Efficiency of Two-Phase Hybrid Stepping Motor Drive Algorithms

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Abstract

Stepping motors are used in numerous applications because of their low manufacturing cost and simple open loop position control capabilities. It is well known that their energy efficiency is low but actual values are generally not available. Moreover, the bulk of the stepping motor applications are driven in open loop, with maximum current, to avoid step loss. A full step drive algorithm results in a low efficiency.

In this paper the influence of the control algorithm on the efficiency of the motor is analyzed, measured and discussed. The basic open loop full-, half- and micro stepping algorithms are considered together with a more intelligent vector control algorithm. For each algorithm, torque/current optimization is discussed. As stepping motors are typically used for a broader range of torques and speeds, nominal values are not given. To present the efficiency of the motor for different control strategies, at every operating point, ISO efficiency curves are used. With these curves, the efficiencies of the different control strategies can be compared.

As stepping motors are mostly used for low-power position control one can argue that stepping motor efficiency is not an issue. However the number of stepping motors installed worldwide is enormous. Moreover, a lower energy consumption can also result in less heat production and cheaper power supply electronics.

Introduction

Stepping motor applications are used in robotics, textile industry, domestic apparatus, etc. The simple and cheap construction, the ease of control and the open-loop capabilities of stepping motors make them very interesting in low power applications. The absence of rotor windings reduces the inertia and weight, so higher dynamics are reached. The lack of contact aging serves the reliability and mechanical ruggedness. Finally, the availability of torque at standstill makes a stepping motor to fit perfectly for diverse applications.

Despite all these advantages, stepping motor control algorithms such as open-loop full-step control often result in very poor torque/current ratios. These low torque/current ratios result in a low overall efficiency [1]. These motors are used in low-power position control, so efficiency was not an issue in research so far. However, the estimated worldwide market in 2009 for stepping motors was 90 million units only for Industrial Automation and control, Textile machines, Medical equipment, Printer Market and the Security camera market. It is obvious that the total amount of stepping motors installed worldwide is enormous. Moreover in some textile machine applications stepping motors are working continuously, and thus continuously consume energy.

In this paper the efficiencies of the basic and most popular open loop drive methodologies, full- half- and micro-stepping are analyzed and compared with a more advanced vector control algorithm. As modern drives allow to reduce the current level for full- half- and micro-stepping profiles these possibilities are analyzed to maximize the torque/current ratio. In this way an overview of the efficiency of a two phase hybrid stepping motor is given.

As stepping motors are typically used for a broader range of torques and speeds, nominal values are not given. To present the efficiency of the motor for different control strategies, at every operating point, ISO efficiency curves are used [2, 3]. With these curves, the efficiency of the different control strategies can be compared.

Stepping Motor Torque Generation

The principle of operation of a two-phase hybrid stepper motor is illustrated in [4, 5] and shown in Fig. 1. The rotor is attracted by the excited stator phase. Fig. 1 shows the static torque-rotor position curves for both phases. The solid curve illustrates the torque-position relation for an excited phase A. For a given load torque T_{load}, a stable operating point p is reached. When a step (full step mode) command is given, phase B is excited and the excitation of phase A is removed. The dotted line illustrates the torque when phase B is excited. For the same load torque T_{load}, the rotor moves until a new equilibrium point q is reached.

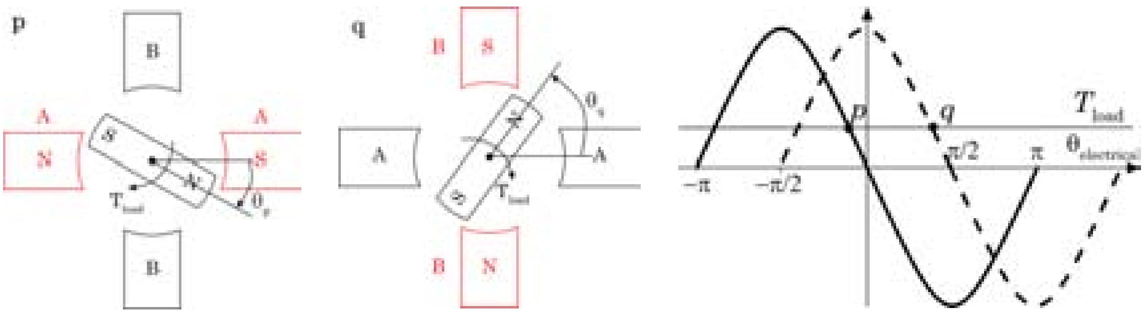

Figure 1. Stepping motor principle (left) and static torque-rotor position curves (right)

As shown in Fig. 1, for an excited phase A, the maximum torque, generated by the dc-current in phase A, is available at $\theta_{electrical}=-\pi/2$ rad. For the load torque in Fig. 1, the motor is used in position p. The maximum torque, related to the applied current is not required to hold the load. The torque/current ratio is not optimal resulting in high copper losses. This results in a low efficiency.

