A Novel Dual-Stator Vernier Machine with Low Temperature Superconducting Excitations

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Background

Vernier permanent magnet machines (VPMMs) possess many advantages including simple configuration, high torque density and efficiency, thus are promising candidates for the motors in wind turbine powertrains, electric vehicles or ship propulsion systems. However, since the PM flux linkage is almost constant, **the flux-weakening capability** of VPMMs is usually inferior than the wound field machines (WFMs). Moreover, the **power factor** the VPMMs is also **lower**. In order to incorporate the merits of VPMMs and WFMs, this paper proposes **a vernier machine with superconducting wound field windings**, which can exhibit **higher torque density, flux weakening capability and power factor** than the conventional VPMMs.

Objectives

- Investigate the operation principles and clarify the slot-pole combinations.
- Compare the proposed LTS WFVM to a regular VPMM with Halbach-array PMs

Conclusion

- **A superconducting (SC) wound field vernier machine (WFVM)** is proposed in this paper.
- The proposed LTS WFVM has a simple structure with high reliability. No brushed and slip rings is needed, and the rotor has a simple reluctance structure.
- Compared to a regular VPMM with Halbach-array PMs, the proposed machine has 29.3% higher torque density, 84.6% larger power factor, stronger flux weakening and overload capabilities.
- The **main drawback** of the proposed LTS WFVM is the high pulsating torque.
- The **overall cost** of the LTS WFVM system would still be competitive compared to that of the regular VPMM system because the inverter cost and machine volume of the proposed machine system are smaller.

Configuration

Cross-sectional view

Two stators and a sandwiched rotor:

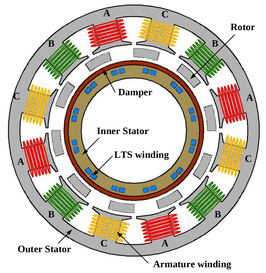
- Inner stator adopts air-core and is wounded with DC SC windings
- Outer stator is wounded with AC armature windings
- Reluctance rotor without any excitations

Advantages:

✓No slip rings and brushes is need

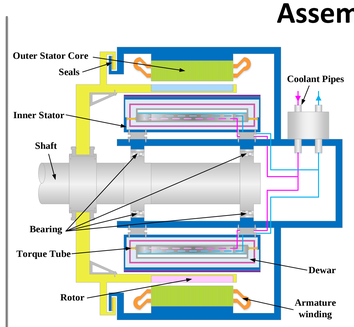
✓Rotor is robust and simple

✓LTS windings easy to be cooled



Configuration of proposed LTS WFVM

Assembly

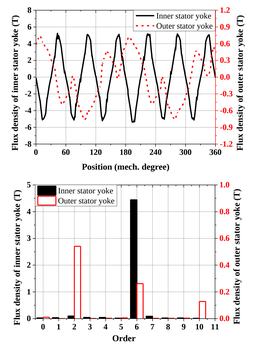


Assembly of proposed LTS WFVM

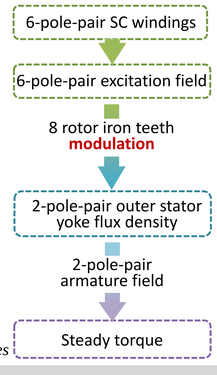
Characteristics:

- Sandwiched rotor is fixed at the left end, and supported by a cantilever.
- Damper helps reduce AC losses of LTS windings
- LTS wires working temperature is 4.2K, made of NbTi material and cooled by liquid helium

Operation Principles



Flux density distribution of stator yokes



Slot-pole Combinations

The superconducting winding pole pair number P_{ins}, rotor modulation teeth number Z_r, and outer stator winding pole pair P_{ous} should satisfy:

