Optimal Load Angle Learning Algorithm for Sensorless Closed-loop Stepping Motor Control

1st Jasper De Viaene
Department of Electrical Energy, Metals, Mechanical Constructions and Systems
Ghent University campus Kortrijk
Department of Electromechanics, Op3Mech
University of Antwerp
Member of EEDT partner of Flanders Make
Kortrijk, Belgium
Jasper.DeViaene@UGent.be

2nd David Ceulemans
Department of Electromechanics, Op3Mech
University of Antwerp
Member of EEDT partner of Flanders Make
Antwerp, Belgium
David.Ceulemans@uantwerpen.be

3rd Stijn Derammelaere
Department of Electromechanics, Op3Mech
University of Antwerp
Member of EEDT partner of Flanders Make
Antwerp, Belgium
Stijn.Derammelaere@uantwerpen.be

4th Kurt Stockman
Department of Electrical Energy, Metals, Mechanical Constructions and Systems
Ghent University campus Kortrijk
Member of EEDT partner of Flanders Make
Kortrijk, Belgium
Kurt.Stockman@UGent.be

***Abstract*—Stepping motors are well suited for open-loop positioning tasks at low-power. The rotor position of the machine is simply controlled by the user. Every time the user sends a next pulse, the stepping motor driver excites the correct stator phases to rotate the rotor over a pre-defined discrete angular position. In this way, counting the step command pulses enables open-loop positioning. However, when the motor is overloaded or stuck, the relation between the expected rotor position based on the number of step command pulses and the actual rotor position is lost. To avoid this, the bulk of the widely used full-step open-loop stepping motor drive algorithms are driven at maximum current. This non-optimal way of control leads to low efficiency. To use stepping motors more optimally, closed-loop control is needed. A previously described sensorless load angle estimation algorithm, solely based on voltage and current measurements, is used to provide sensorless feedback. A closed-loop load angle controller adapts the current level to reach the setpoint load angle to obtain the optimal torque/current ratio. The difficulty is that the optimal load angle depends on the mechanical dynamics. To avoid the requirement of knowledge of the mechanical parameters, a practical learning algorithm to determine the optimal load angle is presented in this paper. Measurements validate the proposed approach.**

***Index Terms*—stepping motor, intelligent sensorless drive, sensorless control, load angle**

The absence of an expensive position sensor makes stepping motors very appealing for low-power positioning. The rotor position of the machine is controlled by sending step command pulses. Every time the user sends a step command pulse, the rotor of the machine makes a discrete rotation. In this way, it is easy to control the position without the explicit feedback of a mechanical position sensor. The two-phase hybrid stepping motor principle is illustrated in Fig. 1(a-b). The stator is equipped with concentrated windings while the multi-toothed rotor is magnetized by means of axially oriented permanent magnets. The north-stack and south-stack of the rotor each have rotor teeth and are shifted with half a tooth pitch relative to each other. By magnetising phase A, the excited stator phase (A^+ and A^-) attracts the rotor teeth. When a new full-step command pulse is given, the excitation of one phase is released while the second phase is excited.

When the motor is overloaded due to too high load torque or acceleration demands, the relation between the setpoint and the actual rotor position is lost. In most cases, this step loss will not be noticed by the stepper controller and will result in malfunction of the application. Until today, to reduce the

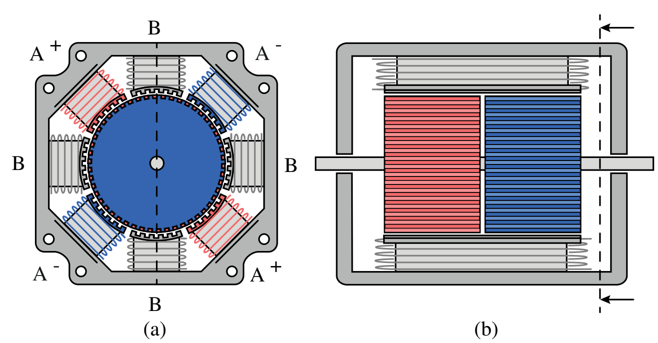

Fig. 1. Two-phase hybrid stepping motor with 50 rotor teeth per stack, front view (a) and cross section (b)

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possibility of step loss, the motor is driven at limited velocity, maximum current level or is over-dimensioned [1]. This means that the bulk of the stepping motors are driven in a non-optimal way with a low efficiency as a result [2].

