Issues on Series-Parallel Circuits and their Drives in the Linear Machine for Heavy Mass Energy Storage System

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Abstract. An energy storage system using a linear machine for lifting heavy mass to convert its potential energy to/from electricity has the following advantages 1) Environment friendliness; 2) Long life span; 3) Potential lower cost-to-life span ratio which tests human-beings patience to see. Such kind of system has rotor or mover and stator structure. For simplicity, the stator can take windings spreading from the bottom to top of interleaved stator structure with windings wound around it. The stator windings are formed by multiple strands of aluminium conductors in parallel to reduce ohmic losses, leading to higher efficiency. The rotor or mover is formed by multiple fundamental units which are reinforced by stainless steel or other reinforcement, each unit consisting of flat copper conductor sandwiched between magnetic materials through insulators. The copper conductor in each unit is joined at terminals either in series or in parallel. In this paper research is on the issues of having proper number of series and parallel circuits.

1. Introduction
Grid-scale energy storage is of paramount importance to solve energy crisis[1-2]. Currently tremendous effort in this field is being carried out by world-wide researchers. To-date, many new advancements have been made. In [3], a hydro-power based on man-made reservoir is proposed. The project “StEnSEA” (Stored Energy in the Sea) is investigating the installation of large storage facilities on the sea floor, in combination with offshore wind farms. A hollow sphere with an inner diameter of 30m will be submerged to a water depth of about 700m, so the hydrostatic water pressure creates an energy potential. Such storage can store about 20 MWh (4 hours discharge time for a 5 MW pump turbine) per storage unit. Multiple spheres are connected to have large storage capacity as shown in Fig. 1. Its charge-discharge efficiency can be as high as 80-85 %. Such system can only built in the place with water and is not suitable for land application.

In [4], the Beacon Gen4 flywheel is designed to provide 100 kW of output and store 25 kWh of energy. Two hundred flywheels will be connected in parallel to provide 20 MW in capacity and can fully respond in less than 4 seconds. The plant can operate at 100% Depth of Discharge with no energy degradation over time and can do so for over 150,000 full charge/discharge cycles. The flywheels are built to last 20 years or more. Minimum maintenance is required in the mechanical portion of the flywheel system. But the cost for developing such technology needs a total Budget of US$52,415,000. Furthermore it can only store energy for several hours and is not suitable for storing solar energy to be used during night.

Battery storage is the most convenient one but it can only last less than ten years.
In [5-7], heavy mass energy storage was adopted for land-based grid-scale energy storage. Nevertheless each of them has the feature of low efficiency. To overcome such a problem, a new design in [8-10] has been worked out and it has the following features: 1) stator structure is interleaved with alternating magnetic and non-magnetic layers; 2) stator windings are wound spreading from the bottom to top of interleaved stator structure; 3) multiple strands of aluminium conductors in the stator windings are in parallel to reduce ohmic losses, leading to higher efficiency; 4) vertical movement of the rotor or mover minimizes friction losses, thereby improving overall efficiency; 5) by using interleaved stator plates, fringing effect is effectively reduced.

Figure 1. Artificial reservoir for storing energy in the Sea

In this paper a detailed study on the series-parallel circuits for the structure as shown in [10] is conducted.

The following contents are arranged as follows: In Section II, review on topologies of the linear machine for the heavy mass energy storage is conducted; Section III examines the series-parallel circuits in the rotor or mover; Section IV presents drive circuits for rotor or mover; Conclusion is drawn in Section V.

2. Review on topologies of the AC-DC linear machine
As described in [9-10] and shown in Fig. 2a, interleaved magnetic structure of the stator has been taken, where distributed rotor or mover structure with interleaved stator plates is used. Multiple parallel strands of aluminium conductors for the stator spreading from the bottom to the top of the passage are arranged to reduce the ohmic losses. One may use the poles spreading from the bottom to the top of the passage to support the magnetic layer as shown in Fig. 2b. By doing so, alternating non-magnetic layers can be left as air. If one wants to reduce the leakage flux produced by the stator currents, then distributed stator windings can be taken, which are wound around each stator magnetic layer and inter-connected in series with each other from the top to the bottom. This is only suitable for the air-layer and magnetic layer alternating structure with enough layer vertical length as shown in Fig. 2b. Furthermore such arrangement needs more stator conductors and incurs more cost. Fluctuating reluctance force in such structure needs be addressed properly. As described in [9-10], the distributed rotor or mover with interleaved stator plates can effectively reduce the fringing effect and produce effective lifting force.

