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Performance Improvement of the Linear BLDC Generator in a NASA Deep Space Explorer

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Abstract - This paper presents methods to improve performance of the power supply system in a NASA deep space explorer. In the Stirling engine driven reciprocating Brushless DC (BLDC) generator, the accurate position information of the prime mover is important to diagnose the performance of the engine and prevent distortion of the output power. Since sensors to detect the position are fragile and unreliable, and conventional sensorless techniques have drawbacks in the low speed region, a novel sensorless position detection technique for the prime mover has been proposed and verified. Another major issue of the generator for the spacecraft is power density maximization. The mass of the power system is important to the mass of the satellite. Therefore, the components of the spacecraft should be lightweight. Conventional rectification methods cannot achieve the maximum power possible due to non-optimal current waveforms. The optimal current waveform for maximizing power density and minimizing machine size and weight in a nonsinusoidal power supply system has been derived, incorporated in a control system, and verified by simulation work.

Keywords: linear BLDC generator, nonsinusoidal power supply system, position characterizing function, power density maximization

1. Introduction

The National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE) have worked in conjunction for over two decades on the Stirling engine driven power supply system to provide spacecraft with on-board electric power for deep space exploration. Their focus has been on linear reciprocating generators using the Stirling engine.

In the Stirling engine driven linear BLDC generator, it is essential to be familiar with the instantaneous position of the mover. This allows us to determine whether the Stirling engine is operating well, prevent distortion of the output electrical power, and improve the performance of the power supply system. In the last two decades, many solutions for sensorless position detection have been offered to eliminate the costly and fragile position sensor. However, none have been successful for low cost, reliable, and accurate operation at all speeds. These drawbacks with the sensorless techniques can create a big problem in the reciprocating generator, which has two zero speed points in every period. To solve this problem, we propose a novel sensorless position detection technique that covers zero to high speed with good accuracy and robustness for the linear BLDC generator.

The second issue related to performance improvement is to maximize the power density and minimize the size and weight of the linear BLDC generator. As compared with other generators, the BLDC generator has many benefits; it is lightweight, has a compact design, and requires low maintenance because it contains a magnetic source within itself. With the inherent advantages of the BLDC generator, additional increase in power density is expected by using advanced control techniques resulting in a considerable reduction of weight and volume. This paper presents our novel control technique to maximize the power density and minimize the size and weight of the linear BLDC generator for a given machine by controlling the current spectrum using active switches, without altering the machine design and increasing the loss of iron and copper. This control technique is highly advantageous for NASA deep space exploration because of the significance of low mass.

2. Basic Understanding of the Linear BLDC Generator

The BLDC generator is a type of permanent magnet (PM) generator that has permanent magnets within the machine. Fig. 1(a) shows the model of the Stirling engine driven linear BLDC generator [1].

Permanent magnets are attached to the prime mover on the shaft of the Stirling engine and move forward and backward by the reciprocating motion. At both ends of the

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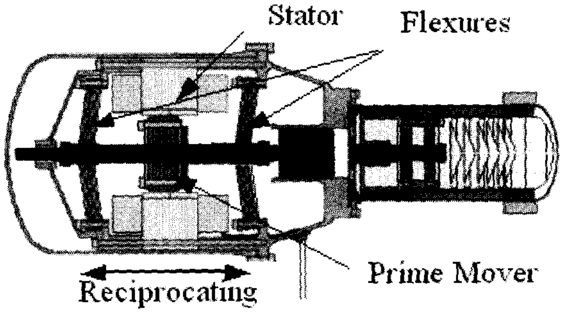
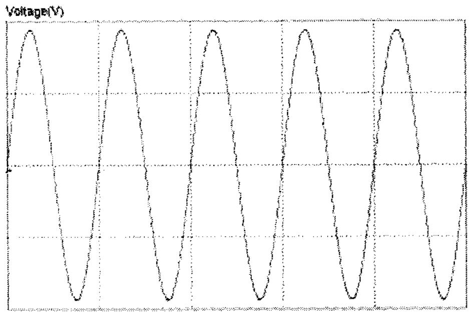
prime mover, there are flexures to protect the system and produce sinusoidal reciprocating motion.



(a) Model



(b) Induced EMF waveform

Fig. 1 The Stirling engine driven linear BLDC generator

The induced EMF waveform of the linear BLDC generator is shown in Fig. 1(b). The induced EMF of the generator is a rectangular waveform by Faradays law. However, there is flux leakage on the edges of the permanent magnets, so the actual induced EMF will be a trapezoidal waveform. This nonsinusoidal EMF is due to the concentric winding of the machine and rectangular distribution of the magnetic flux in the airgap. In the linear BLDC generator, the speed is not constant but periodic and the generator maintains this reciprocating motion. Therefore, the induced EMF waveform is a periodic waveform that is very close to a sinusoidal waveform.