The basic open-loop algorithms are unsatisfactory to drive a stepper motor efficiently. For this purpose, vector-control algorithms, as used in permanent-magnet synchronous machines (PMSM) [3] and induction machines (IM) [4], are of interest. The advanced stepping motor drive algorithms described in [5] use control loops common for PMSM machines. However, positioning by using step command pulses is impossible when these methods described in [5] are implemented. This incompatibility with classic stepping motor drive algorithms hinders the implementation of these methods in industry.

Therefore, a previously described sensorless load angle estimation algorithm, solely based on voltage and current measurements, is used to provide sensorless feedback [6]. Based on this feedback a closed-loop load angle controller adapts the current level to reach the setpoint load angle to obtain the optimal torque/current ratio [7]. An essential advantage of this approach is the fact that optimal performance is obtained without a need to change the control architecture for the stepping motor user. The latter means that the user can still control the position by sending and counting step command pulses while the load angle controller continuously optimises the current level. A drawback is that the optimal load angle greatly depends on the mechanical dynamics. Therefore, to avoid the requirement of knowledge of the mechanical parameters, a practical learning algorithm to determine the optimal load angle is presented in this paper.

I. LOAD ANGLE

The equation describing the electromagnetic motor torque is essential to have the necessary understanding of the stepping motor drive principle. An expression describing the electromagnetic motor torque can be quantified based on the interaction between the stator flux linkage space vector $\boldsymbol{\Psi}_s$ and the stator current space vector $\mathbf{i}_s$ ([8]).

$$\mathbf{T_{em}} = \boldsymbol{\Psi_s} \times \mathbf{i_s} \tag{1}$$

By neglecting saturation and splitting the stator flux linkage to a dq-reference frame which is fixed to the rotor flux, the electromagnetic torque is written as:

$$\mathbf{T_{em}} = (\boldsymbol{\Psi_r} + \mathbf{i}_{\boldsymbol{d}}.\boldsymbol{L_d} + \mathbf{i}_{\boldsymbol{q}}.\boldsymbol{L_q}) \times \mathbf{i_s} \tag{2}$$

Elaboration of the vector products leads to an equation describing the electromagnetic torque as a function of the current amplitude i_s and the load angle δ, defined as the angle between $\mathbf{i}_s$ and the rotor flux $\boldsymbol{\Psi}_r$ (Fig. 3):

$$T_{\text{em}} = \psi_r.i_s.\sin(\delta) + \frac{L_d - L_q}{2}.i_s^2.\sin(2\delta) \tag{3}$$

The first term in (3) describes the torque generated by the interaction between the permanent magnet rotor flux Ψ_r and the stator current i_s. This term depends on the sine of the load angle δ. Because of the multi-toothed rotor and

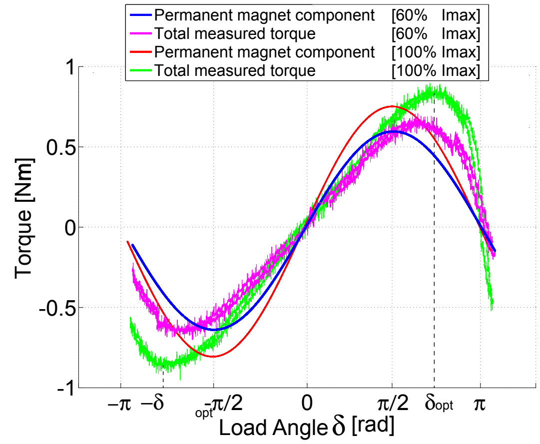

Fig. 2. Measured torque - load angle relation for 60% and 100% nominal current $I_{\max}$

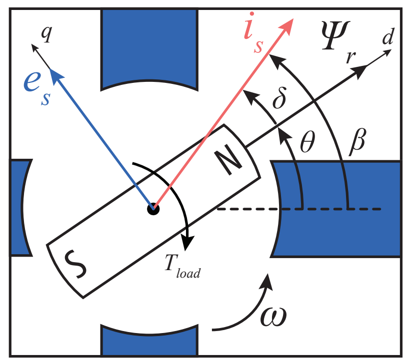

Fig. 3. Vector diagram and load angle δ

stator construction of a hybrid stepping motor, the reluctance effect will increase the maximum electromagnetic torque. This reluctance effect is represented by the second term in (3) and varies sinusoidally with twice the load angle δ. To quantify both effects, the motor torque is measured in [6] at different positions while the rotor is blocked. The load angle δ is modified by changing the phase current setpoints i_a^* and i_b^*. For a current amplitude of 60 and 100% of the nominal current, measurement results are given in Fig. 2. The dominant torque component, which varies with the sine of the load angle δ is the component generated by the permanent magnet effect.

