Artificial neural network based sensorless position estimation and direct torque control for stepper motor

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ABSTRACT

This study describes and illustrates how sensorless location estimation is achieved through the application of artificial neural network (ANN) control. Control stepper motor torque directly. Using stepper motors directly leads to a lot of problems; therefore, automated control systems are now commonly preferred. Stepper motors have several drawbacks when used directly, including the potential for steps to occasionally be missing while the motors are running. When physical sensors are not available, the proposed method estimates rotor position and speed using electrical signals and ANN algorithms. Simulation and experiment results demonstrate accurate position estimation (±1.5°) and efficient torque control. The sensorless direct torque control (DTC)-ANN approach increases the performance, reliability, and cost of stepper motors in robotics, computer numerical control (CNC) machines, and 3D printing.

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1. INTRODUCTION

Motors in open circles can reverberate, but closed-circle motors bear numerous factors and must be coupled to an encoder, and structuring and operating an unrestricted circle motor can be precarious. Still, this influence can be minimized by using sensorless position estimation stepper motors with an artificial neural network (ANN) controller. Sensorless position estimation constantly knows the exact position and speed of the rotor; therefore, speed and positioning mode control are significantly improved. Stepper motors are employed in a variety of operations, including 3D printers, computer numerical control (CNC) machines, and cloth machines. They're also increasingly used in manufacturing associations, similar to packing bottles and aligning factors in some machine diligence to make gears. In this study, the variable disinclination stepper motor is employed. It has a nonmagnetic rotor made of soft iron. When the stepper engine gets a palpitation flag, it pivots at a settled point in the heading decided by the stepper engine. The stepper motor is made up of stator teeth and rotor teeth, each with a specific number of teeth to suit the stepper motor's design. In this study, we've used an 8/6 pole variable reluctance.

To determine the rotor's position, a series of voltage beats is transferred to the motor windings while the motor is stationary as well, and the rotor location information is deduced based on the most elevated current value that was observed [1]. Abbas *et al.* [2] examine developments in the fleetly growing area of sensorless control styles using electric engines, which are being advanced by advancements within the fields of digital signal processing and electrical equipment. Kumar [3] illustrates how to use LabView to control a stepper motor's position. A new sensorless approach for assessing the starting rotor position in hybrid stepping motors is described [4]. The suggested approach was established on the correlations among the maximal principles of electromotivation created in windings that are not generated and rotor position whenever a section of winding gets excited by a DC voltage source.

An enhanced dual-winding dependable magnetized actuator, known as a fault-tolerant permanent magnet motor (FTPMM), orientation estimate of the sensorless controller with dynamic parameter selection via back electromotive force (EMF) gradient [5]. Shen *et al.* [6] establish a utility for controlling a three-phase stepper machine that uses the TI 2000 Model DSP TMS320F2812 and describes the special hardware and software behind the system. The switched reluctance motor (SRM) parameters are acquired using the quick field program's numerical computation of the magnetic field and then included in a MATLAB/Simulink model of an SRM with a stator pole to rotor teeth ratio of 12/8. Cases with varying numbers of stator coil turns have been investigated, and the best option is established [7]. Rajan and Latha [8] present sensorless rotor position estimation of an SRM, with the position computed via the adaptive neuro-fuzzy inference system (ANFIS). A sensorless rotor position estimate approach based on an ANN [9] is described to completely meet the SRM's position feedback requirement. A MATLAB simulation environment is utilized to create a neural network and simulate the suggested sensor-less technique, which yields a good outcome. A new approach [10] for estimating the initial rotor position of a surface-mounted permanent magnet synchronous motor (SM-PMSM) that is simpler and more precise than using position or current sensors. The speed estimator for speed sensor-less direct torque control (DTC) of a three-phase induction motor is presented, based on the constant V/F control approach and an ANN [11]. When compared to conventional voltage lift approaches such as super lift converters and traditional boost converters, ultra-lift converters produce extremely large output transfer gains with geometric development. When compared, it has a smaller footprint and is more efficient. The functioning of an ultra-lift converter is investigated using continuous conduction mode [12].

