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Comparison of Linear BLDC and Linear SRM as Drive Elements in PV Panel System Cleaning

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ABSTRACT: With the increase in energy use, alternative energy sources have gained more importance recently due to the inadequacies in the reserves of fossil fuels and the damage caused by fossil fuels to the environment. This situation increases the utilization rate of alternative energy sources, and it is aimed to provide energy from these sources with maximum efficiency. One of the factors affecting energy efficiency in photovoltaic systems, which have an important place among alternative energy sources, is the pollution on the panels. There are different systems for panel cleaning and various drive elements used in these systems. In this study, linear Switched Reluctance Motor (linear SRM) and linear Brushless Direct Current Motor (linear BLDC) are compared for PV panel cleaning. These two linear motor types are classified in terms of performance, cost, reliability, and application advantage, and the results are given in detail.

***Keywords** – Linear SRM, Linear BLDC, PV System.*

FV Panel Sistem Temizliğinde Tahrik Elemanı Olarak Doğrusal FDAM ve Doğrusal ARM'nin Karşılaştırılması

ÖZET: Enerji kullanımının artması ile fosil yakıtların rezervlerindeki yetersizlikler ve fosil yakıtların çevreye verdiği zararlardan dolayı alternatif enerji kaynakları son zamanlarda daha fazla önem kazanmıştır. Bu durum alternatif enerji kaynaklarının kullanım oranını artırmakta ve bu kaynaklardan maksimum verimde enerji sağlanması hedeflenmektedir. Alternatif enerji kaynakları içinde önemli yer tutan fotovoltaik sistemlerdeki enerji verimliliğini etkileyen unsurlardan biri de panellerde meydana gelen kirlenmelerdir. Panel temizliği için farklı sistemler ve bu sistemlerde kullanılan çeşitli tahrik elemanları bulunmaktadır. Bu çalışmada FV panel temizliğinde kullanılabilecek Doğrusal Anahtarlamalı Relüktans Motor (doğrusal ARM) ile doğrusal Fırçasız Doğru Akım Motor (doğrusal FDAM) karşılaştırması yapılmıştır. Bu iki doğrusal motor tipi performans, maliyet, güvenilirlik ve uygulama avantajı açısından sınıflandırılarak sonuçlar detaylı olarak verilmiştir.

***Anahtar Kelimeler** – Doğrusal ARM, Doğrusal FDAM, FV Sistem.*

1. Introduction

Solar energy is the most important alternative energy source and the basis for other sources. Electricity is produced from solar energy by various methods, and the use of PV panels is the most common of these methods. Since the system efficiency of PV panels is low, it is aimed to operate these systems with maximum efficiency. The amount of electrical energy produced is directly related to the solar irradiance falling on the panel surface (Fouad et al., 2017; King et al., 2002). Therefore, the amount of energy produced by the system decreases with the reduce in the solar irradiance falling on the PV panel. One of the parameters that reduces the electric energy produced is the pollution caused by dust, pollen, grime etc. accumulated on the PV panel surface (Costa et al., 2016; El-Shobokshy and Hussein, 1993; Mani and Pillai, 2010; Zaihidee et al., 2016) . It is aimed to increase the energy gain of the system by cleaning the dust. PV panel cleaning methods are carried out in different categories. Basically; there are different classifications according to the type of cleaning method, such as cleaning with human-assisted or robotic systems, cleaning method with water-based or dry methods, or control method of the cleaning system (Aly et al., 2016; Deb and Brahmbhatt, 2018; Lu et al., 2013; Maghami et al., 2016; Ronnaronglit and Maneerat, 2019). Electric motors are generally used as the drive element in cleaning methods that are used other than human-assisted power and utilize machine power. In the literature, the number of studies on different types of motors as drive elements in PV panel cleaning is quite high (Fouad et al., 2017). Basically, the aim is to perform PV panel cleaning with maximum efficiency and minimum energy consumption.