A. Load angle estimation

The load angle δ can be used to identify the quality of the torque generation because it contains information of the torque/current ratio. The load angle is therefore interesting to estimate. The load angle δ equals to β - θ (Fig. 3). Unless an encoder is used, the location θ of the rotor flux vector $\boldsymbol{\Psi_r}$ is unknown. Therefore to estimate the load angle, the back-EMF is considered. Based on Lenz's law the resultant back-EMF vector $\mathbf{e}_s$ induced in the stator windings by the rotor flux $\boldsymbol{\Psi_r}$ can be written as:

$$\mathbf{e}_s \quad = \quad C\frac{\boldsymbol{d\Psi_r}}{dt} \tag{4}$$

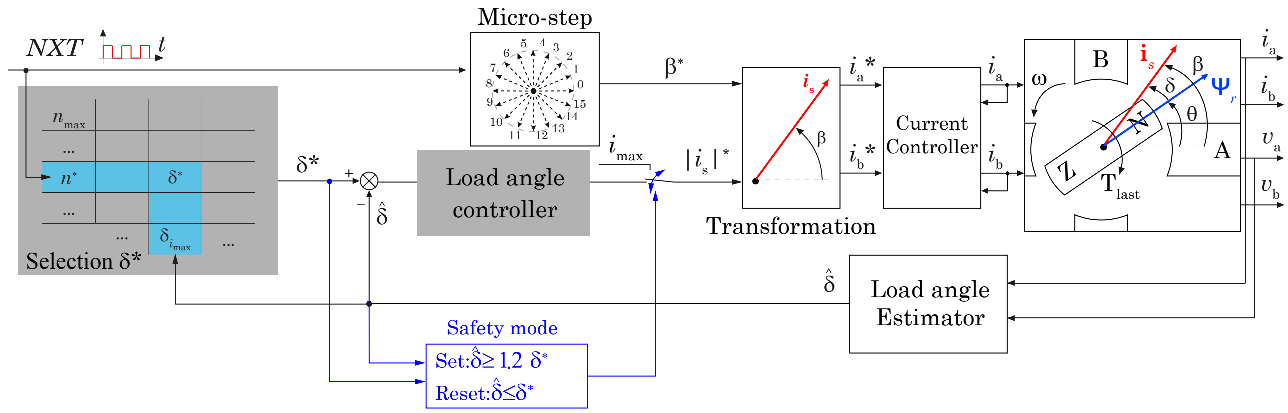

Fig. 4. Typical stepper motor drive principle where current vector $\mathbf{i}_s$ position β is determined by step command NXT pulses sent by the user and current level is adapted by a load angle controller

As a result, $\mathbf{e}_s$ leads the $\boldsymbol{\Psi_r}$ by $\frac{\pi}{2}$. Therefore, the load angle can be redefined as:

$$\delta = \frac{\pi}{2} - (\angle \mathbf{e}_s - \angle \mathbf{i}_s) \tag{5}$$

This means that the load angle can be estimated based on the vectors $\mathbf{e}_s$ and $\mathbf{i}_s$. To obtain these vectors, phase back-EMF e_a and e_b and phase currents i_a and i_b have to be known. In equation (5), the location of the current and the back-EMF vectors $\angle \mathbf{i}_s$ and $\angle \mathbf{e}_s$ are unknown. Because the phase currents i_a and $i_b$can be easily measured, the problem of estimating the load angle is reduced to a problem of estimating the position of the back-EMF e_s. The back-EMF can be estimated based on the voltage equation of the stator windings. There is no interaction between the two phases because they are perpendicular to each other [9]. Therefore, the mutual inductance is neglected, and the back-EMF can be written as:

$$e_s(t) \quad = \quad u_s(t) - R_s.i_s(t) - L_s\frac{di_s}{dt} \tag{6}$$

The derivative in eq. (6) will cause problems if the measured current contains noise. Determining the derivative of noisy signals would result in distorted estimations. Therefore [6] suggests to write (6) in the frequency domain, where ω represents the signal pulsation:

$$E_\mathrm{s}(\mathrm{j}\omega) = U_\mathrm{s}(\mathrm{j}\omega) + R_\mathrm{s} I_\mathrm{s}(\mathrm{j}\omega) + \mathrm{j}\omega.L_\mathrm{s} I_\mathrm{s}(\mathrm{j}\omega) \tag{7}$$

According to this method, only electrical parameters such as the stator resistance and inductance and the complex representation of the phase current and voltage are needed to estimate the load angle. In stepping motor applications the position and speed setpoints are determined by step command pulses sent by the user as long as no step loss occurs. This means that the speed and consequently also the instantaneous signal pulsation ω are always known. The complex components $U_\mathrm{a}(\mathrm{j}\omega)$ and $I_\mathrm{a}(\mathrm{j}\omega)$ of the measured voltage and current signals are determined via transformation of the signals from the time to the angular domain. [10] describes a load angle estimator based on Transfer function analyzer which can determine the complex components even during speed transients.

