Optimal Design of a Direct Driven Slotless Tubular Linear Generator for Renewable Energy Extraction

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Abstract. This paper is aimed to present the systematic design scheme of a direct driven slotless tubular linear generator for renewable energy retraction. To reduce operational cogging and increase energy conversion efficiency, the generator stator is equipped with slotless concentrated annular multiphase windings and its mover is encircled by quasi-Halbach arranged permanent magnets. By systematic comparisons and classifications, the preliminary design and operational specifications of supplying maximum flux that can link the stator windings are fulfilled by setting appropriate factor level combinations from the Taguchi’s method. Along with the stator winding selections, potential energy generations from the proposed slotless tubular linear generator can then be estimated. Verified by three-dimensional finite element analyses, the constructed machine prototype can show its adequacy for the operational and design requirements.

1. Introduction
With the demands for generating electricity from various carbon-free renewable energy sources, many efforts have been developed on the designs of appropriate mechanical and electrical conversion systems that can fulfill these requirements. A tubular linear generator (TLG) [1], with slotless stator windings and quasi-Halbach mover permanent magnet (PM) arrangement [2], [3] that can operate in reciprocating manner to incorporate with those reciprocating energy extraction mechanisms, will be reported in this paper. In addition, with specific operational requirements and constraints, a systematic scheme that can assist to design the most appropriate slotless tubular linear generator (STLG) will also be illustrated. Aside from empirical basis, the idea of properly selecting sets of machine parameters that can supply the optimal combinations with desired performance as commonly adopted in the quality engineering, namely as Taguchi’s method [4], will be introduced to perform the relative machine parameter selections and performance assessments.

2. The Slotless Tubular Linear Generator
Figure 1 shows the conceptual structure of a STLG. The main flux direction in the mover is determined by the magnetization of permanent magnets and the generated voltage level is dominated by the interactions between stator and mover. For those STLGs with traditional axial and radial magnetizations, ferromagnetic materials are generally required to guide the desired flux paths. Inevitably, the operational temperatures and the induced eddy currents in these materials will produce...
extra system power losses and also degrade the PMs. For construction simplicity and cost reduction, as well as provide flexibility in the machine axial rod material selections, the quasi-Halbach PM arrays have been selected to fulfill the STLG mover requirements [5], [6]. Due to the asymmetrical stator winding arrangements and mechanical end effects, the induced voltages will be unbalanced in the stator three-phase windings. Besides, with position-dependent operational flux linkages, harmonics on the voltages will also affect the operations of such direct driven STLG. Proper performance indices on the voltages at both the generator AC side and the regulated DC side must be incorporated in the determinations of adequate machine parameters.

3. Optimal Design of the Generator

3.1 Problem Definitions

Figure 2 shows the related design parameters of the STLG. The objective is to design a laboratory-class generator prototype capable of supplying 1/2 hp of power and a minimum regulated DC-side voltage of 60 V. By selecting the key optimization factors and assigning every factor with three feasible levels, the classified factor-level combination for design are illustrated in Table 1.

To find the optimal parameters, the operational objective along with certain constraints are:

\[
\begin{align*}
\text{Maximize: } & \phi(r_g, z, d_m) = \int_S B(r, \theta, z, d_m) \cdot d\mathbf{s} \\
\text{Subject to: } & 0 \leq z \leq l_s, 0 \leq d_m \leq l_m - l_s, r_0 \leq r_e < r_s,
\end{align*}
\]

where \( \phi \) is the axial-directional flux passing through the stator winding and \( \mathbf{B} \) is the flux density enclosed by the corresponding winding coil.