Linear motor types are rarely encountered among such studies. In a study by Eker, 2022, for the first time, a system design has been realized in which both linear motion and circular motion can be obtained from the linear motion of the Linear Brushless Direct Current (linear BLDC) motor and presented it as a suitable method. In the study, a linear motor was used as an actuator in a sample sweeper system. At the end of the study, the energy loss due to dusting was reduced from 42% to 5% with a low energy consumption was concluded. In this study, a comparison of linear BLDC and linear Switched Reluctance Motor (linear SRM) was carried out based on the measured load conditions in the system given in (Eker, 2022). Firstly, 3D magnetostatic analysis of the linear motors with Finite Element Method (FEM) was performed and the electromagnetic properties of the motors were compared. Experimental tests were performed under the required load conditions for the system. The results are compared in 4 different aspects: performance, cost, reliability, and application advantage.

2. Materials and Methods

2.1 Linear BLDC and linear SRM

Linear motors produce direct linear motion based on Faraday and Ampere's laws. These motors, like rotary motors, convert electrical energy into mechanical energy. In cases where circular motion is inadequate or unsuitable, linear motion is preferred. Although the design of linear motors dates back many years, they have become more preferred in recent years with the development of power electronics technology and control methods (Çıra, 2019; Dursun, Mahir; Özbay, 2011; Garcia-Amoros et al., 2020). Designs and manufactures in different topologies such as rotary motors (Azrina Binti Hishamuddin and Darul Ridzuan, 2012). Two of these structures are linear BLDC and linear SRM structures. These two topologies have similar characteristics. The main difference is the presence of permanent magnets in the translator of the BLDC motor. Linear motor provides precise speed and position control (Barış et al., 2018; Lu et al., 2015; Zhao et al., 2007). For this reason, it has many applications in industry (Eguren et al., 2020).

2.2 Mathematical model of linear BLDC and linear SRM

The operating principle of linear motors is based on Faraday and Ampere's laws. The flux density in a material depends mainly on the flux and the cross-sectional area perpendicular to the flux. The flux depends on the current and type of the material. The operation of linear motors is basically based on rotating machines (Boldea, 2013). The movement of the motor parts is explained by Newton's laws depending on the force generated in the motor. In this study, the moving part for two linear motors is the translator. Therefore, the force generated for the movement of the translator must be greater than the sum of the translator and load force (Boldea, 2013).

$$M_t \frac{dv(t)}{dt} = \sum F_t \tag{1}$$

It could be expressed as in Eq (1). The moving part's total mass is denoted by M_t (kg), its acceleration is denoted by $dv(t)/dt$ (m/s^2), its net force is denoted by F_t (N), and its time-dependent velocity is denoted by $v(t)$. For the translator to motion, the generated force must be higher than the static friction force. The Coulomb friction force is used in the system motion to represent the frictional forces resulting from the forces parallel to the surface, and

$$F_c = \mu_k N = \mu_k M_t g \tag{2}$$

Equation 2 is used to obtain this force. As seen in Equation 10, static friction force is also provided.

$$F_s = \mu_s N = \mu_s M_t g \tag{3}$$

Equations 2 and 3 represent the Coulomb friction force (F_c), the kinetic friction coefficient (μ_k), the static friction force (F_s), the static friction coefficient (μ_s), the gravitational acceleration (g, 9.80665 m/s^2), and the force acting perpendicular to the surface (N). The overall friction force of the system (F_d) is given as Equation 4 when the viscous friction force (α), another friction factor that varies with speed, is taken into consideration.

$$F_d = \alpha\, v(t) + F_c + F_s \tag{4}$$

If the expressions in Equation 4 are implemented,

$$M_t \frac{dv(t)}{dt} = F_e(t) - \alpha\, v(t) - F_c - F_s - F_{load} = F_e(t) - F_d - F_{load} \tag{5}$$

Equation 5 uses the terms F_e and F_{load} to denote the electrical force created by the motor and the force produced by the load, respectively. The time-dependent force generated by the motor may be expressed as $F_e(t) = Ki_a(t)$ in terms of current. Finally, the differential equation for the linear motor's moving component using respectively Newton's and Kirchhoff’s laws are

$$\frac{dv(t)}{dt} = \frac{Ki_a(t)}{M_t} - \frac{\alpha v(t)}{M_t} - \frac{F_{load}}{M_t} \tag{6}$$