II. LOAD ANGLE CONTROLLER

The large majority of the stepping motors in the industry are driven in open-loop using a full, half or micro-stepping algorithm. These algorithms impose a stator current vector $\mathbf{i}_\mathrm{s}$. In these typical stepping motor drives, the angular position of the stator current vector is determined by step command pulses. Many commercial stepping motor drives allow to adjust the current vector amplitude, labelled i_s in Fig. 4. Based on i_s and the step command pulses sent by the user, the transformation to the two-phase system is made, and the current controller injects the desired currents in the motor as indicated in Fig. 4. By doing so, the position of the rotor can be controlled in open-loop. The advantage of this method is that the position of the rotor is directly imposed. The disadvantage is that the position of the permanent rotor flux $\boldsymbol{\Psi}_\mathrm{r}$ has not been taken into account to inject the two phase currents in order to achieve optimal torque generation.

[7] suggest a closed-loop load angle controller which is complementary to the conventional stepping motor drives or to the controller tested on BLDC motor platform [11]. A PI controller adjusts the current level to obtain the setpoint load angle. In other words, the controller determines the amplitude of the stator current vector while the step commands determines the position of this vector. The controller reduces the current from the nominal level to the minimum current necessary to drive the motor at a specific speed and load torque setpoint. Information of the load angle estimator is used as an input for the control of stepping motor in an energy-efficient way. This principle implemented on a BLDC motor is This approach is challenging as the optimal load angle depends on the operating point of the motor.

III. OPTIMAL LOAD ANGLE δ_{opt}

Before the current level can be optimized based on the difference between the setpoint load angle δ^* and the estimated load angle $\hat{\delta}$, the setpoint load angle δ^* has to be chosen carefully. By reducing the current step-wise until step loss occurs, as indicated in figure 5, the optimal load angle δ_{opt}

can be determined based on the feedback of the load angle estimator.

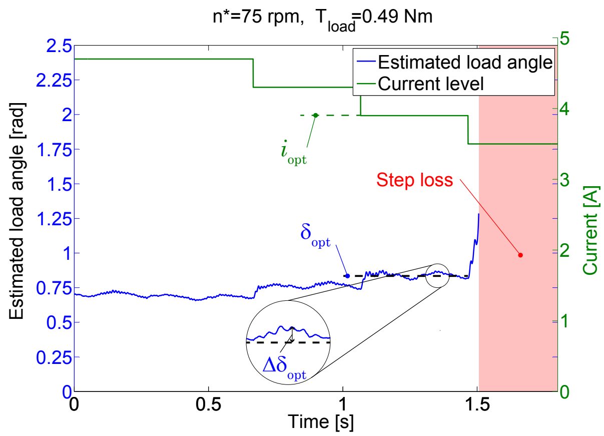

Fig. 5. Step-wise reduce of the current level to determine the optimal load angle δ_{opt}

By measuring the optimal load angle δ_{opt} for the entire machine's operating area, figure 6 is obtained. The outcome clearly shows that the optimal load angle δ_{opt} varies greatly and can deviate strongly from the optimal load angle values based on the measured static torque - load angle relation (Figure 2). Optimal load angle of $\frac{\pi}{2}$ or higher are totally not achieved when the loaded machine is driven at a certain speed, as shown in figure 6.

