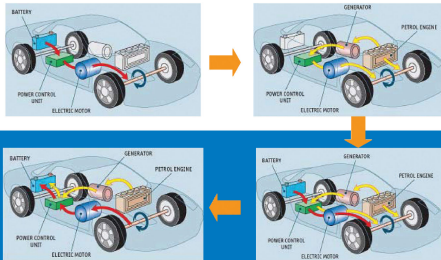




Sung In Jeong (Autor)

## Comparative Study of Linear Oscillating Generators



Sung In Jeong

Comparative Study of Linear  
Oscillating Generators



Cuvillier Verlag Göttingen  
Internationaler wissenschaftlicher Fachverlag

<https://cuvillier.de/de/shop/publications/7093>

Copyright:

Cuvillier Verlag, Inhaberin Annette Jentsch-Cuvillier, Nonnenstieg 8, 37075 Göttingen, Germany

Telefon: +49 (0)551 54724-0, E-Mail: [info@cuvillier.de](mailto:info@cuvillier.de), Website: <https://cuvillier.de>



---

# Table of Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Linear Oscillating Machines</b>	<b>5</b>
2.1	Linear Machine .....	5
2.2	Linear Oscillating Machine .....	6
2.2.1	Introduction .....	6
2.2.2	Period Studies and Application .....	7
2.3	Application Fields .....	8
2.3.1	Hybrid Vehicles .....	8
2.3.2	Free Piston Generator .....	9
<b>3</b>	<b>Analysis Procedure</b>	<b>11</b>
3.1	Proposed Topologies .....	12
3.1.1	Cartesian .....	12
3.1.2	Cylindrical .....	13
3.1.3	Hybrid Stepping .....	14
3.1.4	Tubular Reluctance .....	14
3.1.5	Transverse Flux .....	15
3.2	Equivalent Magnetic Circuit .....	16
3.2.1	Leakage Fluxes .....	17
3.2.2	Effects by EMC Analysis .....	17
3.3	Finite Element Analysis .....	17
3.4	Calculation for Magnetic Energy .....	18
3.4.1	Method I .....	19
3.4.2	Method II .....	20
<b>4</b>	<b>Cartesian Topology</b>	<b>21</b>
4.1	Introduction .....	21
4.2	Principle of Force Generation .....	22
4.3	Comparison of Type I, II and III .....	23
4.4	Analytical Calculation .....	25
4.4.1	One-Phase System with Two Magnets and Two Pole-Pairs .....	26
4.4.2	Two-Phase System with One Magnet and One Pole-Pair (Half-Side) .....	28
4.4.3	Two-Phase System with One Magnet and One Pole-Pair (Double-Side) .....	30



4.5	Optimal Design .....	31
4.5.1	Height of Magnet .....	33
4.5.2	Width of Magnet .....	33
4.5.3	Width of Yoke .....	34
4.5.4	Length of Yoke .....	35
4.5.5	Width of Teeth .....	35
4.5.6	Length of Slot-Opening .....	36
4.5.7	Summary .....	37
4.6	Discussion .....	39
<b>5</b>	<b>Cylindrical Topology</b> .....	<b>41</b>
5.1	Introduction .....	41
5.2	Configuration .....	42
5.3	Principle of Force Generation .....	43
5.4	Numerical Calculation .....	44
5.5	Analytical Calculation .....	44
5.5.1	One-Phase System .....	45
5.5.2	Two-Phase System .....	49
5.5.3	One-Phase System with 3 Coils and Long Stroke .....	49
5.6	Discussion .....	52
<b>6</b>	<b>Hybrid Stepping Generator</b> .....	<b>53</b>
6.1	Introduction .....	53
6.2	Proposed Topologies .....	54
6.2.1	Surface Mounted PMs Mover .....	55
6.2.2	Flux Concentrating PMs Mover .....	55
6.3	Analytical Calculation .....	56
6.4	Comparison Results .....	57
6.4.1	Surface Mounted PMs Mover .....	57
6.4.2	Flux Concentrating PMs Mover .....	58
6.5	Selection of Surface Mounted and Flux Concentrating PMs Mover Types .....	59
6.6	Proposal Model .....	60
6.6.1	Analytical Calculation of Proposed Model .....	61
6.6.2	Comparison of Flux Concentrating Slanted PMs and Proposed Model .....	63
6.7	Discussion .....	65
<b>7</b>	<b>Cylindrical Reluctance Machine</b> .....	<b>67</b>
7.1	Introduction .....	67
7.2	Configuration .....	68