$$e(t) = R_a i_a(t) + L_b \frac{di_a(t)}{dt} + e_b(t) \tag{7}$$

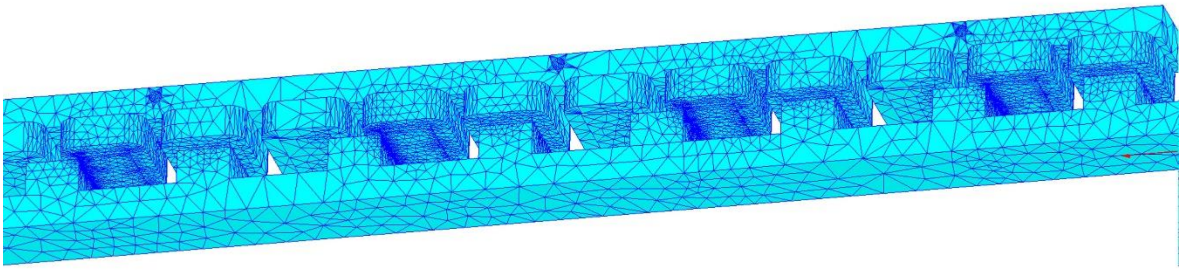
can be expressed using expressions.

2.3 Motor controller

The drive circuits act as a power source that takes control of the commands required to energize the motor phases at the appropriate times. The activation of the motor phases and the duration of the transmission are realized through these circuits. Therefore, they not only supply electrical energy to the motor, but also regulate the current required for proper motor operation. For linear motors to operate properly, the rotor position must be determined by a position sensor, taking into account the inductance profile of the motor (Wach, 2011). The motor phases are excited according to these positions determined by the position sensor. The controller regulates the motor performance. There are different drive circuits used in linear motors (Boldea, 2013; Garcia-Amoros et al., 2020; Lu et al., 2015).

3. Results and Discussion

In the study, firstly, magnetic analysis of linear SRM and linear BLDC motors were performed with 3D FEM. In the magnetic analyses, the forces to be generated for the two motor types were analyzed. Linear motors can be designed so that either the stator or translator can be movable. In both topologies used in this study, the moving part is the translator. The stator is a fixed structure in motors and is designed as 3 equal parts so that the force produced can be used on a longer axis. In this way, a gain of two pole distances is obtained. The accuracy of the results in the analysis with FEM is directly related to the mesh (number of solution points) created on the parts. TAU Mesh structure was used in both motor structures. Fig. 1 shows the 3D solid model and mesh structure of the linear SRM and linear BLDC.



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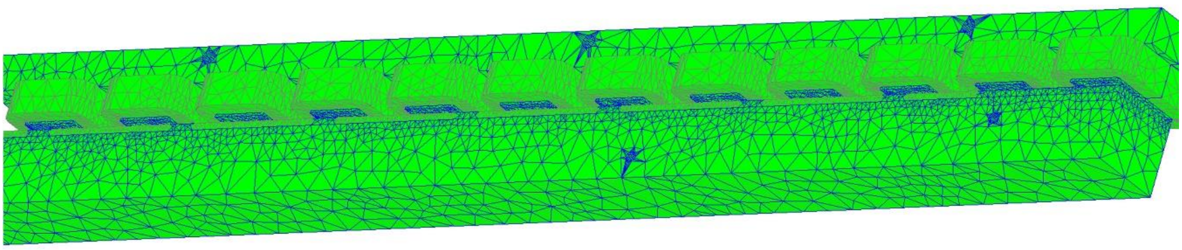

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Figure 1. Mesh structure a) linear SRM b) linear BLDC

At the end of the meshing process, a total of 466410 meshes were generated in linear SRM, 120808 in the stator and 28744 in the translator core. In the linear BLDC motor, 81816 meshes were generated in the stator, 67596 meshes in the translator and totally 560862 meshes. Table 1 shows the material properties of the motors.

Table 1. Material properties

Description	Linear SRM	Linear BLDC
Stator	M350 Steel	M350 Steel
Translator	AISI 1045 Steel	AISI 1045 Steel
Magnets	-	NS40SH
Stator windings	Copper	Copper

3.1 Forces

In the linear motor structure, unlike linear machines, the evaluation is made based on the forces occurring in the motor, not the output torque. The images of the thrust and pull forces resulting from the 3D FEM analysis of both motors are given in Fig.2 and Fig.3.