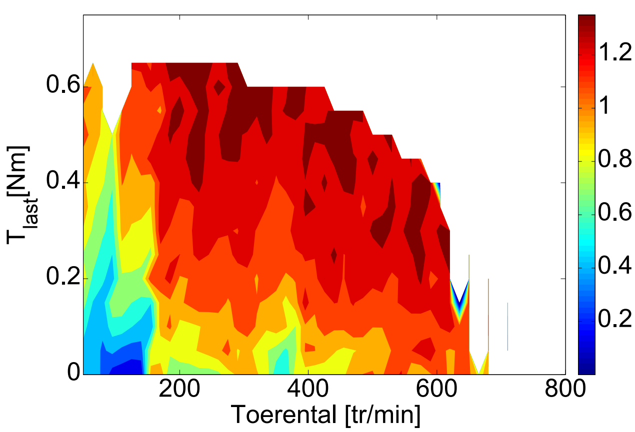

Fig. 6. Optimal load angle [rad] for the entire operating area of the stepping motor

This can be theoretically explained by the study of the system dynamics of a hybrid stepping motor. In [7], a linear model of the dynamics of a stepping motor is described where a certain current i_s results in a load angle δ with J the inertia, b the damping and C_T the torque constant:

$$\frac{\delta(s)}{I(s)} = \frac{-C_T.\sin(\delta^*)}{\dfrac{b.\omega^* + T^*_{\text{load}}}{\tan(\delta^*)} + b.s + J.s^2} \qquad (8)$$

In this way, linear control theory in the s-domain can be used to examine the dynamic system behaviour. The process dynamics are characterized by the location of its poles being the roots of the denominator. [7] and (9) describe the location of the system poles and shows that the linearized dynamics clearly are dependent on the operating point $(T^*_{\text{load}}, \omega^*, \delta^*)$.

$$J.s^2 + b.s + \frac{b.\omega^* + T^*_{\text{load}}}{\tan(\delta^*)} = 0 \qquad (9)$$

First, the load impact on the process dynamics is examined. As indicated by (9), the process dynamics depend on i.a. the sum of the friction torque $b.\omega^*$ and the load torque T^*_{load} which can be seen as the total load. With the motor and test bench data (J=6.28e-5 kgm^2, b=0.02 Ns/m) the characteristic equation is written as:

$$1 + (0,02.\omega^* + T^*_{\text{load}}) \cdot \frac{1}{1,61.10^{-4}s^2 + 0,051s} = 0 \qquad (10)$$

Fig. 7 shows the root locus describing the load angle dynamics ranging from an unloaded machine at low speed ($n^* = 50\text{tr/min}$) up to full load ($n^* = 500\text{tr/min}$, $T^*_{\text{load}} = 0,49\text{Nm}$). Fig. 7 shows that the load angle responds faster on current level changes for a more loaded machine at higher speeds. In this case, the load angle response is 12.5 times faster for the fully loaded machine ($n^* = 500\text{tr/min}$, $T^*_{\text{load}} = 0,49\text{Nm}$) compared to the unloaded machine at low speed ($n^* = 50\text{tr/min}$). This will make the control more robust at high speeds so that the optimal load angle δ^* can be set higher at higher speeds.

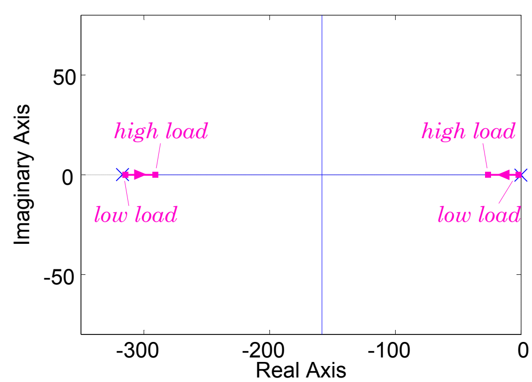

Fig. 7. Root locus describing the load angle dynamics as a function of the load $b.\omega^* + T^*_{\text{load}}$

Also the choice of the setpoint load angle δ^* influences the stability of the load angle control. Therefore, the impact of the setpoint load angle and the load are examined together. The load ($b.\omega^* + T^*_{\text{load}}$) may vary strongly and is difficult to estimate. However, if steady-state is assumed, the electromagnetic motor torque based on (3) neglecting the reluctance effect equals the sum of the load T^*_{load} and friction $b.\omega$:

$$C_T.i_s.\sin(\delta) = b.\omega^* + T^*_{\text{load}} \qquad (11)$$

Each time prior to the current reduction, the total load of the motor is estimated by estimating the load angle at maximum current level. The load of the motor is described in function of the load angle at maximum current $\delta_{i_{\max}}$. This value is determined merely using feedback of the load angle estimator.

$$b.\omega^* + T^*_{\text{load}} = C_T.I_{\max}.\sin(\delta_{i_{\max}}) \tag{12}$$

Therefore, the characteristic equation can be written as follow:

$$Js^2 + bs + C_T.I_{\max}.\frac{\sin(\delta_{i_{\max}})}{\tan(\delta^*)} = 0 \tag{13}$$

