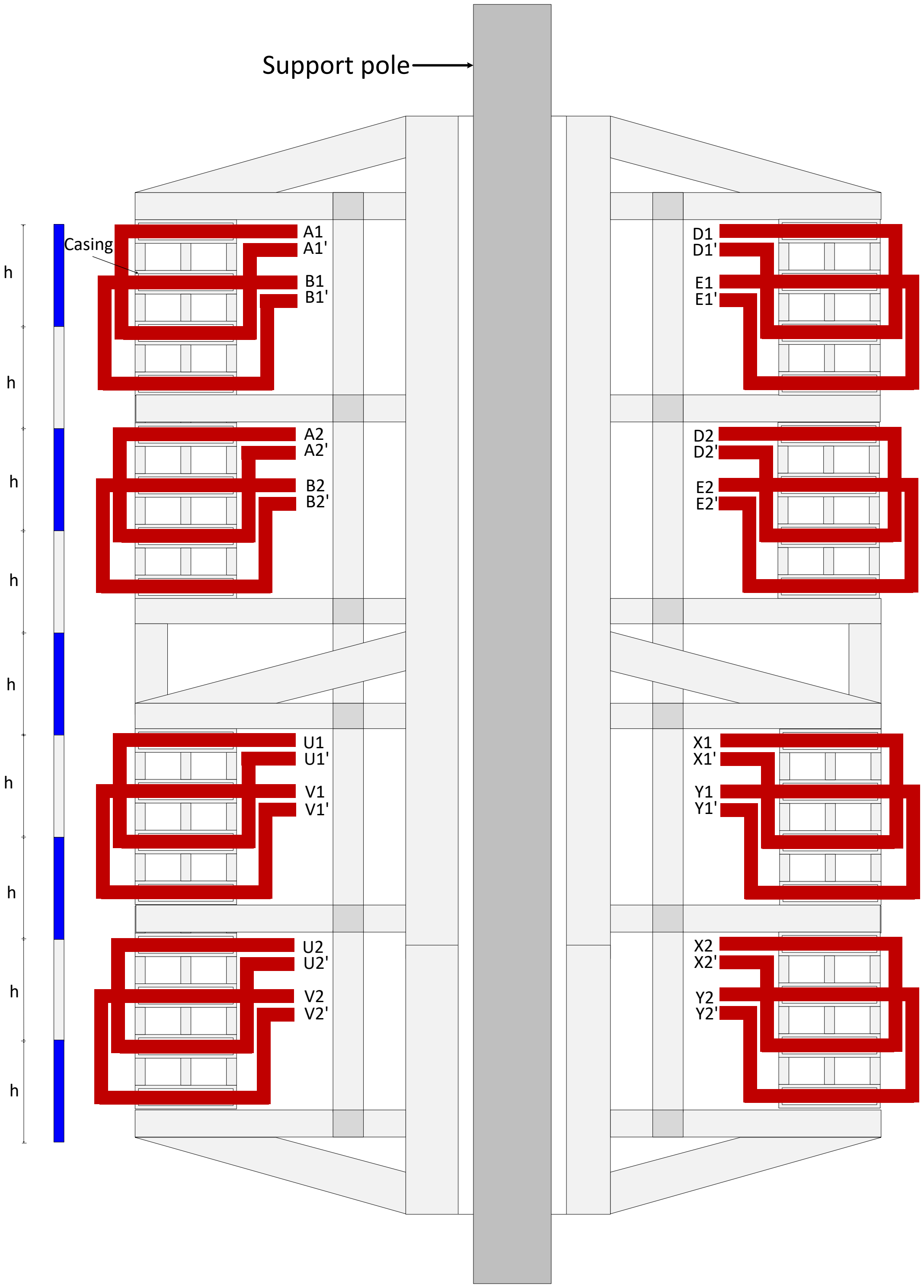


Fig. 2. Details of cross section view including support pole for mover windings and its reinforcement

magnetic plates to reinforce whole system stiffness and rigidity. Parking space is necessary for the whole mover at top of the passage.

The support poles for carrying stator cores spread from the bottom to the top, installed firmly on base at the bottom parking platform. At each layer there is one bar holding the stator magnetic core. Inter stator magnetic layers can be further supported by several small poles.