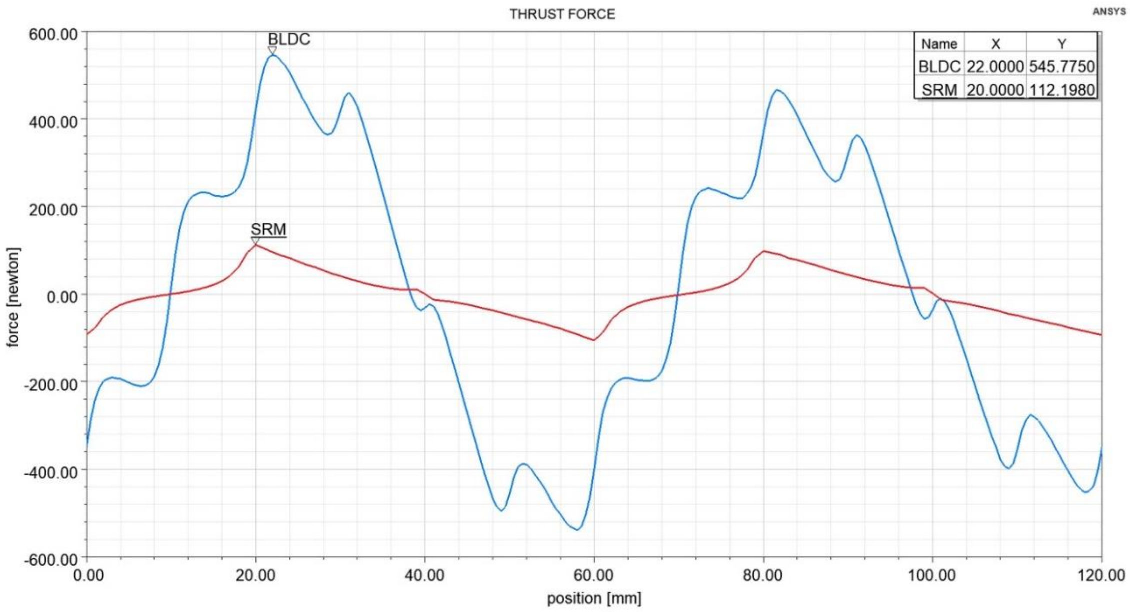

Figure 2. Thrust force curves

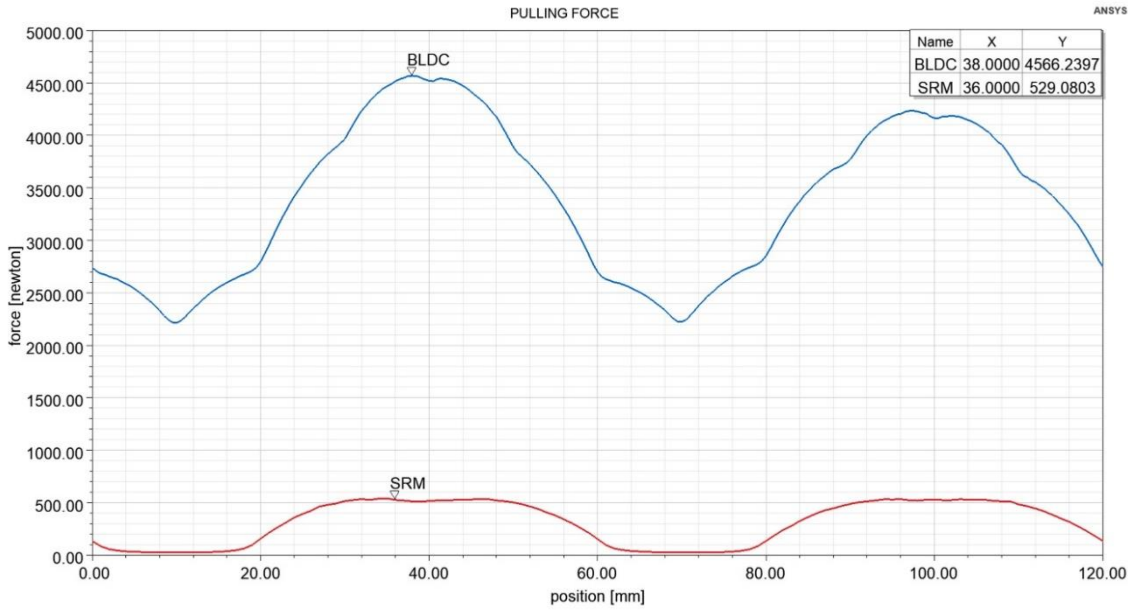

Figure 3. Pulling force curves

Fig. 2 and Fig. 3 show the graphs of the thrust and pulling forces obtained by 3D FEM analysis of linear SRM and linear BLDC. In this study, linear SRM and linear BLDC are designed to be used in solar panel cleaning. In the two designed motors, the thrust force is expected to be greater than the force required to move the system. Since the linear motion of these two motors will take place along the X-axis, the maximum values of the forces in the X-axis direction were obtained as 112.98 N for SRM and 545 N for BLDC. It is concluded that the BLDC structure produces 5 times more