The control technique and ANN structure are used to calculate and reorganize the estimated stator current equation. An extended Kalman filter (EKF)-based high-performance sensorless control was used to anticipate stator resistance in a fault-tolerant PMSM motor system [13]. Conventional DTC is one of the excellent control strategies available to control the torque of the induction machine (IM) [14]. A crossover consonant concealment strategy [15] is displayed for upgrading the adaptability of virtual synchronous generator (VSG), which is basically composed of a voltage consonant control circle and a lattice current-controlled circle. A straightforward and strong electromagnetic torque-based demonstration versatile framework speed estimator in an overhang pseudo subordinate criticism controller for sensorless surface mount changeless magnet in low-speed and stop zones, its execution is advanced by parallel powerplant (SMPMSM) drive [16]. Together with the principles and criteria of the second-degree sliding-mode spectator computation relying upon the super-twisting technique, a second-degree flexible sliding-mode spectator strategy [17] was presented. A higher-order sliding mode observer-based (SMO) vigorous backstepping control is proposed in [18], for sensorless speed control of an inside changeless magnet synchronous engine (IPMSM). A diagram of a few sorts of footing engines for electric vehicles (EVs) and hybrid electric vehicle (HEVs), as well as a tall temporal execution speed sensorless footing drive control [19].

The expanded Kalman channel calculates the area and speed essential for field-based management. The streams as well as the polarities of the stepper motor's two stages are checked and utilized for state estimation through an amplified Kalman channel. The anticipated position is compared to the expected position, and the engine is halted at the wanted area [20]. A state gauge approach for closed-loop operation of half-breed stepper engines (HSMs), which are commonly utilized as actuators over a wide extend of operational speeds. The proposed innovation permits for closed-loop control of HSMs without the utilization of any additional sensors [21]. Physics-guided neural network (PGNN) feedforward controller [22] for HSMs that can learn the impact of ectopic powers from information and redress for them, driving in expanded precision. Wind, PV, and battery-based crossover vitality frameworks create power for stand-alone AC microgrid applications [23]. A sensorless DTC framework built on a neural arrangement. This arrangement is planned to handle the work of selecting the ideal exchanging state for an acceptance engine based on data approximately its electromagnetic torque and stator flux (position and greatness). In reality, due to its long computation time, this approach, which leverages a standard exchange table, is unacceptable for one-line and real-time control [24]. The coordinate torque control (DTC) approach is inspected for this engineering. Since extra inverter states are accessible in the three-level inverter, voltage determination alternatives are extended [25].

The aim of this research is one technique for determining the location of stepper motors without the usage of additional sensors is ANN-based sensorless position estimation. Stepper motors are unique because they operate in tiny, accurate increments, which makes them ideal for applications like robotics and 3D printers where precision is crucial. Since external sensors are not required, this technology saves money and space by tracking the motor's location by monitoring the electrical impulses inside the motor. In order to better regulate the motor's motions, this approach estimates the motor's location based on its inherent properties. Without requiring additional equipment, it's a clever method to guarantee the motor reaches the desired location, making it an appealing choice for engineers wishing to optimize their creations.

2. RESEARCH METHOD

This research aims to enhance by integrating DTC techniques with ANN-based position estimation to assess stepper motor performance in sensorless settings. Real-time torque control, data-driven position estimate, and analytical modeling of torque generation are the three main pillars of the methodology. An effective and reliable motor control system appropriate for robotics and automation applications is constructed with the help of each component.

2.1. Artificial neural network-based position estimation

An ANN may recognize an object's position in a range of applications, including robotics and navigation, by manipulating rotor position and speed without the use of a sensor. The system is trained on labeled datasets with inputs corresponding to known locations and is capable of interpreting a variety of data formats, including sensor readings. Using a real-time control signal, Figure 1 demonstrates the basic block diagram of the ANN controller. ANN can foresee the stepper motor's position, removing the need for manual feature design. They can be more noise-resistant, making them excellent for active areas. The requirement for costly sensors can be decreased by relying on predictive modeling.

Figure 1. Basic block diagram of an ANN controller

2.2. Direct torque control strategy

To augment the effectiveness of the stepper motor, the torque should be adjusted instantly; therefore, DTC is used. It employs high-performance variable-frequency speed control technology. It employs minimum control structures and the direct control approach. The DTC strategy is used based on the motor's parameters, and it assumes that the rotor flux is constant and that the torque may be directly controlled by modifying the stator voltage. DTC is simple and outperforms other commonly used techniques, making it suitable for robotic systems. The fundamental notion underlying DTC is to regulate both torque and flux.