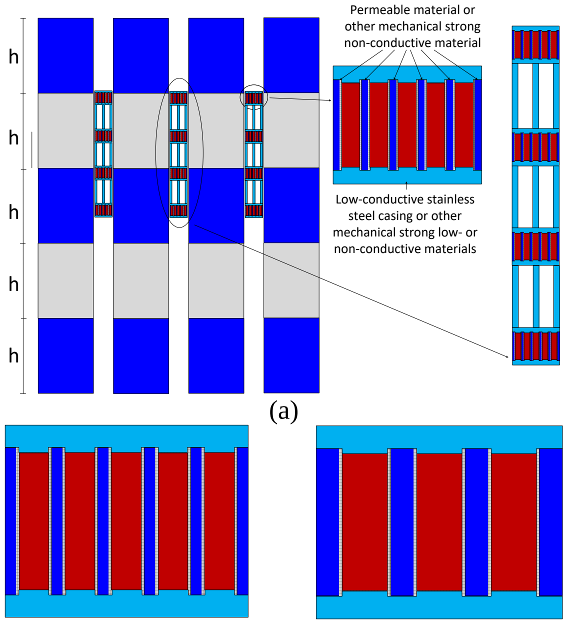


Fig. 3 Detailed mover winding structure

Fig. 3a shows the cross sectional view of detailed mover windings sandwiched in interleaved magnetic plates. This view direction is perpendicular to that in Fig. 2. Each mover conductor is reinforced by permeable materials in thin layer form with necessary insulation to increase mechanical strength. All the conductors and support permeable materials and their insulation are placed in casings to further increase mechanical strength.

Fig. 3b shows different cross sections of the individual mover conductors in red, permeable supports in blue and also their support casing.

To make system easier to be maintained and avoid serious damage due to free-falling, a multi-layer structure as shown in Fig. 4 can be adopted, where there are two layers, each of which can be around 100m high. Two sets of machine systems are installed at respective layer. Roof cover is built to shield against natural influence, like rain, snow etc. Drainage system is also necessary to drain the seeped or perforated water from neighboring soil.

Fig. 5 shows a modified configuration with stronger stator and mover supports. In this modified structure, mover support and stator cores' support are joined together.

For the interleaved magnetic plates between which the distributed mover windings are sandwiched, besides joining parts for different layers of interleaved magnetic plate cores and strong links with base supports, it is also necessary to have fixtures at their top, which are joined with movers' and stator magnetic cores' support poles as shown in the structure in Fig. 5 to reduce vibration.

Fig. 6 shows a second new configuration in which some stator air gaps only accommodate one set of mover windings while the others are the same as the distributed air gaps sandwiched by interleaved magnetic plates.

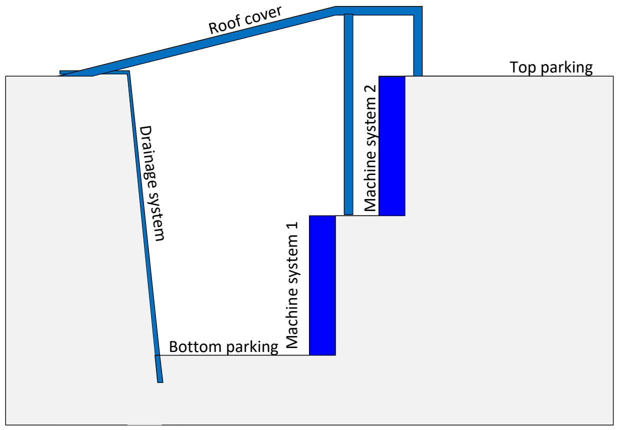


Fig. 4 Multi-layer structure

As seen from Eqn. (1), another good solution is to use more air gaps, each of which is to accommodate one set of mover coils with less turns in each coil. When doing so, more parallel connections for the mover windings need be fulfilled. Furthermore, one may use more vertical sets as shown in Fig. 2 [3-7], in which there are two sets of A1A1', B1B1', and A2A2', B2B2', also two sets of U1U1', V1V1' and U2U2',V2V2'. When necessary, one can use three sets, namely by adding one more set of A3A3', B3B3', four sets even more to reduce the number of turns in each set of mover windings accommodated in each air gap. By doing so, the induced voltage given by (1) is reduced and moreover armature effect brought by the currents flowing through mover windings can be effectively contained as the mover ampere-turns are reduced accordingly at one vertical layer. Certainly this measure will make vertical span of the mover longer.