Two possible configurations for rotor or mover conductors are shown in Fig. A1 [9-10], each one being insulated and embedded in magnetic materials. To reduce the air gap and thereby decrease ampere-turns requirement on the stator winding, flat conductors are adopted and shown in Fig. 2c.

Figure A2 shows a symmetrical structure with distributed rotor or mover structure, in which there are two nearly closed-loop magnetic paths, which are mirror arrangements of the structure as shown in Fig. 2a. There are also reinforcing mechanic parts on the rotor or movers. Due to symmetry in Fig. A2, it is relatively easier to minimize the friction losses when the heavy masses are lifted vertically along
the support poles [9-10]. Figure A2 also shows the carbon brushes which contact the vertical conductors spreading from the bottom to the top of the passage. Between brushes and terminals of the rotor or mover conductors there are converter circuits described in a later paragraph. Such brush structure can also be applied to the configuration in which full magnetic stator structure or non-interleaved stator structure is used as shown in [8].

Figure A3 shows vertical cut cross section of rotor or mover structure with combined sets where each layer of the stator structure accommodates two rows of the rotor or mover conductors. Rows CRA1 and CRA3 wound in the way as shown in Fig. A1b form two sides of one coil [10]. CRA2 and CRA4 wound also in the way as shown in Fig. A1b form two sides of another coil. Each of the coils is supplied with AC current to ensure the electromagnetic force always uplifting. CRA1-CRA3 is grouped into set 1; CRA2-CRA4 is grouped into set 2. There could be three rows or even more rows of the rotor or mover conductors across one stator layer. By doing so, the system becomes more compact.

Figure 2. (a) Stator structure and distributed rotor or mover structure sandwiched between interleaved stator plates; (b) Interleaved stator structure with pole supported magnetic layer and non-magnetic air layer; (c) Flat rotor or mover conductors sandwiched between magnetic materials through insulators
Figure 3 shows a distributed rotor or mover structure with container carrier and two vertical support poles. Each time two identical containers are carried at two terminals of the carrier. Stainless steel is a good choice for the mechanical reinforcement for joining different parts of the distributed rotor or mover structure. More details on the three-dimensional view of the rotor or mover structure can be found in [10].

Figure 3. Rotor or mover structure with two distributed rotor or mover parts

3. Issues on drive circuits
One may use the basic configuration as shown in Fig. A2 to achieve the lifting of heavy masses.

Figure 4. A new symmetrical structure of the linear machine system (a) rectangular corners; (b) circular corners

Alternatively, another new structure of the linear machine system is shown in Fig. 4, where double U-shape stator structure is taken. There are two identical rotor or mover units, each of which is distributed one and sandwiched in interleaved stator plates with air space separation as that in Fig. A2. There are also two sets of the stator windings wound on the interleaved stator structure as that in Fig. A2. The flux produced by the two sets of the stator winding enhances each other. Conductors spreading from the bottom to the top of the passage are necessary to provide currents into the rotor or mover through carbon brush contacts. The style of the rotor or mover windings are the same as those shown in Fig. A1b and A3. In Fig. 4a, rectangular corners are used for the U-shape. One may also use circular corner for the U-shape as shown in Fig. 4b. The interleaved stator structure can be formed by
magnetic material layer and air layer and supported by several poles, the same as that shown in Fig. 2b.

By using pulse current waveform as shown in Fig. 5b during the transition of one pair of rows or two rows of the rotor or mover conductors at the boundary between stator magnetic and non-magnetic layers, the effective lifting force is enhanced. To lift certain weight of the container with heavy mass, the number of the rotor or mover conductors can be determined. All the conductors in the rotor or mover are arranged to form a number of identical circuits, each of which consists of multiple turns of the rotor or mover conductors in series as shown in Fig. A1b. The effective inductance in each identical circuit influences the transition of the rotor or movers between stator magnetic and non-magnetic layers as the current in each coil needs to change between 0 and ±I_{rated}. Also the currents in some circuits need be facilitated to change between ±I_{rated} and ±kI_{rated} with k being around 1.5.

![Figure 5. Waveforms of currents flowing through rotor or mover conductors with two rows of rotor or mover conductors across one stator layer](image)

The effective inductance in each rotor or mover circuit can be estimated by the following formula:

\[ L = \frac{N^2}{\mathfrak{R}_{eq}} \]  

(1)

where \( N \) denotes the number of rotor or mover conductors in series and \( \mathfrak{R}_{eq} \) is the equivalent reluctance seen by each coil. When one interleaved stator layer accommodates multiple rows of the rotor or mover conductors, such as that in Fig. A3 where there are two rows of the rotor or mover conductors across each interleaved stator layer, \( \mathfrak{R}_{eq} \) is calculated as follows:

\[ \mathfrak{R}_{eq} = \frac{N_{tot} \times \text{Thickness} / (\mu_0 A)}{\text{RowNum}} \]  

(2)

where \( N_{tot} \) is the total number of conductors in one row, \( \text{Thickness} \) is the rotor or mover conductor thickness and \( \text{RowNum} \) indicates the number of the row of rotor or mover conductors across each interleaved stator layer.