The location of the system poles can be considered as a function of the ratio of the load angle at maximum current $\delta_{i_{\max}}$ to the setpoint load angle δ^*. The characteristic equation is therefore rewritten as:

$$1 + \frac{\sin(\delta_{i_{\max}})}{\tan(\delta^*)}.\frac{C_T.I_{\max}}{Js^2 + bs} = 0 \tag{14}$$

The ratio of the load angle at maximum current $\delta_{i_{\max}}$ to the setpoint load angle δ^* is thus written as $\frac{\sin(\delta_{i_{\max}})}{\tan(\delta^*)}$. As long as this ratio is equal or bigger than 1, the setpoint load angle δ^* will always be smaller than the load angle at maximum current $\delta_{i_{\max}}$. In such a case the setpoint load angle δ^* cannot be reached and controlling the current level is not possible.

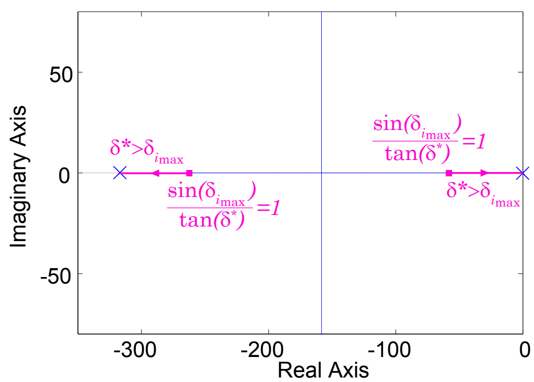

Fig. 8. System dynamics as a function of the setpoint load angle δ^* and the load $\delta_{i_{\max}}$

When the setpoint load angle δ^* is bigger than the load angle at maximum current $\delta_{i_{\max}}$, the dominant system pole will move to the right, causing a slower response of the system on current level changes and the system becomes possibly unstable. The location of the system poles based on equation (14) are shown in Figure 8. When the load angle at maximum current $\delta_{i_{\max}}$ is 0.2 rad, and the controller wants to increase the setpoint load angle δ^* to 1.5 rad, the dominant system pole will move to the right such that the settling time increase to a high value of 5.86 s. Even at low speed (5 % n_{nom} or 35 rpm) this corresponds to 3.4 full rotor rotations. Therefore, the setting of δ^* made by the user is essential to have a stable system. The setpoint load angle δ^* should not be much larger than the load angle at maximum current $\delta_{i_{\max}}$. When the difference between the setpoint and real load angle becomes too high, the load angle control may become unstable.

To use these insights to determine the setpoint load angle δ^*, knowledge about the relationship between the optimal load angle δ_{opt} and the current level i_s based on the mechanical dynamics is required. However, this depends on the load inertia J and damping b. Therefore, using the above insights in practice is impossible for unknown mechanical loads parameters. A more practical learning algorithm is discussed in the next section.

IV. Learning Algorithm for Selecting the Optimal Load Angle δ_{opt}

Both theoretical insights (Fig. 7 and 8) and practical measurements (Fig. 5) show that the optimal load angle (Fig. 2) characterized by the statically measured torque - load angle relation characteristics cannot be used as setpoint value δ^* for controlling the load angle during motor operation. The relationship between the current level and the reluctance effect initially ensures that the optimal load angle increases for higher current levels. A larger mechanical load requires a higher current level. As a result of its impact on the optimal current, the load also influences the optimum load angle. Besides, the setpoint speed also has an impact on the optimum achievable load angle δ. Therefore, a method for determining the setpoint load angle δ^* as a function of the operating point is required. That operating point can always be determined. The user imposes the speed by sending next pulses. The load angle at maximum current $\delta_{i_{\max}}$ is proportional to the mechanical load (12) and can be determined by the load angle estimator. The optimal setpoint load angle in function of speed and mechanical load or $\delta_{i_{\max}}$ which is proportional to the mechanical load can be stored in a table, as indicated in Figure 4.

A too large setpoint load angle δ^* results in an unstable controlled system. The estimated load angle $\hat{\delta}$ will then violently oscillate which results in exceeding a well-chosen threshold which is followed by activating the safety mode. In this mode, the stepping motor is controlled again at maximum current. When the safety mode is triggered, this means that the selected setpoint load angle δ^* was too large and should be adjusted downwards, as illustrated in Figure 9. In this way, the contents of the table (Fig. 4) is changed systematically. The threshold value and the step size that determines how much the load angle δ^* must be adjusted downwards is set by the user and is is described in [12]. Here, a threshold of 120 % of the setpoint load angle δ^* is chosen. For each operating point, a rather large setpoint load angle is chosen first. The activation of the safe mode results in a downward adjustment of the setpoint load angle.