3. Sensorless Position Detection of the Prime Mover in the Linear BLDC Generator

3.1 Conventional Flux Estimation Method

If the instantaneous speed profile of the prime mover of the Stirling engine were known, we could easily obtain the position information using (1):

$$Position = \int v(t)dt \tag{1}$$

However, it is difficult to know the speed profile of the prime mover directly. There is a conventional technique for using the induced voltage for sensorless position detection, which is called the flux estimation method or EMF integration method. The speed of the prime mover of the Stirling engine and the induced output voltage have the same profile. Because position information is the integration of the speed and linkage flux is the integration of the induced voltage, there is a one-to-one relationship between position and linkage flux. Therefore, the position information is driven from the linkage flux, λ, which is obtained by integration of the induced EMF that is calculated from the voltage equation as shown in (3):

$$Linkage\ flux = \int e(t)dt \tag{2}$$

$$e(t) = Ri(t) + L\frac{di(t)}{dt} + V(t) \tag{3}$$

Where, $V(t)$ is the instantaneous terminal voltage; R and L are the resistance and inductance of the stator winding, respectively. From the measured current and voltage, the induced EMF and linkage flux are calculated by a digital signal processor. However, the induced EMF is proportional to the speed and it is so small at low speed that it is very difficult to obtain an accurate value in the low speed region. Therefore, it is not possible to use the flux estimation method to acquire position information at low speed. In other words, we may lose the position information near the end of the stroke every cycle because the operating speed is almost zero near the end of the stroke in the reciprocating linear BLDC generator. To overcome this drawback, an analytical characterization method is proposed in this paper.

3.2 Derivation of the Position Characterizing Function

Since the waveform of the position function, $X(t)$ is periodic in every cycle, we can characterize $X(t)$ in every period as in (4), and use this Fourier series for position information.

$$Position = X(t_k) = \sum_{i=1}^{n}\{A_i \sin i(wt_k - \frac{\pi}{2}) + A_i\} \tag{4}$$

There are four unknown variables, $X(t_k)$, t_k, w, and A_i in the above equation. $X(t_k)$ is the position at the time t_k. A_i is the coefficient of the above Fourier series. From the flux estimation method at the time t_k, we can attain the $X(t_k)$, position information.

Therefore, by selecting around five t_k points in the convenient high-speed region we can solve the above equation for its five unknowns. The w is the frequency of the mover. If the frequency is known from the Stirling

$$\begin{bmatrix} X(t_1) \\ X(t_2) \\ X(t_3) \\ X(t_4) \\ X(t_5) \end{bmatrix} = \begin{bmatrix} \sin(wt_1-\frac{\pi}{2})+1 & \sin 2(wt_1-\frac{\pi}{2})+1 & \sin 3(wt_1-\frac{\pi}{2})+1 & \sin 4(wt_1-\frac{\pi}{2})+1 & \sin 5(wt_1-\frac{\pi}{2})+1 \\ \sin(wt_2-\frac{\pi}{2})+1 & \sin 2(wt_2-\frac{\pi}{2})+1 & \sin 3(wt_2-\frac{\pi}{2})+1 & \sin 4(wt_2-\frac{\pi}{2})+1 & \sin 5(wt_2-\frac{\pi}{2})+1 \\ \sin(wt_3-\frac{\pi}{2})+1 & \sin 2(wt_3-\frac{\pi}{2})+1 & \sin 3(wt_3-\frac{\pi}{2})+1 & \sin 4(wt_3-\frac{\pi}{2})+1 & \sin 5(wt_3-\frac{\pi}{2})+1 \\ \sin(wt_4-\frac{\pi}{2})+1 & \sin 2(wt_4-\frac{\pi}{2})+1 & \sin 3(wt_4-\frac{\pi}{2})+1 & \sin 4(wt_4-\frac{\pi}{2})+1 & \sin 5(wt_4-\frac{\pi}{2})+1 \\ \sin(wt_5-\frac{\pi}{2})+1 & \sin 2(wt_5-\frac{\pi}{2})+1 & \sin 3(wt_5-\frac{\pi}{2})+1 & \sin 4(wt_5-\frac{\pi}{2})+1 & \sin 5(wt_5-\frac{\pi}{2})+1 \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \end{bmatrix} \tag{5}$$

engine, it can be used directly. Otherwise, from detection f the zero-crossing points of the EMF, we can compute the frequency and use it to solve the above equation because the frequency of the EMF is identical to the frequency of the mover. Therefore, we have one equation and one unknown value, A_i and we can solve the above equation easily. Equation (5) shows the matrix form for (4) when we use five samples. By solving this matrix, we arrive at the position characterizing function as shown in (6) and continuous position information in real time is obtained even at low speeds.