The time constant \( \tau = L/R \) in one rotor or mover circuit also influences speed of transition, where \( R \) and \( L \) are the copper resistance and inductance of one circuit in the rotor or mover respectively.

Tables 1 through 7 show one example design using the basic structure in Fig. A2. Table 1 includes dimensions of the stator core. Totally the height of the passage is 160m with 160 alternating layers, either stator magnetic layer or non-magnetic layer being countered as one separate layer. Hence vertical height of each layer is 1m. Table 2 includes the basic information such as air permeability, saturation flux density, steel density etc. It also includes rated currents for the rotor or mover and stator. The material costs are shown in Table 3. The electricity tariff per kWh is also shown there. Table 4 shows the rotor or mover information. Table 5 show extra information such as loss factor and cost factor etc. The loss factor is adopted in order to take into account the friction losses which cannot
be calculated in the current approach. The breakdown construction cost is shown in Table 6. Table 7 includes efficiency and electric loss components.

For one row of the rotor or mover conductors, there are totally $4 \times 2 \times 20 = 160$ rotor or mover conductors for each side, just like CRA1 and CRA3 in Fig. A3 in the Appendix. Totally there are ten pairs of such double-side coil, spreading $2 \times (160m/160) \times 10 = 20m$, which is defined as the length of the rotor or mover. Each interleaved stator layer accommodates three rows of the rotor or mover conductors. Hence totally the current flowing through one side of the coil pair is $500A \times 160 \times 3 \times 10 = 2,400,000A$. It is not affordable to provide current into each rotor or mover conductor separately. Instead one needs to group the rotor or mover conductors in the way as shown in Fig. A1a or Fig. A1b. That is to say, all the rotor or mover conductors are divided into multiple groups each of which contains the same number of the rotor or mover conductors. All the rotor or mover conductors in each group are connected in series. The less group leads to higher current demand. If more rotor or mover conductors are connected in series, then its inductance becomes greater, thereby posing a challenge to the current transition, as higher voltage is required.

According to the formula $v(t) = L \cdot \frac{di}{dt}$, in order to complete the transition of the current in the rotor or mover conductors, the required voltage applied across the series connected rotor or mover conductors needs be high enough in order to complete transition within time limit.

For a practical application to achieve high pulse voltage for facilitating current change, multiple drive circuits as shown in Fig. 6 can be adopted. To reduce the weight of the converter, the isolation transformers in Fig. 6 need to work at high frequency.

In this design, the thickness of flat rotor or mover conductor and the sandwiching magnetic material as shown in Fig. 2c is the same and equal to 2mm each. For better rigidity and stiffness of the rotor or mover, such ratio could be changed to 4mm:4mm. If one wants to reduce the rotor or mover weight, the thickness of the sandwiching magnetic material can be reduced, such as 3mm:4mm, 3mm being for the thickness of the sandwiching magnetic material and 4mm being for that of the rotor or mover conductor or other ratios. Certainly in order to have higher rigidity, 5mm:4mm could be used. In this case, the ratio of mass weight to the rotor weight is reduced, leading to less effective movement of the heavy masses.

Figure 6. Drive circuits for the rotor or mover through DC conductors spreading from the top to the bottom of the passage

As an example if one connects all 160 rotor or mover conductors in one row in series, the equivalent inductance is approximately $48mH$. To change a current of $500A$ to zero within $1ms$, the demanded voltage is $48E-03 \times 500A / 1E-03 = 24,000V$. Such high voltage could be produced by the cascaded output connections in the circuit as shown in Fig. 6. Under normal operation, the total
induced voltage for 160 conductors in series is around $B_1*V*160=1.25*1*160=1200\text{V}$, which is provided by by-passing or short-circuiting some output stages of the circuit in Fig. 6. By doing so, there will be $3*10$ or 30 pairs of DC conductors spreading from the bottom to the top of the passage, providing high voltage and high current DC power to the rotor or mover through carbon brush contacts. Instead of using 30 pairs, one may use less pairs with each conductor taking greater size in order to carry higher currents.

Figure 7 shows a drive circuit with AC conductors spreading from the top to the bottom of the passage. This implementation needs high-frequency transformer and high-frequency carbon brush contacts, which are more challenging compared with that in Fig. 6.