The controller sets the current level at maximum if the load torque increases to such an extent that the estimated load angle $\hat{\delta}$ exceeds 120 % of the setpoint load angle δ^* . The load angle $\delta_{i_{\max}}$ at maximum current will be higher as a result of the increased load torque. In this way, the load angle controller is informed about a change in the operating point. The setpoint

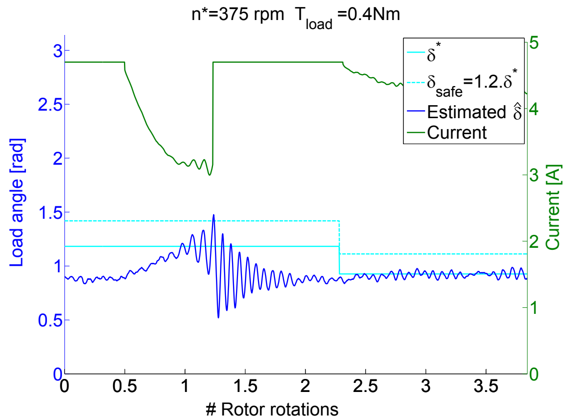

Fig. 9. Activation of the safe mode will result in a downward adjustment of the setpoint load angle because the previously selected setpoint load angle was too high resulting in unstable control

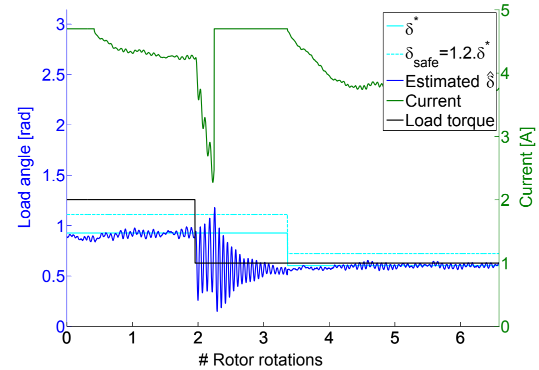

Fig. 11. Decrease of the setpoint load angle δ^* after load torque drop from 0.4Nm to no load at 375 rpm

load angle δ^* is requested from the table, indicated in Figure 10.

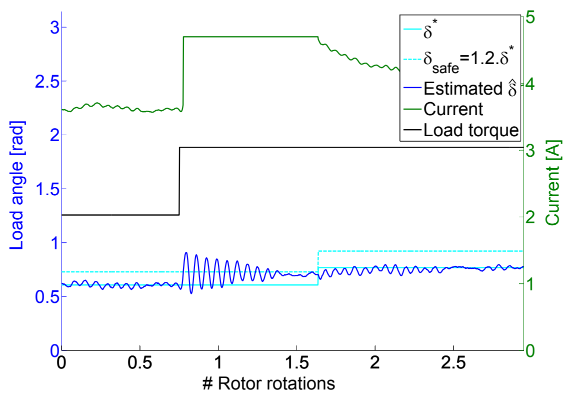

Fig. 10. Increase of the setpoint load angle δ^* after load torque increase from 0.2Nm to 0.3Nm at 375 rpm

The optimal load angle becomes smaller if a lower current level is required. Since a smaller load requires a lower current level, the achievable setpoint load angle will also decrease when the load torque drops. Figure 11 shows that the load angle oscillates violently when the load torque is suddenly reduced. The setpoint load angle δ^* is too large for this low load torque. The oscillation exceeds the level of 120 % of δ^* [12] which is followed by deactivation of the load angle controller. The motor is driven again at maximum current. Then it becomes clear that the load angle at maximum current $\delta_{i_{\max}}$ has dropped which has as a consequence that the setpoint load angle δ^* is adjusted downwards.

The extended sensorless load angle controller is shown in figure 4. The load angle is determined during motor operation at maximum current to have an indication of the total load of the motor. The user imposes the speed by sending next pulses. In this way, the operating point is known and the corresponding optimal setpoint load angle δ^* is requested from the look-up table. As long as the estimated load angle does not exceed 120 % δ^*, the control is stable and the setpoint load angle δ^* is chosen well. When the load angle exceeds this level, the controller sets the current level at maximum. This happens when a change in load occurs. Also when a speed change is imposed by the user, the current is automatically set at maximum level. In these cases, the estimation algorithm indicates a different load angle $\delta_{i_{\max}}$ at maximum current. As a result, the setpoint load angle δ^* is adjusted as illustrated in Figure 4.