force than the SRM structure with the same stator and the same translator length. In addition, the bearings used for the movement of the system will be affected by the pulling force between the stator and the translator as well as the system weight. For this reason, the pulling force (in the Z axis) of both motors was analyzed. The maximum values of the pulling force in SRM and BLDC structures are 543 N and 4566 N, respectively. These results show that the BLDC structure produces 8.45 times more force than the SRM structure in pulling force.

3.2. Magnetic Flux Distributions

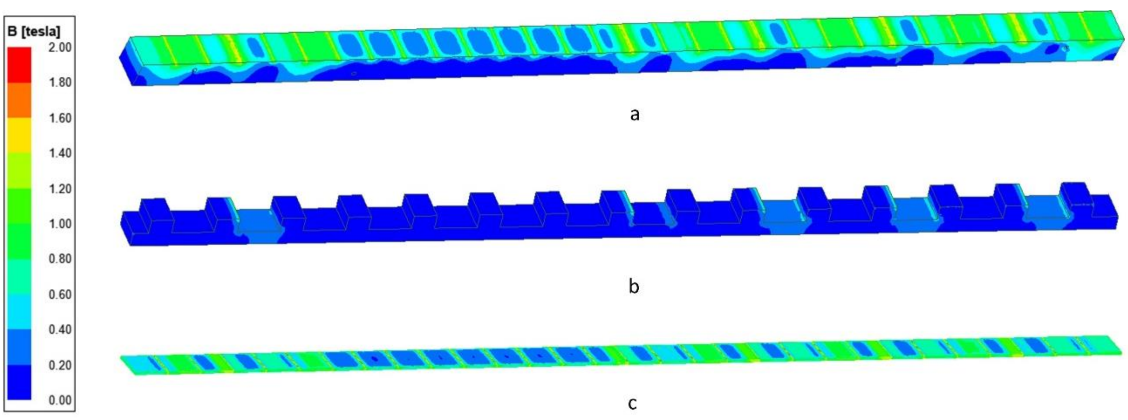

Figure 4. Flux distribution at translators a) BLDC translator core b) SRM translator core c)BLDC magnets