2.3. Torque equation

A qualitative technique is not always appropriate for dealing with stepper motor circuitry characteristics. Figure 2 demonstrates the torque positioning characteristics. So, a theory based on magnetic energy and co-energy will be examined in order to understand the process of torque creation using a dynamic method. The analysis begins with an ideal situation in which the rotor and stator cores are magnetically saturated.

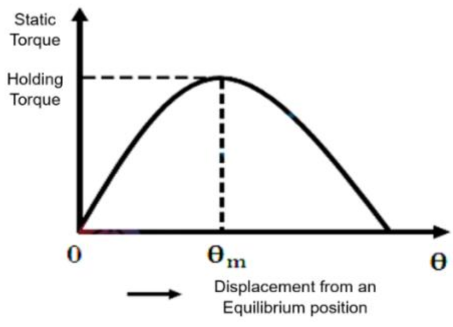

Figure 2. Torque positioning characteristics

2.3.1. Case I: infinitely permeable cores

According to Ampere's law, the position of the airgap's Hg-magnetic force magnitude, the cores' HI-magnetic force magnitude, and the cores' l-total electromagnetic path $H_i(l) = 0$ when the permeability of cores is very high.

$$\oint H.dl = nI \tag{1}$$

$$\oint H.dl = H_g\,({}^{g}/_{2}) + H_g\,({}^{g}/_{2}) + H_i(l) = H_g\,(g) + H_i(l) \tag{2}$$

$$\oint H.dl = H_g\,(g) \tag{3}$$

$$H_g\,.\,g = nIHg = \frac{nI}{g}, Bg = \mu_0 Hg\,\&\; Hg = \frac{Bg}{\mu_0} \tag{4}$$

Substitute Hg in (4), $Bg = \frac{\mu_0 nI}{g}$.

$$Bg = {}^{\emptyset}/_{A} = \frac{\emptyset}{xw} \tag{5}$$

$$\emptyset = \frac{\mu_0 nIxw}{g} \tag{6}$$

Flux linkage, $\varphi = n\emptyset$ (7)

$$\varphi = \frac{xw\mu_0 n^2 I}{g} \tag{8}$$

$$\Delta\,\varphi = \frac{w\mu_0 n^2 I\infty}{g} \tag{9}$$

$$\text{Emf, } e = \frac{\Delta\varphi}{\Delta t} = \frac{-w\mu_0 n^2 I}{g}\,.\frac{\Delta x}{\Delta t},\; \textit{work done}, \Delta Pi = I|e|\Delta t \tag{10}$$

$$\Delta Pi = \frac{w\mu_0 n^2 I^2}{g}\Delta x \tag{11}$$

$$\Delta Pi = \frac{B_g^2 .gw\Delta x}{\mu_0} \tag{12}$$

Where, μ_0-permeability in the gap length, let w be the thickness of the press component's transverse length and x be the distance between the press piece and the rotor teeth across the overlapped sector, the product xw represents the effective overlapping area, and an incremental displacement Δx at time Δt is assumed. The source's effort is partially transformed into mechanical work, with the remaining portion going toward strengthening the magnetic field of energy in the gaps. ΔPi is transformed into the electricity of the magnetic field, whereas the remaining half of Pi is transformed into mechanical work. The mechanical work is equal to the force 'f' times a distance Δx, and comparing (13) and (14).

$$\Delta Wm = {}^{1}/_{2}\,\Delta Pi = \frac{{}^{1}/_{2} Bg^2}{\mu_0}.\,g.\,w\Delta x \tag{13}$$

$$f = {}^{1}/_{2}\frac{B_g^2}{\mu_0}gw \tag{14}$$

Substitute (14) to Bg,

$$f = {}^{1}/_{2}\frac{{\mu_0}^2 n^2 I^2}{g^2 \mu_0}\,gw, f = {}^{1}/_{2}\frac{w{\mu_0}^2 n^2 I^2}{g^2} \tag{15}$$