![Drive circuits for the rotor or mover through AC conductors spreading from the top to the bottom of the passage](image)

**Figure 7.** Drive circuits for the rotor or mover through AC conductors spreading from the top to the bottom of the passage

| Table 1. Dimensions |  |
|----------------------|--|
| **Dimensions**       | m  |
| Core width B1 (Fig. 8) | 1.0m |
| Core length L1 (Fig. 8) | 2.80m |
| Core inner space distance D1 (Fig. 8) | 2.688m |
| Height of the passage | 160m |
| Alternate layers     | 160 |

| Table 2. Parameters |  |
|---------------------|--|
| **Parameters**      |  |
| Air permeability    | $4\pi \times 10^{-7} \text{H/m}$ |
| Saturation flux density | 1.25 T |
| Steel density       | $8\times10^3 \text{kg/m}^3$ |
| Copper mass density | $8.96\times10^3 \text{kg/m}^3$ |
| Copper conductivity | $5.96\times10^7 \text{S/m}$ |
| Aluminum conductivity | $3.5\times10^7 \text{S/m}$ |
| Stator current rating | 500A |
| Rotor or mover current rating | 500A |
| Cross sectional area of individual stator conductor | $3.5\times10^{-4} \text{m}^2$ |
| Stator conductor increment factor | 8 |
| Total each stator conductor’s area | $8\times3.5\times10^{-4} \text{m}^2$ |
| Cross sectional area of individual rotor or mover conductor | $3.5\times10^{-4} \text{m}^2$ |

| Table 3. Material cost |  |
|------------------------|--|
| **Dimensions**         | m  |
| Copper                 | 0.65US$/kg |
| Aluminium              | 2000US$/m^3 |
| Steel                  | 600x8 US$/m^3 |
| Concrete or cement     | 30US$/ton |
| Electricity tariff per kWh | 0.20US$/; |

| Table 4. Rotor or mover information |  |
|-------------------------------------|--|
| **Rotor or mover conductor pair per row** | 4 |
| **Rotor or mover conductor number per section** | 20 |
| **Total number of conductors per layer** | $4*2*20=160$ |
| **Number of rows of rotor or mover conductors per stator alternate layer** | 3 |
| **Rotor or mover conductor coil number (formed by two rows of the conductors)** | 10 |
| **Conductor** | Copper |
| **Thickness of rotor or mover conductor** | 2mm |
| **Length of rotor or mover conductor** | 17.5cm |
| **Air gap in rotor or mover** | 0.32m |
| **Width of the rotor or mover (L2 in Fig. 7)** | 0.64m |
Travel speed of the rotor or mover | 6.0m/s
---|---
Number of rotor or movers | 1
Height of each rotor or mover set | 2*10=20m

| Table 5. More information |
|-------------------------|
| Number of containers | 800 |
| Loss factor | 2.7 |
| Cost factor | 1.5 |
| Mass per container | 200.28/2 =100.14ton |
| Rotor or mover weight | 188.16ton |
| Yearly usage rate | 80% |
| Total energy stored | 139.72MWh |

Profit return year | Less than nine years

| Table 7. Losses and efficiency |
|-----------------------------|
| Power losses in the rotor or mover | 78.62 kW |
| Power losses in the stator | 571.43 kW |
| Power at 6m/s | 23.040 kW |
| One-way efficiency with a loss factor of 2.7 | 92.38% |
| Round-way efficiency | 85.34% |

| Table 6. Breakdown construction cost |
|----------------|
| Parts | Million dollars |
| Steel | 3.9456 |
| Heavy mass | 9.3226 |
| Copper for the rotor or mover | 0.0548 |
| Aluminium for the stator | 1.2544 |
| Total Cost | 1.5*29.15=43.73 |
| Income per year | 8.159 |

Figure 8. Dimensions of the magnetic structure for the stator (cross sectional view)

Losses like the friction losses, converter losses and also movement of the containers along the top or bottom platforms are hard to quantify. Instead multiplying the electric losses, both stator copper losses and rotor copper losses by a factor is adopted. In this case, the factor is set to 2.7. Such approach could be optimistic. Hence in a real system, the efficiency could be less than 85% as shown in Table 7. Nevertheless a proper design could lead to higher efficiency. Conservatively an efficiency being above 80% could be reached for a practical system.

For the above design, the estimated profit return is less than nine years.

From Table 5, one can see that the total mass of the two containers is 200.28ton while the rotor or mover mass is 188.16ton. The regeneration during the rotor or mover downward movement from the top to the bottom of the passage is nearly equal to half of the total energy lifted up. For a practical massive energy storage, multiple units like that in Fig. A2 or Fig. 4 could be built around a re-shaped mound. At one time, some run in the motoring mode while minority others run in the regeneration mode when the system converts electricity into potential energy. Vice versa when the system converts potential energy to electricity, some run in the generating mode while minority others run in the motoring mode with no containers.