$$Z_r = |P_{ins} + \mathrm{sgn} * P_{ous}|$$

$$\frac{Z_{ous}}{\mathrm{GCD}(Z_{ous}, P_{ous})} = mi, \quad i = 1, 2, 3...$$

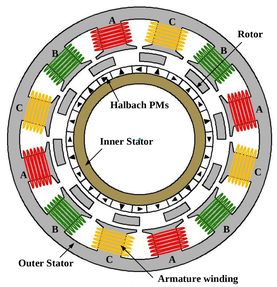
SOME FEASIBLE COMBINATIONS OF THE THREE-PHASE LTS WFVM

Z_{ous}	P_{ins}	3	4	5		6		7		8		9		10		11		12		13	
3i, i=1,2,3 ...	P_{ous}	1	1	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
	Z_r@sgn=1	4	5	6	7	7	8	8	9	9	10	10	11	11	12	12	13	13	14	14	15
	Z_r@sgn=−1	2	3	4	3	5	4	6	5	7	6	8	7	9	8	10	9	11	10	12	11
	Pole Ratio	3	4	5	2.5	6	3	7	3.5	8	4	9	4.5	10	5	11	5.5	12	6	13	6.5

PS: only lists the combinations whose pole ratio is no smaller than 2.5

Performance Comparisons

Comparison condition



Configuration of a regular VPMM

KEY PARAMETERS OF THE PROPOSED AND REGULAR VERNIER MACHINES

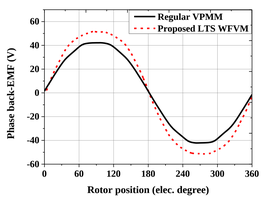
Parameters	Proposed LTS WFVM	Regular VPMM with Halbach PMs
Outer stator outer diameter	124mm	
Stack length	120mm	
AC winding pole pair	5	
Winding pitch	1	
AC current	4A	
Physical airgap length	0.6mm	
Rotor modulation teeth number	11	
Inner stator outer diameter	74.6mm	
Inner stator inner diameter	56mm	
Inner stator pole pair	6	
DC current	750A	-
PM thickness	-	3.5mm

Comparison conditions:

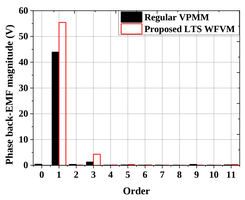
- Same outer stator core, outer stator windings, rotor and air-core inner stator.
- Same outer stator outer diameter, stack length, AC armature winding current, rotation speed.
- **Only difference is**: proposed WFVM excited by LTS windings; regular VPMM excited by Halbach-array PMs.

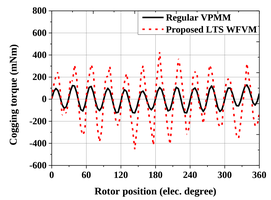
Results

No-load Condition



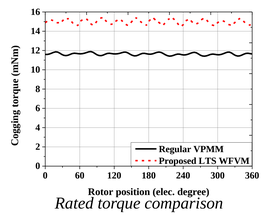
Phase back-EMF comparison



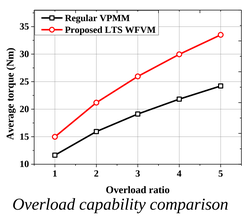


Cogging torque comparison

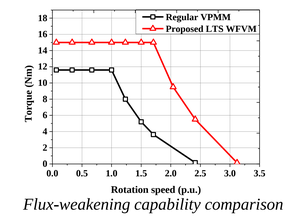
Load Condition



Rated torque comparison



Overload capability comparison



Flux-weakening capability comparison

PERFORMANCES OF THE PROPOSED AND REGULAR VERNIER MACHINES

Performances	Proposed LTS WFVM	Regular VPMM with Halbach PMs
Average torque	15.0Nm	11.6Nm
Cogging torque/Rated torque	5.9%	2.2%
Ripple torque/Rated torque	6.5%	4.1%
Back-EMF magnitude	55.5V	43.9V
Power factor	0.96	0.52
Synchronous inductance	13.5mH	33.4mH
Inverter rating (p.u.)	0.54	1

Strengths:

- Proposed machine has 29.3% higher torque density, 84.6% larger power factor, stronger flux weakening and overload capabilities.

Weaknesses:

- Proposed machine has 3.7% larger cogging torque and 2.4% larger ripple torque.

Well-matched:

- The overall cost of the two vernier machine systems would be comparative, as the inverter cost of the proposed machine is lower while the LTS wires cost is higher than that of the regular vernier machine.

Presented at the International Conference on Magnet Technology , 2017 Aug. 27 – Sept. 1, Amsterdam, Netherlands; Paper I.D. number: Tue-Af-Po2.06-07