Magnetic energy $Wm = fx, Wm = {}^{1}/_{2}\frac{B_g^2}{\mu_0}g \times w$

$$Wm = {}^{1}/_{2}\frac{\mu_0 n^2 I^2}{g}xw \tag{16}$$

Compare (13) and (15), $f = \left[\frac{\partial w_m}{\partial x}\right] I = \text{constant}$ (in rigorous form).

$$f = -\left[\frac{\partial w_m}{\partial x}\right] \emptyset = \text{constant (coil resistance is not zero)}$$

2.3.2. Case II: constant permeabilities

In the infinity permeable cores, especially in the voids does a field of magnets shows up. When centers are of limited penetrability, the attractive vitality shows up moreover in the centers and spaces other than the holes. The magnetic energy, $\omega_m = ½LI^2$, Emf, $e = \frac{-\Delta\Psi}{\Delta t}$.

$$\varphi = LI \quad (17)$$

$$e = -I\frac{\Delta L}{\Delta t} \quad (18)$$

$$\Delta Pi = I^2\Delta L \quad (19)$$

Increase in the magnetic energy $\Delta\omega_m = ½\Delta Pi$.

$$\Delta\omega_m = ½I^2\Delta L \quad (20)$$

Mechanical work,

$$\Delta P_D = f\Delta \quad (21)$$

Comparing (20) and (21), $f\Delta x = ½\, I^2\Delta L$.

$$f = ½\, I^2\frac{\Delta L}{\Delta x} \quad (22)$$

The work done by two power supplies during Δt,

$$\Delta Pi = -(e_1 I_1 + e_2 I_2)\Delta t = -[-I_1\frac{\Delta L_1}{\Delta t} - I_1 I_2\frac{\Delta M}{\Delta t} - I_2^2\frac{\Delta L_2}{\Delta t} - I_1 I_2\frac{\Delta M}{\Delta t}]$$
$$\Delta Pi = I_1^2\Delta L_1 + I_2^2\Delta L_2 + 2I_1I_2\Delta m$$

The increment of magnetic energy,

$$\Delta wm = ½\Delta Pi = ½[I_1^2\Delta L_1 + I_2^2\Delta L_2] + I_1I_2\Delta m$$

Mechanical output,

$$\Delta Po = T\Delta\theta \quad (23)$$

As, $T = ½\, I_1^2\frac{\partial L_1}{\partial\theta} + ½\, I_2^2\frac{\partial L_2}{\partial\theta} + I_1I_2\frac{\partial M}{\partial\theta}$ Torque can be expressed.

3. RESULTS AND DISCUSSION

Figure 3 demonstrates the simulation diagram of sensorless position estimation for a stepper motor using an ANN controller. Figure 4 demonstrates the current from the stepper motor, which means that when the supply voltage is given to the sensorless position estimation of the stepper motor circuit, it will convert the DC voltage to the AC voltage by using the converter. The torque output of the circuit can also be observed by using an ANN-based controller to eliminate the non-linear disrupting torques at low speed, and depending on the current, position of the motor, and speed of the stepper motor's current, it is ideally sinusoidal but is frequently approximated by an exhaustive step waveform. A full-step waveform is a crude approximation of the sinusoidal.

Figure 5 demonstrates a sinusoidal output torque waveform of a stepper motor, exhibiting a circular rotating magnetic field in space. This increases stepper motor rotational stability and diminishes motor output torque variations. Figure 6 shows the output waveform for the speed. The speed of a stepper motor is established by the pulse frequency (Hz) conveyed to the driver. Output of the speed based on the motor position and the rotational speed of the stepper motor, which is calculated via the pulse frequency.