4. Start/stop issues
The lifting force during start/stop can be calculated by the formula below

\[ F - mg = ma = m \frac{dv}{dt} \]  

Under normal travel, the total lifting force produced by the rotor or mover just needs be close to the total weight, an addition of the rotor or mover weight and the weight of the containers with heavy mass. At the start-up for the bottom-to-top movement, the required force is greater in order to accelerate the rotor or mover from the stationary to full speed. From equation (3), one can see that the required lifting force is equal to the total rotor or mover weight plus the term due to acceleration.
Assume that the rotor or mover is accelerated form zero speed to 6m/s using 1s. Then the required start-up force is

\[ F = m(g + a) = m \left[ 9.81 + \frac{(6-0)}{1.0} \right] = 15.81m \text{ or } 15.81m / (9.81m) = 1.612 \text{ times total weight.} \]

If one adopts two rows of rotor or mover conductors under one stator layer and each conductors carries 80% of the rated current, then under normal operation, when the transition between magnetic and non-magnetic layers occurs for one row of the rotor or mover conductors, another row of the rotor or mover conductors needs to take at least 160% of its rated current. In contrast, if one adopts three rows of rotor or mover conductors under one stator layer and each conductor carries 80% of the rated current, then under normal operation, when the transition between magnetic and non-magnetic layers occurs for one row of the rotor or mover conductors, another two rows of the rotor or mover conductors only needs to take at least 120% of its rated current. Therefore in terms of reducing the burden of the current carried by each rotor conductor, it is better to place more rows of the rotor or mover conductors under one stator layer. But such arrangement will increase the inductance which demands higher voltage to facilitate the current change from one value to the other within short time during transition. Nevertheless more rows of the rotor or mover conductors can effectively relieve the start-up current demand.

If one adopts the three rows of the rotor or mover conductors across one stator layer, then during start-up as described in the above, each rotor or mover conductor needs to take 80% x 3 x 1.612 / 3 = 80% x 1.612 = 128.96% of rated current during the non-transition movement. During transition, to keep the same lifting force, each of the conductors in the two rows with non-zero current needs to take 128.96% x 3 / 2 = 193.44% of rated current. Such high current during transition can cause over-heat problem. To alleviate such problem, a reduced current such as 150% of the rated current can be conducted by the non-transition rotor or mover conductors. Then the total acceleration takes slightly longer than the targeted one second. During the start-up, forced cool-air can be blown towards the rotor or mover conductors to ventilate. By doing so, the rotor or mover temperature can be kept within limit.

When the rotor or mover reaches the bottom during downward movement and is ready to stop, the same high up-lifting force needs be produced in order to reduce the rotor or mover full speed to zero.

When the containers are lifted upward and reach the top of the passage, the stoppage can be achieved by reducing rotor or mover currents.

5. Conclusion

This paper presents a study on rotor or mover circuits and their driving converter circuit for the linear machine used in heavy mass energy storage system. Compared with other grid-scale massive energy storage system, the proposed system has the advantages of 1) Environment friendliness; 2) Long life span; 3) Potential lower cost-to-life span ratio. For simplicity, the stator can take windings spreading from the bottom to top of interleaved stator structure with windings wound around it. Alternatively distributed stator windings around each stator magnetic layer are still possible as air-layer could be taken for the non-magnetic stator layer. This paper further studied the number of rotor or mover circuits and rationale to choose the right number. To reduce the voltage demand, it is preferable to have less turns in series in each circuit. But less turns lead to more converter circuits which make the system more complex.

To reduce the fringing effect during the transition of the rotor or mover between interleaved layers of the stator structure, interleaved stator plates are used to sandwich the distributed rotor or movers. By doing so, de-rating effect on the electromagnetic force could be mitigated.

References

[1] Daniel E. Olivares, and Nikos D. Hatzigioryiou 2014 IEEE TRANSACTIONS ON SMART GRID, VOL. 5, NO. 4, pp.1905-1919
[2] Alan J. SANGSTER 2016 J. Mod. Power Syst. Clean Energy 4(4) pp. 659–667
[3] https://forschung-energiespeicher.info/
Appendix

Figure A1. (a) First way to wind the winding; (b) Second way to wind the winding
Figure A2. Horizontal cross section of the AC-DC induction machine

Figure A3. Vertical cut cross section of rotor or mover structure with combined sets where each layer accommodate two rows of rotor or mover conductors