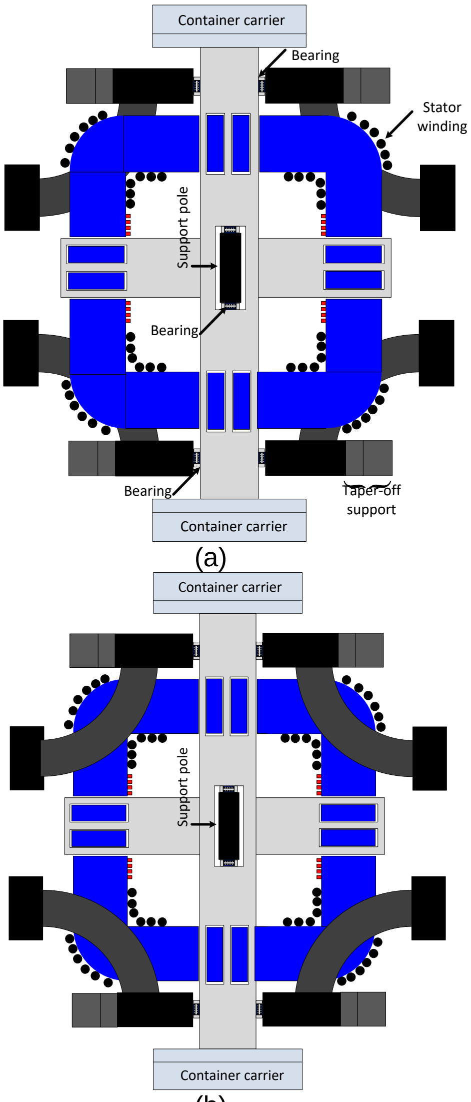


Fig. 5 Modified configuration

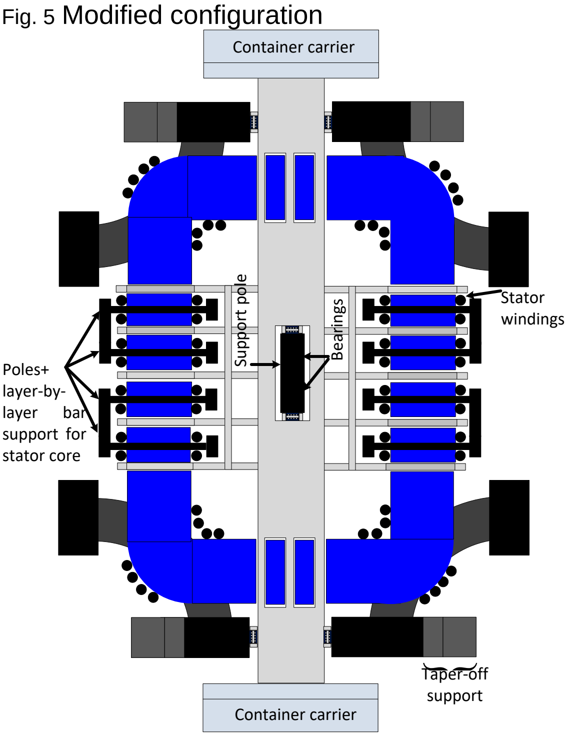
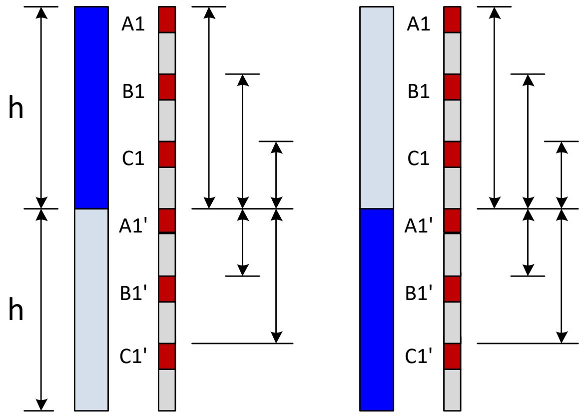


Fig. 6 New configuration 2



(a) (b)

Fig. 7 Structure for calculating induced voltages

One more measure that could solve induced voltage issues is to increase the cross sectional area of each individual mover conductor as shown in Fig. 3b. Compared with the left-hand-side configuration in Fig. 3b, the mover conductor cross sectional area in the right-hand-side configuration is increased. By doing so, less turns are used in one coil or winding inserted in each distributed air gap. Nevertheless such increment of area cannot lead to area-proportional increase in current as heat is harder to be dissipated in larger area. So overall current-carrying capability by the mover conductors in one air gap deteriorates slightly. Nevertheless due to the reduced number of turns and decreased ampere-turns, both induced voltages in non-transitional coils and armature reactance are reduced. As the current flowing through the mover conductor becomes greater, several parallel-connected driving circuits may need be used.