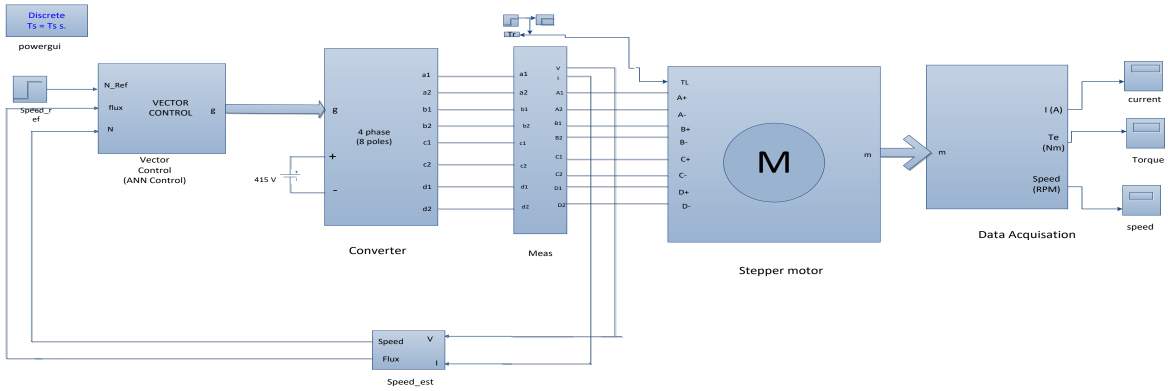

Figure 3. Simulation diagram of sensorless position estimation for a stepper motor using ANN control

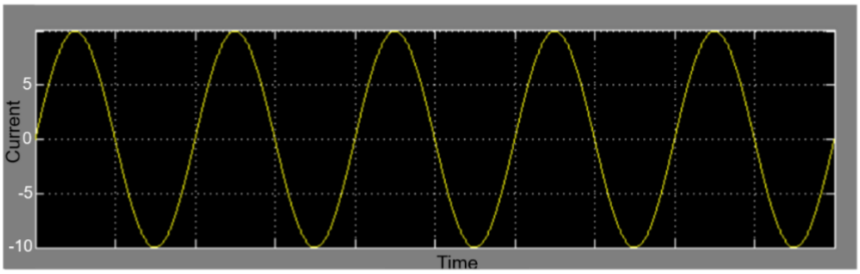

Figure 4. Output waveform of the current of the stepper motor

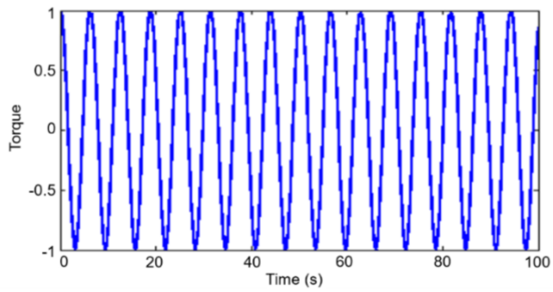

Figure 5. Output waveforms of torque

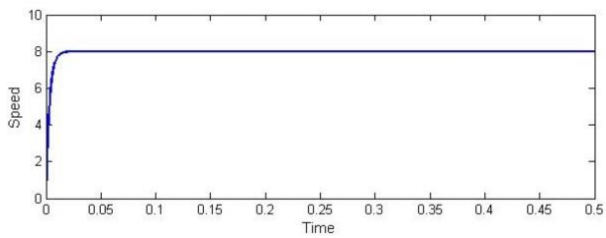

Figure 6. Output waveform of the speed of the stepper motor

4. CONCLUSION

Subsequently, a Martyr controller is used for estimating the location of a stepper motor, as seen by the waveforms of speed, torque, and current above. A large number of subblocks were employed, as well as the switching table and vector control block. It is used to boost motor performance, reduce motor noise, improve process accuracy, and extend motor endurance. When operating the stepper motor, it may fail to follow a pulse command when the stepping rate or inertial load is too high; these types of errors can be avoided by using the ANN control, which is also used to estimate the real-time position of the stepper motor rotor. By doing so, the motor's overall performance and efficiency can be improved. Stepper motors are widely used in industrial and many consumer applications. Advanced approaches, including fuzzy sliding observers, SMO, ANFIS, and fuzzy logic control, are all included in the suggested future framework for sensorless speed control systems. This seeks to maximize performance while keeping costs down by boosting speed control precision without raising physical expenses.

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AUTHOR CONTRIBUTIONS STATEMENT

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Thiruveedula Madhu Babu	✓	✓		✓	✓	✓	✓			✓		✓	✓	✓
Srinidhi Gollapudi	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tarun Kumar Dommeti	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Abhishek Kummari	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mahith Shambukari	✓			✓			✓	✓	✓		✓	✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [NA], upon reasonable request.

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