$$X(t) = \sum_{i=1}^{n} \{A_i \sin i(wt - \frac{\pi}{2}) + A_i\} \tag{6}$$

The instantaneous position information obtained diagnoses the performance of the prime mover, resulting in prevention from the distortion of the output electrical power in the linear reciprocating BLDC generator.

4. Power Density Maximization of the Linear BLDC Generator

The induced EMF of the BLDC generator is a trapezoidal waveform and contains harmonics due to the machine design and structure. However, in the linear BLDC generator, the speed is not constant but sinusoidal, so that the induced EMF is similar to a sinusoidal waveform, but it still contains harmonics because of the unevenness of the permanent magnet and leakage flux. As is commonly known, the product of each voltage and current harmonic produces electrical output power. Consequently, we must consider all the harmonics included when calculating the output power. The average power is presented as in (7), and each phase voltage and current is presented as in (8):

$$P_{avg} = \frac{1}{T}\int_0^T e(t)i(t)dt \tag{7}$$

$$\begin{aligned} e(t) &= E_1 \sin(wt) + E_2 \sin 2(wt) + E_3 \sin 3(wt) \ldots \\ i(t) &= I_1 \sin(wt - \phi_1) + I_2 \sin 2(wt - \phi_2) + I_3 \sin 3(wt - \phi_3) \ldots \end{aligned} \tag{8}$$

Where, the capital letters E and I represent the peak magnitude of each harmonic of the voltage and current. ϕ_n represents the phase difference between each voltage and current harmonic. For power density maximization, each voltage and current harmonic should be in phase. Otherwise, the output power has a negative value during every cycle and the average power cannot be the maximum possible. Therefore, ϕ_n should be zero and the average power is given simply as in (9):

$$\begin{aligned} P_{avg} &= \frac{1}{T}\int_0^T e(t)i(t)dt \\ &= \frac{1}{T}\int_0^T \begin{bmatrix} \{E_1 \sin wt + E_2 \sin 2wt + E_3 \sin 3wt + \ldots\} \\ \cdot \{I_1 \sin wt + I_2 \sin 2wt + I_3 \sin 3wt + \ldots\} \end{bmatrix} dt \\ &= \frac{1}{2}(E_1 I_1 + E_2 I_2 + E_3 I_3 + \ldots) \end{aligned} \tag{9}$$

Another constraint for power density maximization is the RMS value of the voltage and current. Since the object of this research is to maximize the power density in the generator for a given rating, the RMS value of the current and voltage should be maintained at the rated value as in (10):

$$\begin{aligned} i_{rms} &= \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = \frac{1}{\sqrt{2}}\sqrt{I_1^2 + I_2^2 + I_3^2 + \ldots} \\ &= \sqrt{i_{1,rms}^2 + i_{2,rms}^2 + i_{3,rms}^2 + \ldots} = \mathit{rated\ value} \\ I_1 &= \sqrt{2i_{rms}^2 - I_2^2 - I_3^2 - \ldots} \\ E_1 &= \sqrt{2e_{rms}^2 - E_2^2 - E_3^2 - \ldots} \end{aligned} \tag{10}$$

From (9) and (10), the average power can be given as in (11):

$$\begin{aligned} P_{avg} = \frac{1}{2}[&\left(E_1 \cdot \sqrt{2i_{rms}^2 - I_2^2 - I_3^2 - \ldots}\right) \\ &+ E_2 I_2 + E_3 I_3 + \ldots] \end{aligned} \tag{11}$$

For maximum power density, the differentiation of average power by the peak value of each harmonic current should be zero as in (12). The results are shown in (13):

$$\frac{\partial P_{avg}}{\partial I_n}=0 \qquad \mathrm{I}_n : I_1,\ I_2,\ I_3,\ I_4,\ldots \tag{12}$$
$$\frac{\partial P_{avg}}{\partial I_1}=0,\ \frac{\partial P_{avg}}{\partial I_2}=0,\ \frac{\partial P_{avg}}{\partial I_3}=0,\ \frac{\partial P_{avg}}{\partial I_4}=0,\ldots$$

$$\Rightarrow I_2=\frac{I_1}{E_1}E_2,\ I_3=\frac{I_1}{E_1}E_3,\ I_4=\frac{I_1}{E_1}E_4,\ldots \tag{13}$$