V. CONCLUSIONS

The bulk of the stepping motor applications are driven in open-loop at the maximum current to avoid step loss. To use stepping motors more optimally, closed-loop control is needed. A previously described sensorless load angle estimation algorithm is used to provide the necessary feedback. The load angle is an indication for the torque/current ratio of the stepper motor drive. The closed-loop load angle controller adapts the current level to reach the setpoint load angle to obtain the optimal torque/current ratio. An essential advantage of this approach is the fact that optimal performance is obtained without changing the control architecture for the stepping motor user. A drawback is that the optimal load angle depends on the mechanical dynamics. Therefore, to avoid the requirement of knowledge of the mechanical parameters, a practical selection learning algorithm to determine the optimal load angle is presented in this paper. The setpoint load angle δ^* is determined during motor operation at maximum current. The estimated load angle $\delta_{i_{\max}}$ at this operating point is an indication of the mechanical load. In this way, the operating point is known and the corresponding setpoint load angle δ^* is requested from a look-up table. As long as the estimated load angle does not exceed the threshold, the control is stable and the setpoint load angle δ^* is chosen well. When the load angle exceeds this level, the controller sets the current level at maximum and the selection learning algorithm is re-iterated.

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References

[1] W. Lu, Q. Wang, K. Ji, H. Dong, J. Lin, and J. Qian, "Research on Closed-Loop Drive System of Two-Phase Hybrid Step Motor Based on SVPWM," *2016 IEEE Vehicle Power and Propulsion Conference, VPPC 2016 - Proceedings*, 2016.

[2] S. Derammelaere, B. Vervisch, F. De Belie, B. Vanwalleghem, J. Cottyn, P. Cox, G. Van Den Abeele, K. Stockman, and L. Vandevelde, "The efficiency of hybrid stepping motors: Analyzing the impact of control algorithms," *IEEE Industry Applications Magazine*, vol. 20, no. 4, pp. 50–60, 2014.

[3] M. Seilmeier and B. Piepenbreier, "Sensorless Control of PMSM for the whole speed range using Two-Degree-of-Freedom current control and HF test current injection for low speed range," *IEEE Transactions on Power Electronics*, vol. PP, no. 99, pp. 1–1, 2014. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6891366

[4] Y.-d. Yoon, "Sensorless Control for Induction Machines Using Square-wave Voltage Injection," *Electronics*, pp. 3147–3152, 2010.

[5] W. Kim, C. Yang, and C. C. Chung, "Design and implementation of simple field-oriented control for permanent magnet stepper motors without dq transformation," *IEEE Transactions on Magnetics*, vol. 47, no. 10, pp. 4231–4234, 2011.

[6] S. Derammelaere, C. Debruyne, F. De Belie, K. Stockman, and L. Vandevelde, "Load angle estimation for two-phase hybrid stepping motors," *IET Electric Power Applications*, vol. 8, no. 7, pp. 257–266, 2014.

[7] S. Derammelaere, B. Vervisch, J. De Viaene, and K. Stockman, "Sensorless load angle control for two-phase hybrid stepper motors," *Mechatronics*, vol. 43, pp. 6–17, 2017.

[8] W. Lin and Z. Zheng, "Simulation and Experiment of Sensorless Direct Torque Control of Hybrid Stepping Motor Based on DSP," *2006 International Conference on Mechatronics and Automation*, pp. 2133–2138.

[9] M. Bendjedia, Y. Ait-Amirat, B. Walther, and A. Berthon, "Position control of a sensorless stepper motor," *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 578–587, 2012.

[10] J. De Viaene, S. Derammelaere, and K. Stockman, "Load angle estimation for dynamic stepping motor motion applications," *Mechatronics*, vol. 53, 2018.

[11] J. De Viaene, F. Verbelen, S. Derammelaere, and K. Stockman, "Energy-efficient sensorless load angle control of a BLDC motor using sinusoidal currents," *IET Electric Power Applications*, vol. 12, no. 9, pp. 1378–1389, 2018.

[12] S. Derammelaere, F. Verbelen, and K. Stockman, "Open loop control of a stepping motor with step loss detection and stall detection using back-EMF based load angle estimation," *IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM*, pp. 788–793, 2014.