Another solution for solving induced voltages thoroughly is: instead of using large vertical span h in one stator layer in Fig. 7 to accommodate sides A1, B1 and C1 of multiple coils A1A1', B1B1' and C1C1', one may reduce each layer height h from around 1m to around 0.45cm or even less to only accommodate the side of one coil. Such configurations have been proposed in both [4] and [7]. Nevertheless such arrangement needs to divide all the mover windings into more sets and span them longer along vertical direction, and also needs more distributed air gaps along circumferential stator magnetic path and more separate driving circuits to reduce the induced voltages. When the vertical distance h between neighboring stator layers (air-layer and magnetic layer) is quite small, there will be cross coupling effect between stator magnetic layers. Such coupling could cause severe vibration, thereby leading to collapse of the stator system if their support poles are not mechanically strong enough. For these configurations, besides the poles with support bars for holding stator magnetic cores, there should be small pole supports in between any two neighboring stator magnetic layers. These small poles are also applicable to other configurations to increase mechanical strength.

One such a design is shown in Fig. 9, where there are two sets of mover windings to cancel reluctance force influence. The first set is A1A1’, B1B1’, C1C1’, while the other set is D1D1’, E1E1’, F1F1’. Each of them comes with necessary insulations.

A1A1’ in Fig. 9 is a coil or winding with several turns in series. So are other coils which have exactly the same number of turns in series.

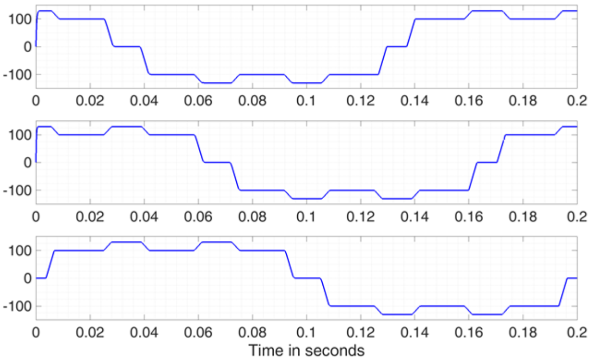


Fig.8 Example currents in the coils in Fig. 7

Group B1B1’ is shifted in relative position with reference to the relative position of A1A1’ by 2h+h/3 while C1C1’ is shifted further in relative position with reference to the relative position of B1B1’ by 2h+h/3.

D1D1’ is shifted from A1A1’ by 7h.

In the design, each of group A1A1’, group B1B1’, and group C1C1’ just conduct 80% of its rated current during non-transitional operation. When one coil experiences current reversing during transition, the other two conduct 120% of their rated currents in short time. Such change of currents in non-transitional coils also induces voltages in the transitional coil, which needs be addressed as well.

To achieve the current waveforms in Fig. 8 for each of groups A1A1’, B1B1’, and C1C1’ in Fig. 9, one may adopt either high voltage during transition or PWM methods to control them. During non-transitional operation, PWM can also be taken to keep the currents nearly constant with very small fluctuation.

When the mover windings are properly connected in parallel, the driving circuits could be also used to compensate the induced voltages during transitions between stator magnetic and non-magnetic layers. So long the driving circuits can make the currents flowing through the three sets of mover windings as close as possible to the waveforms as shown in Fig. 8 relative to mover physical positions with reference to stator structure, the linear machine can work properly. Such current tracing could be achieved by a sophisticated controller over driving circuits.

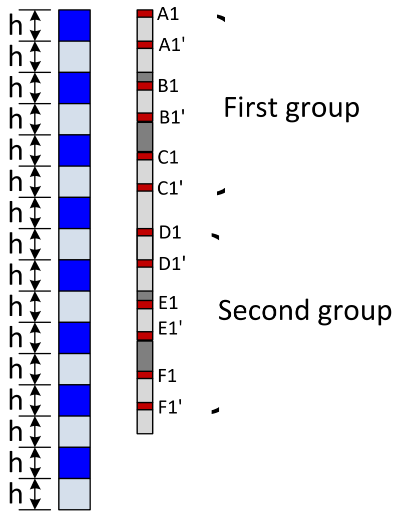


Fig. 9 Cut cross sectional view of more suitable mover coils’ arrangement

The design in Fig. 9 makes the mover span relatively long along vertical direction. One less lengthy design is shown in Fig. 10, where group Y is shifted in relative position with reference to group X by 2h+h/3 while group Z is shifted in relative position with reference to group Y by 2h+h/3. Corresponding driving circuits need be designed. For such a configuration in Fig. 10, the vertical distance h could be further reduced. Certainly the height of each of the thin mover conductors along vertical direction need be shortened. Other groups of mover windings to cancel reluctance force need be used. For this configuration, there are still induced voltages which need be attended.