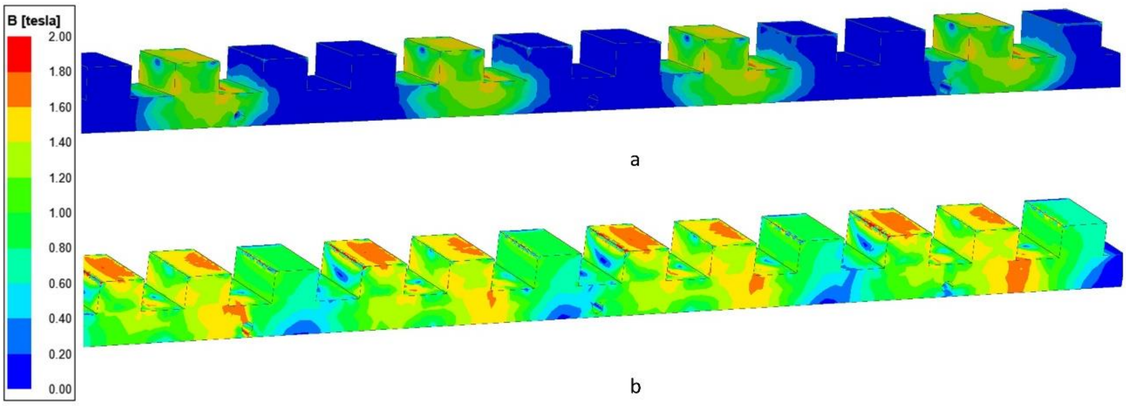

Figure 5. Flux distribution at stator cores a) linear SRM b) linear BLDC

The flux distributions in the materials of linear SRM and linear BLDC motors were also analyzed. Fig. 4 shows the flux distributions in the moving parts of the motors, while Fig. 5 shows stator flux distributions common to both motors. When the results are examined, the maximum flux values occurring in the translator and stator in the SRM structure are 2.42 T and 2.32 T, respectively. For the BLDC structure, these values are 2.31 T in the stator, 1.70 T in the translator core and 2.33 T in the magnets. The average flux density in SRM is 0.98 T in the stator (around the energized coil) and 0.88 T in the translator. For the linear BLDC structure, these values are 1.02 T for the stator and about 0.80 T for the translator.

3.3. Mechanical

Structural analysis is one of the important factors in motor design for electric motors for motor efficiency and continuity of motor performance. Distortions that will occur both in the motor parts and in the system will directly affect the motor operation and cause a reduction in system efficiency. While the forces occurring in the stator and/or translator cause displacements in the material, this causes distortions in the air gap. This will change the flux distribution in the air gap used in energy conversion and will cause the air gap magnetic distribution to be uneven, thus causing changes in the generated force. The negativities that will occur in the system negatively affect the motor's mobility and even expose it to unpredictable results.

The force generated in linear BLDC and linear SRM motors basically affects the motor operation in two axes. These are defined as thrust force (x-axis) and pulling force (y-axis). In the study, Eker 2022 detailed the use of Linear BLDC motor as a drive element in cleaning the PV system. In Eker's study in 2022, the displacements, Von Mises value and safety coefficients caused by the tensile force of 4650 N generated by the linear BLDC were also examined. The displacement value occurring in the translator, which is the moving part of the motor, is 0.005 mm, while the aluminum body on which the motor moves is 0.3 mm. In the system, the lowest safety coefficient is given as 4.31. These values show that there will be no negativity in the operating conditions of the motor.

For the linear SRM, the pulling force in the Y axis was obtained as 543 N as a result of magnetostatic analysis with FEM. While the stators and the aluminum case in which the motors are placed are common in both motor topologies, only the translators are different. For this reason, the traction force produced by the BLDC structure is much higher than the traction force produced by the SRM. Therefore, it is clearly predicted that the displacement and safety factor that will occur in the linear SRM will not cause any negative results for the system, since the pulling force analyzed for BLDC does not cause any negative effects on the motor parts and the system.

3.4. Thermal

Investigation of the thermal operation of the motor is as important a criterion as magnetic design and structural design. Especially at high operating temperatures of motors containing magnets such as BLDC, demagnetization failure occurs in the magnets. As a result of demagnetization faults, the motor efficiency decrease, and the motor will not produce the required force. Linear SRM and linear BLDC motors are designed for PV system cleaning in this study. The operating times of the two structures are simulated in very short periods (60 s on average). Therefore, the motors complete their operation without reaching thermal saturation in both structures. So the thermal resistance of the motors was not analyzed.

3.5. Motor production

In general, the manufacturing process and costs of linear motors are more advantageous than other motors. Due to their simple structure, mechanical costs are lower. Except for the translator part of the linear SRM and linear BLDC motors used in this study, other motor parts (stator, outer case, bearings) are common. Translator manufacturing cost is higher in BLDC structure. The magnets in the translator of the BLDC motor significantly increase the motor cost and have a large role in the total cost of the motor. In the SRM structure, the cost of the rotor consists of the solid steel used and opening of the rotor slots with CNC.

3.6. Test results

After the design phases were completed, prototype production of linear SRM and linear BLDC motors was carried out. Images of the produced motors parts are in Fig. 6. Firstly, the values in the no-load operating conditions of the motors were obtained. The National Instruments' cDAQ-9174 cabinet, NI9227 current module for current measurement and NI 9225 voltage module for voltage measurement were used to obtain the data of the motors.