By substituting (13) into (10), each harmonic magnitude of the phase current should be (14):

$$\therefore\ \frac{I_1}{E_1}=\frac{i_{rms}}{e_{rms}} \tag{14}$$
$$\Rightarrow I_1=\frac{i_{rms}}{e_{rms}}E_1,\ I_2=\frac{i_{rms}}{e_{rms}}E_2,\ I_3=\frac{i_{rms}}{e_{rms}}E_3,\ldots$$

Therefore, the optimal current waveform for maximum power density in the given rating of the linear BLDC generator is:

$$\therefore\ I_n=\frac{i_{rms}}{e_{rms}}E_n \ \Rightarrow\ i(t)=g\cdot e(t) \tag{15}$$

Where g is the gain for the current reference.

Maximum power density in the non-sinusoidal system is accomplished by matching all of the harmonics of the current with those of the induced EMF. Knowing each harmonic of the EMF is very difficult without an FFT, (Fast Fourier Transform) which is time-consuming and complicated. Therefore, the simple linear tracking method, which causes the current waveform to track the calculated voltage waveform, is used to accomplish this harmonic matching for power density maximization.

5. Simulation Results of the Proposed Control

The proposed control for sensorless position detection and power density maximization has been verified through numerical simulation. Fig. 2 shows the block diagram of the overall system. Here, the linear tracking method is used. Current and DC-link voltage are measured by sensors for EMF calculation. Once we identify the EMF waveform using (3), we can calculate the position characterizing function by (5). We are also able to make the optimal current waveform reference for power density maximization by using the calculated EMF and (15).

The actual position, computed position by using flux estimation method, and computed position by using the proposed method, of the prime mover in the linear BLDC

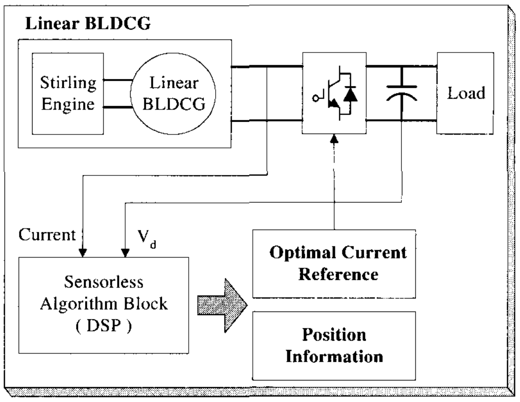
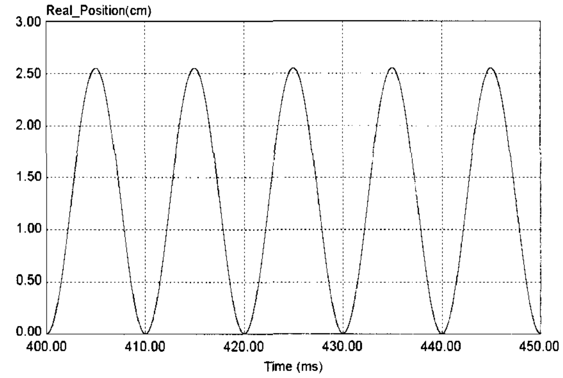
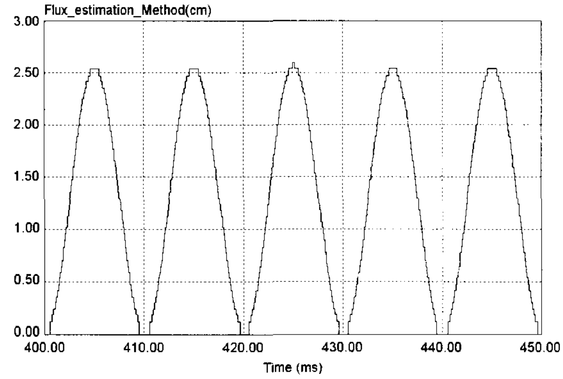