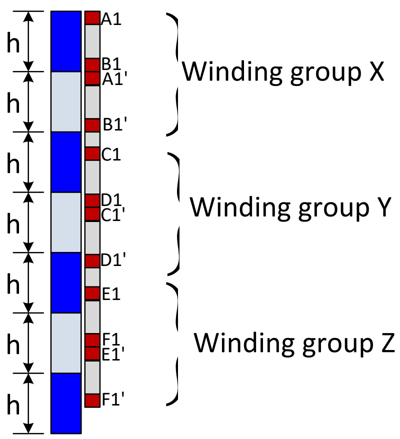


Fig. 10 Another coil arrangement

Again A1A1’ in Fig. 10 is formed by several turns in series as shown in Fig. 3. So are others.

The connections of these coils in series and in parallel need to meet

1) nearly equal current sharing in the parallel branches by having enough turns.

2) induced voltages in other windings due to transition of one winding is sufficiently small without

causing malfunction. Nevertheless the induced voltages could be compensated by transformer based measures as aforementioned. In such a case, moderate values are tolerable. Moreover proper control over driving circuits could also compensate the induced voltage as well.

3) armature reactance or reduction of magnetic field established by stator current by that produced by mover currents is contained to an acceptable level.

Instead of designing a system to carry large container with heavy masses, one can design a relatively small system to carry lighter container with heavy masses, e.g. from 60 tons of each container with heavy masses to 30 tons. By doing so, the mover currents are reduced and armature effect is reduced to an acceptable level. Certainly as described above, one can reduce the number of mover winding turns in each air gap and have more mover winding sets spanning longer along vertical direction to reduce the armature effect.

III. CONCLUSION

This paper presents a series of improved configurations for the heavy masses potential energy storage using linear machines. To avoid induced pulse voltages in neighboring coils, one may use one coil instead of several coils across one pair of interleaved stator magnetic structure, one being magnetic layer while the other being non-magnetic or air layer. For such an arrangement, vertical distance for each stator layer needs be reduced and more air gaps need be introduced along circumference of the stator magnetic path. The design should ensure that sufficient mechanic support is used to avoid vibration due to cross coupling between neighboring two stator magnetic layers.

Alternatively more air gaps sandwiched by interleaved magnetic plates are introduced along the stator magnetic path, and the total mover windings are divided into more sets. By doings so, less turns of mover conductors are installed in each air gap and the complete mover windings are spread along vertical direction longer. Due to the reduction of the number of mover coils in each air gap, the induced voltages in neighboring coils are reduced to a safe level when one coil experiences transition.

Furthermore greater cross sectional area of individual mover conductors can be taken to reduce the number of turns, thereby leading to reduced induced voltages.

Such a method by the reduction of the number of mover conductors in each air gap and dividing mover windings into more sets and spreading them longer along the vertical direction can effectively reduce armature effect to an acceptable level.

REFERENCES

[1] Alan J. SANGSTER, "Massive energy storage systems enable secure electricity supply from renewables", J. Mod. Power Syst. Clean Energy (2016) 4(4):659–667.
[2] Tom Scott, ViewTekz LLC., "ENERGY STORAGE", USA patent, US 7,973,420 B2.
[3] 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.
[4] 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.
[5] Daming Zhang, "Energy Buffer and Other Issues in Heavy Mass Energy Storage with Vertical Movement by Linear Machine", Journal of Multidisciplinary Engineering Science and Technology (JMEST) on-line link: http://www.jmest.org/, ISSN: 2458-9403, Vol. 6, Issue 6, June – 2019.
[6] Daming Zhang, "Issues on Heavy Mass Energy Storage with Vertical Movement by Linear Machine", ICPES 2019, Perth, Australia.
[7] Daming Zhang, "Issues on Heavy Mass Energy Storage with Vertical Movement by Linear Machine", ICPES 2019, Perth.