7.3	Cylindrical Linear Switched Reluctance Machine .....	69
7.4	Proposal of Study Models .....	70
7.4.1	Case I .....	71
7.4.2	Case II (Rectangle Shape) .....	71
7.4.3	Case III (Trapezoid Shape) .....	72
7.5	Analytical Calculation .....	74
7.5.1	Rectangular Shape .....	75
7.5.2	Trapezoidal Shape .....	77
7.6	Comparison Results .....	79
7.7	Discussion .....	81
<b>8</b>	<b>Transverse Flux Machine</b> .....	<b>83</b>
8.1	Introduction .....	83
8.2	Subjects of Investigation .....	84
8.2.1	Single-sided TFE .....	85
8.2.2	Double-sided TFPM .....	86
8.3	Analytical Calculation of TFE .....	87
8.3.1	Fundamental Operation Principle .....	87
8.3.2	Analytical Calculation of MMF .....	88
8.3.3	Thrust Force in the Direction of X-axis .....	90
8.3.4	Lateral Force in the Direction of Y-axis .....	91
8.3.5	Attractive / Normal Force in the Direction of Z-axis .....	92
8.4	Analytical Calculation by 2-D EMC .....	93
8.5	Analytical Calculation of TFPM .....	95
8.5.1	Two-Dimension EMC .....	95
8.5.2	Three-Dimension EMCN .....	97
8.6	Comparison Results .....	104
8.6.1	Limitations of 2-D Analysis .....	105
8.6.2	FE Simulation by 3-D Analysis .....	105
8.6.3	Verification by 3-D FEM .....	106
8.7	Discussion .....	106
<b>9</b>	<b>Selection of Optimal Topology</b> .....	<b>107</b>
9.1	Introduction .....	107
9.2	Operating Characteristic .....	107
9.2.1	Voltage Equations .....	108
9.2.2	Generator in Stand-alone Operation .....	109
9.3	Evaluation Standard .....	111
9.3.1	Characteristics Evaluation of Each Topology .....	112



9.3.2	Academic Difference of Single-Phase and Three-Phase .....	113
9.3.3	Comparative Evaluation by Factor Variations .....	116
9.4	Discussion .....	119
<b>10</b>	<b>Detailed Design of Optimal Model</b> .....	<b>121</b>
10.1	Introduction .....	121
10.2	Magnetic Saturation Effects .....	122
10.3	Design considering Nonlinearity of Core .....	124
10.3.1	Calculation of Magnetic Field Distribution .....	124
10.3.2	Flux Calculation .....	127
10.3.3	Resistance Calculation .....	129
10.3.4	Flux Linkage and Force Calculation .....	129
10.3.5	Comparison of Force Characteristics between Analytical and Numerical Calculation .....	129
10.4	Calculation of Machine Weight .....	131
10.4.1	Stator Region .....	131
10.4.2	Mover Region .....	132
10.4.3	Coil Region .....	132
10.4.4	PM Region .....	132
10.4.5	Summary .....	133
10.5	Calculation of Losses .....	133
10.5.1	Hysteresis Loss .....	134
10.5.2	Eddy Current Loss .....	135
10.5.3	Excess Loss .....	136
10.5.4	Total Losses .....	137
10.5.5	Comparison of the Loss Calculation using Example M250-35 .....	137
10.5.6	Loss Analysis for using Example M400-50 .....	139
10.5.7	Calculation of Iron Loss Improvement of the Approach for Eddy Current Loss .....	140
10.5.8	Comparison of the Iron Loss using Example Soft Magnetic Composites	143
10.5.9	Copper Loss .....	144
10.5.10	Eddy Current Loss in Permanent Magnets .....	145
10.5.11	Comparison Results .....	149
10.6	Concrete Dimension of Single-Phase Cylindrical Linear Generator .....	150
10.7	Discussion .....	151
<b>11</b>	<b>Shaft Design through Kinetic Characteristic</b> .....	<b>153</b>
11.1	Introduction .....	153
11.2	Kinetic Equation considering Mechanical Load .....	154



11.2.1	Numerical Calculation .....	154
11.2.2	Analytical Calculation .....	155
11.3	Determination of Shaft Diameter .....	156
11.3.1	Design Procedure .....	157
11.3.2	Fatigue Failure .....	157
11.3.3	Determination of Shaft Diameter .....	160
11.4	Machine Elements Assemblies with Shaft .....	160
11.4.1	Bolt of Uniform Strength .....	160
11.4.2	Tensile and Compressive Strength in Forms of Normal Stress .....	162
11.4.3	Choice of Bolt .....	163
11.5	Concrete Dimension of Machine Elements and Shaft .....	165
11.6	Discussion .....	165
<b>12</b>	<b>Thermal Analysis</b> .....	<b>167</b>
12.1	Introduction .....	167
12.2	Determination of Heat Transfer Coefficients .....	167
12.2.1	Nusselt Number using Dittus-Boelter equation .....	168
12.2.2	Prandtl Number .....	168
12.2.3	Reynolds Number .....	169
12.2.4	Convection Heat Transfer by Water .....	170
12.3	Assignment of Heat Transfer Coefficients .....	171
12.4	Simulation Results .....	172
12.4.1	Comparison by Each Region .....	172
12.4.2	Comparison by Frequency .....	174
12.4.3	Summary .....	176
12.5	Discussion .....	177
<b>13</b>	<b>Assessment</b> .....	<b>179</b>
13.1	Introduction .....	179
13.2	Determination of the Parameters of the Equivalent Circuit from Test Data .....	180
13.2.1	Open Circuit Test .....	181
13.2.2	Short Circuit Test .....	181
13.3	Measurements .....	182
13.3.1	Open Circuit Test .....	182
13.3.2	Short Circuit Test .....	183
13.3.3	On Load Test .....	185
13.4	Discussion .....	187



<b>14 Conclusion &amp; Outlook</b>	<b>189</b>
14.1 Conclusion .....	189
14.2 Outlook .....	190
<b>Symbols and Acronyms</b>	<b>191</b>
<b>List of Figures</b>	<b>197</b>
<b>List of Tables</b>	<b>201</b>
<b>Bibliography</b>	<b>203</b>