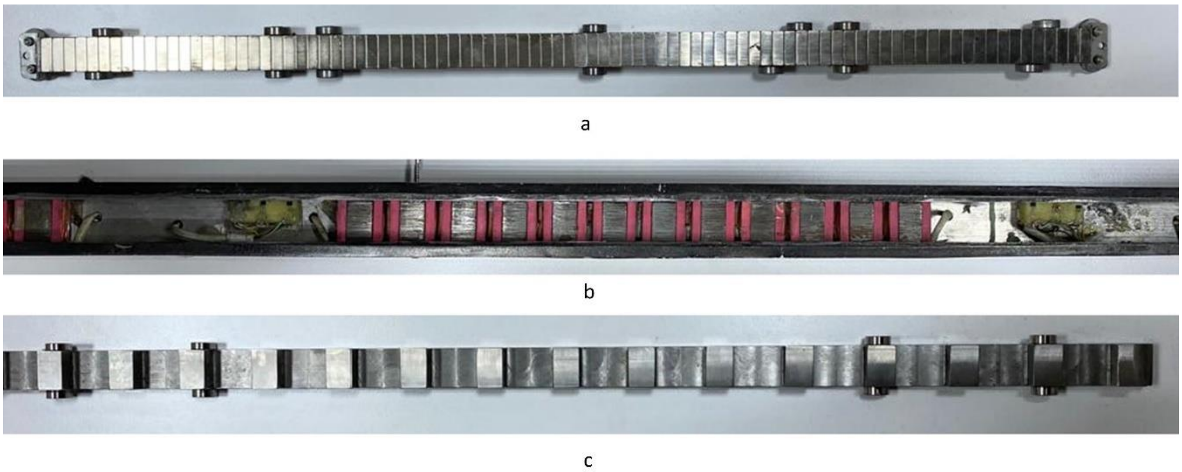

Figure 6. Motor equipment a) linear BLDC rotor b) Stator c) linear SRM rotor

The total load value that will occur in the motors when integrated into the system to be used in PV panel cleaning was measured (Eker, 2022). The sweeper weight is approximately 1.72 kg. When the frictional forces of the rack gear used to provide circular motion in the sweeper are added, the force required to move the system was measured to be approximately 38 N Experimentally, load value of 4 kg value was applied externally on the translator. In no-load operation, linear SRM and linear BLDC motors draw 1.74A and 1.18 A current respectively, while these values are 2.67A and 2.08A respectively under the load created for the system. The results show that the linear BLDC motor draws less current at the same voltage than the linear SRM structure. Considering the system operation, it can be said that both motors are suitable in terms of energy efficiency since their total operating times will be short periods.

4. Conclusion

In this study, a comparison of linear SRM and linear BLDC motors designed to be used in PV panel cleaning was carried out. Comparisons were carried out under 4 different headings. One of the criteria was realized in terms of cost. Except for the translator parts, the other parts and the cage are common in both motor structures. In terms of cost, the cost of the SRM motor is lower compared to the BLDC structure. While the translator is created by cutting slots on solid steel with CNC at linear SRM, the magnets in the BLDC motor create additional cost. The performance values of the motors were also compared and for this, magnetostatic analysis of the motors was performed with FEM. According to the magnetic analysis, the linear BLDC motor produces more force than the SRM structure. So, with the BLDC structure, more PV panel cleaning opportunities can be provided in modular structures in PV panel systems. In addition, the flux distributions occurring in the motors were analyzed with FEM and it was concluded that the flux distributions occurring in the materials in both motor structures are within the limit values. Both motors are controlled from the same driver board and both motors operated fault-free in the tests. In terms of applicability, the linear BLDC motor is more suitable for larger systems, although it has the same dimensions. However, the possibility of failure due to the magnets in its structure should also be taken into consideration. In case of broken or demagnetized magnets, the power obtained from the motor will decrease and will negatively affect the motor performance. Thanks to the simple structure of linear SRM, the motor provides problem-free operation. Maintenance requirement is less than BLDC motor. When both motors are used in PV cleaning systems, their total operating time will be very low. Since the total energy consumed by the motors is very low and negligible in PV systems, their use as drive elements in PV cleaning systems will contribute positively to energy efficiency.

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