A systematic and efficient search of the optimal factor-level combinations based on the Taguchi’s method is developed. There are only total 9 experiments are designed for performing the desired performance index evaluations. The axial-directional magnetic fluxes passing the stator windings of the STLG, can then be calculated by using three-dimensional (3-D) finite element analyses (FEA) [7] with one of the simulated results shown in Figure 3. The exhibited magnetic fluxes and the total harmonic distortion (THD) can be expressed in the forms:

\[
\phi(r_g, z, d_m) = F_0 + \sum_{n=1}^{\infty} F_n \cos(2\pi n \frac{d_m}{l_m} - \theta_n), \text{ and } \text{THD} = \left( \frac{1}{F_1} \left( \sum_{n=2}^{\infty} F_n \right) \right)^{1/2}.
\]

where \( F_i \) is the magnitude of the stator winding flux at the corresponding \( i^{th} \) space harmonic.

Table 1. Design factor and level classifications of the slotless tubular linear generator

| Design factor | Level 1 | Level 2 | Level 3 |
|---------------|---------|---------|---------|
| A: \( \tau_i \) | 42 mm   | 33.4 mm | 25 mm   |
| B: \( h_m \)  | 10 mm   | 11 mm   | 12 mm   |
| C: \( h_c + g \) | 9 mm    | 10 mm   | 11 mm   |
| D: \( h_c / g \) | 1.57    | 1.25    | 1.0     |

Figure 1. Conceptual structure of a slotless tubular linear generator with quasi-Halbach arranged permanent magnets on the mover.

Figure 2. Physical parameters of the STLG.
3.2 Optimization Specifications

By taking either the fundamental component or the THD as the target, different optimization designs can be obtained with the signal-to-noise ratio (SNR) at two distinct objectives as:

\[ \text{Smaller the better: } \text{SNR}_{\text{STB}} = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right), \quad \text{or Larger the better: } \text{SNR}_{\text{LTB}} = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right). \quad (3) \]

where \( n \) is the number of experiments and \( y_i \) is the \( i \)-th experimental result. It is apparent that \( \text{SNR}_{\text{LTB}} \) must be picked for the flux fundamental component \( F_1 \), and \( \text{SNR}_{\text{STB}} \) must be picked for the flux THD.

By taking the averaged effects contributed from individual factor-level, the resultant optimal combination for providing maximized \( F_1 \) is \( A_3-B_3-C_1-D_2 \), and for exhibiting minimized THD is \( A_2-B_3-C_3-D_1 \). Thus, to provide optimal system design guidance, compromised selections of the possible factor-level combinations are required. Since there are three levels for every of the design factor, a systematic analysis of variance (ANOVA) scheme that introduces the sum of squares is defined as:

\[ SS_i = 3 \sum_{j=1}^{3} (m_{ij} - m_{i\text{all}}), \quad (4) \]

where \( i \) is the corresponding design factor, \( m_{ij} \) is the averaged \( \text{SNR} \) of factor \( i \) at the \( j \)-th level, and \( m_{i\text{all}} \) is the averaged \( \text{SNR} \) of factor \( i \) at all three levels. For evaluating the impacts on the two optimization objectives, contributions from those design factors are summarized in Table 2. By selecting the dominant combinations, it can be seen that the corresponding level for the individual factor should be:

\textbf{Factor A:} THD \( \rightarrow \) A2, \textbf{Factor B:} \( F_1 \rightarrow \) B3, \textbf{Factor C:} \( F_1 \rightarrow \) C1, and \textbf{Factor D:} THD \( \rightarrow \) D1.

From this systematic ANOVA, the individual dominant factor-level that will affect the machine design can then be determined. Thus the combination that can provide the optimized solution about the STLG structure, with its axial-directional flux as the design objective, will be A2-B3-C1-D1.

3.3 Stator Winding Selections

Since the generated 3-phase AC voltages from STLG will be rectified to DC for further utilization, the generator stator windings are thus designed based on the desired DC-side voltage level. At an input speed of 3 m/s, if the desired DC voltage is 80 V with an adjustable range of 10%, a preliminary investigation shows both of the above devised combinations, A3-B3-C1-D2 and A2-B3-C3-D1, can achieve this voltage level by using the AWG18 or thinner wires. However, with their different physical dimensions, the compromised one with combination of A2-B3-C1-D1 requires less winding turns and thus smaller resistances, and better electric characteristics can then be expected.