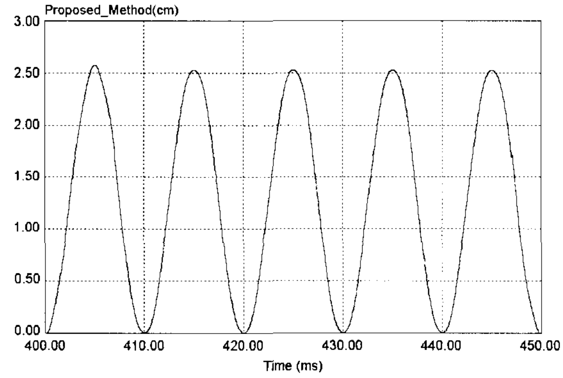
Fig. 2 Block diagram of the overall system



(a) Actual position



(b) Flux integration method



(c) Proposed method

Fig. 3 Position information of the prime mover of the linear BLDC generator

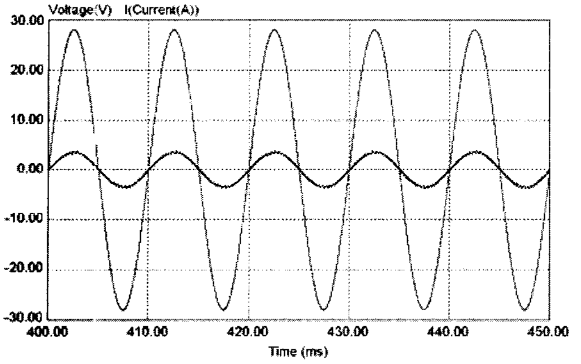


Fig. 4 Induced EMF and optimal current waveform for power density maximization

Table 1 Electrical output power comparison

	Operating Frequency	RMS Current	Output Power	Increase
Diode Rectifier	100 [*Hz*]	2.0 [*A*]	30.6 [*W*]	-
Proposed Control	100 [*Hz*]	2.0 [*A*]	35.5 [*W*]	16.0 [%]

generator are shown in Fig. 3. In this case, the full length of stroke of the prime mover is 2.54[*cm*]. In the flux estimation method, the low-speed region cannot provide accurate position information since the EMF measurement contains errors near the end of the stroke in the reciprocating linear BLDC generator as shown in Fig. 3(b). As such, we picked up 5 points from the flux estimation method in the high-speed region and solved the position characterizing function suggested in (5). As shown in these Fig.s, the computed position information by using the proposed method is almost identical with actual position information even in the low-speed region. The maximum error of the position information is 0.24[*mm*], which is less than 1%.

Fig. 4 and Table I indicate the simulation results of the power density maximization of the linear BLDC generator. For the current shaping, hysteresis control is used. The induced EMF of the linear BLDC generator is almost sinusoidal because of the reciprocating motion. Therefore, the optimal current reference for power density maximization is similar to a sinusoidal waveform, but note that the current contains all the harmonics even though the magnitude of the harmonics is small.

Table 1 presents the output power comparison between a conventional diode rectifier and the proposed method. Here, the most important thing for comparing the electrical output power is to maintain the RMS current values the same in both cases. In other words, the rating of the machine should be identical in both cases. In the same speed (100[*Hz*]) and same RMS current (2[*A*]), the proposed method increases electrical output power by 16% without making changes to the machine design and increasing the loss of iron and copper. That is, the weight and volume of the generator can be reduced by 16[%] because the volume of the machine is proportional to the electrical output power. This is a considerable reduction and in spacecraft applications, reductions in mass and size are particularly of interest.

6. Conclusion

For performance improvement of the power supply system in the NASA deep space explorer, 1) a novel sensorless position detection technique of the Stirling engine prime mover and 2) an advanced current control for power density maximization have been presented. By diagnosing the status of the Stirling engine prime mover in operation, we can prevent distortion of the output power and improve the performance of the linear generator. Because sensors to detect the position are fragile and unreliable, they cannot be used in spacecraft. In addition, a linear reciprocating generator has two zero speed points in every period, so conventional sensorless techniques cannot achieve the low speed position detection. In this paper, a novel position sensorless technique that is characterizing the position function and solving the above problems has been proposed and verified by the numerical simulation. An advanced current control technique for power density maximization of the linear BLDC generator has also been presented and verified. By matching all the harmonics of the voltage and current, we can maximize the output power, and minimize the weight and volume of the generator. Simulation results indicate an increase of 16% in the output power without changes in the machine design and increase in the loss of iron and copper. That is, the mass and volume of the generator can be reduced by 16% by applying the proposed control method. This reduction is a considerable improvement for spacecraft application, particularly in regards to decrease in mass and size.

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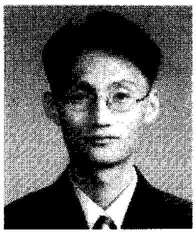

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