From the above investigations, clearly that the selections of winding sizes will greatly affect the performance of designed STLG based on different specifications. By assembling the generator stator windings using different wires, further detailed comparisons have also been performed based on the following table.

| Design factor | \( F_1 \) | THD |
|---------------|-------------|-----|
| SS_i          | Contribution | SS_i | Contribution |
| A             | 1.4417      | 24.88% | 0.1560 | 27.04% |
| B             | 3.7606      | 64.90% | 0.2662 | 46.14% |
| C             | 0.5551      | 9.58%  | 0.0057 | 1.00%  |
| D             | 0.0368      | 0.64%  | 0.1490 | 25.82% |
| Total         | 5.7942      | 100.00% | 0.5769 | 100.00% |

Figure 3. Flux density distribution in the STLG calculated by 3-D FEA.
same structural design (A2-B3-C1-D1). Figure 4 shows the output no-load regulated DC-side voltages of the STLG at different mechanical input speeds. With the same physical space allowances, it is certain that more turns can be wound by using thinner wires and consequently higher voltages will be induced. In addition to the no-load performance, the output power generation capabilities with different stator windings have also been investigated as shown in Figures 5 and 6. From these illustrations, possibility of selecting the AWG18 wire can be eliminated due to the relatively poor power output characteristics. While from the two intersection points shown on the power-speed and power-voltage characteristics, selections of the other two types of wires for the STLG stator winding constructions are clearly determined by the objective operational speed and voltage levels.

4. Design Confirmations

The systematic design scheme as provided in the preceding section showed that the A2-B3-C1-D1 structure combined with AWG19 stator windings, which has a maximum current allowance of 2.57 A, of the STLG can meet the desired design objective, and the laboratory STLG prototype based on such design is shown in Figure 7 for demonstration. By using the same wires for stator winding constructions, further comparison investigations on the other structural parameter combinations will be conducted to validate the optimization scheme. These structures are the empirical design (A3-B1-C3-D2), the maximized fundamental flux design (A3-B3-C1-D2), the minimized total harmonic distortion design (A2-B3-C3-D1), and the optimized design (A2-B3-C1-D1) through the proposed systematic

**Figure 4.** No-load DC-side voltages of the STLG with various driven speeds and stator windings.

**Figure 5.** Output power capabilities of the STLG at a fixed 3 m/s with various DC-side voltages and stator windings.

**Figure 6.** Output power capabilities of the STLG at a fixed 84 V DC-side voltage with various driven speeds and stator windings.

**Figure 7.** Constructed laboratory STLG prototype based on the optimal design scheme.
scheme. As illustrated in Figures 8 and 9, the STLG output powers at various operational specifications are provided for comparisons. Clearly, the one based on either empirical or maximized fundamental flux design will not exhibit competitive performance. Though the one based on minimization of THD will supply larger power output at certain operational ranges (higher output voltages or lower input speeds), its relatively larger power losses in these conditions also downgrade the possibility of selecting such structure. At a rated input mechanical speed of 3 m/s, the STLG with optimized design will supply electric power outputs larger than 340 W if the regulated DC-side voltages are smaller than 84 V. Or if this terminal voltage is fixed, the output powers will be larger than 340 W with higher mechanical speed inputs. The design objectives based on the optimized structure can thus certainly be confirmed.

5. Conclusions
This paper presents a systematic design scheme of a direct driven slotless tubular linear generator for direct renewable energy retraction. Based on Taguchi’s method, comparisons and classifications were performed to identify the optimal machine structure for the design objectives. Appropriate stator windings, by thoroughly estimating the feasible STLG power generations, can then be selected. From the developed scheme and the machine prototype, adequate guidance for designing the related renewable energy retraction mechanisms has successfully demonstrated.

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