One possible solution to optimize the torque/current ratio is to reduce the current as shown in Fig. 2a. This current reduction results in a new equilibrium point. However, because of the high number of pole pairs, this change in rotor position is in most cases not relevant. A further current reduction is not possible because of the required acceleration torque to move the rotor.

Fig 2a. shows the maximum current reduction, which is valid for a zero rotational speed. When the speed increases, the excitation time of a single phase t_{step} decreases. To avoid step loss, the time t_{move}, during which the rotor rotates from p to q, has to be smaller than t_{step}. Therefore it can be necessary to increase the acceleration torque as in Fig. 3.b. The time t_{move} is determined by equation (1):

$$C_T \cdot I.\sin(\theta) = T_{load} + b.\frac{d\theta}{dt} + J.\frac{d^2\theta}{dt^2} \qquad (1)$$

The constraint that t_{move} has to be smaller than t_{step} determines the maximum current reduction (Fig. 3).

Furthermore the torque ripples will result in vibrations and possible resonances. Therefore the next step command may not be given between $t_{res\ low}$ and $t_{res\ high}$.

These limits, clearly visible in the ISO-efficiency curves, are inherent to the mechanical parameters of the test bench, such as inertia, and will vary for other applications.

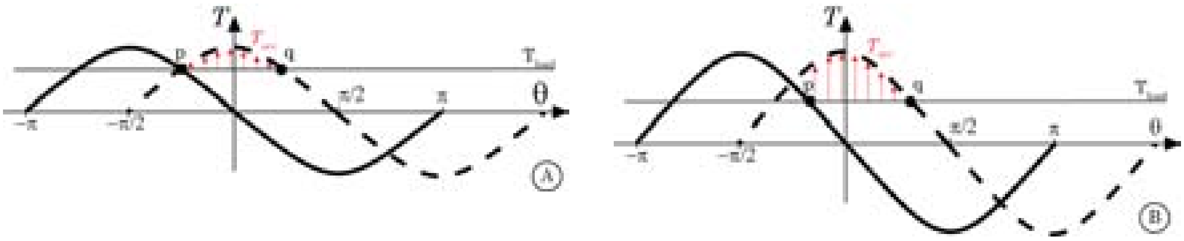

Figure 2. Reducing the current to optimize the torque/current ratio. (A) Full-step minimum current, (B) Full-step with higher accelaration torque

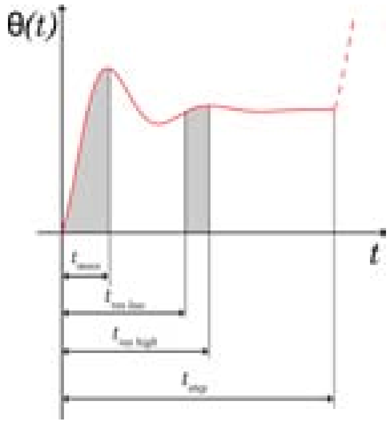

Figure 3. t_{move} **has to be smaller than** t_{step}

Stepping Motor Drive Algorithms

This paper discusses the influence of stepping motor drive algorithms on the overall efficiency of the system. Therefore the different stepping motor drive algorithms are considered in this paragraph. Next to the basic and most used full-, half- and micro-stepping algorithms, which are all based on discrete steady-state rotor positions, a more advanced vector control algorithm is discussed.

Full-, Half- and Micro-Stepping

The stepping motor construction is ideally suited for open loop positioning. When constant phase current setpoints are applied at certain moments, the rotor will move from one discrete steady-state position to another. By counting the step command pulses, open loop positioning is made possible.

The full step algorithm illustrated in Fig. 4a is based on the fact that there is only one excited phase at every moment. When a full-step command is given, the excitation of one phase is released while another phase is excited. This results in rather large steps.

When both phases are excited simultaneously at maximum current, a stable operating point q between p and r is obtained. The step angle between two discrete operating points is halved in comparison to the full step algorithm. This is called half step operation.

Finally micro-stepping is based on additional current setpoints which are a fraction of the maximum current. This approach makes it possible to obtain much more discrete operating points and thus decrease the step angle. As the step angle decreases, the movement will become more smoothly as illustrated in Fig. 5.

It is obvious that there is more acceleration torque needed to move the rotor at once from point p to q, than the amount of torque required to move the rotor from point p over point q to point r. The conclusion here is that the necessary current to operate the motor will be lower as the step angle decreases and the movement becomes more smoothly.

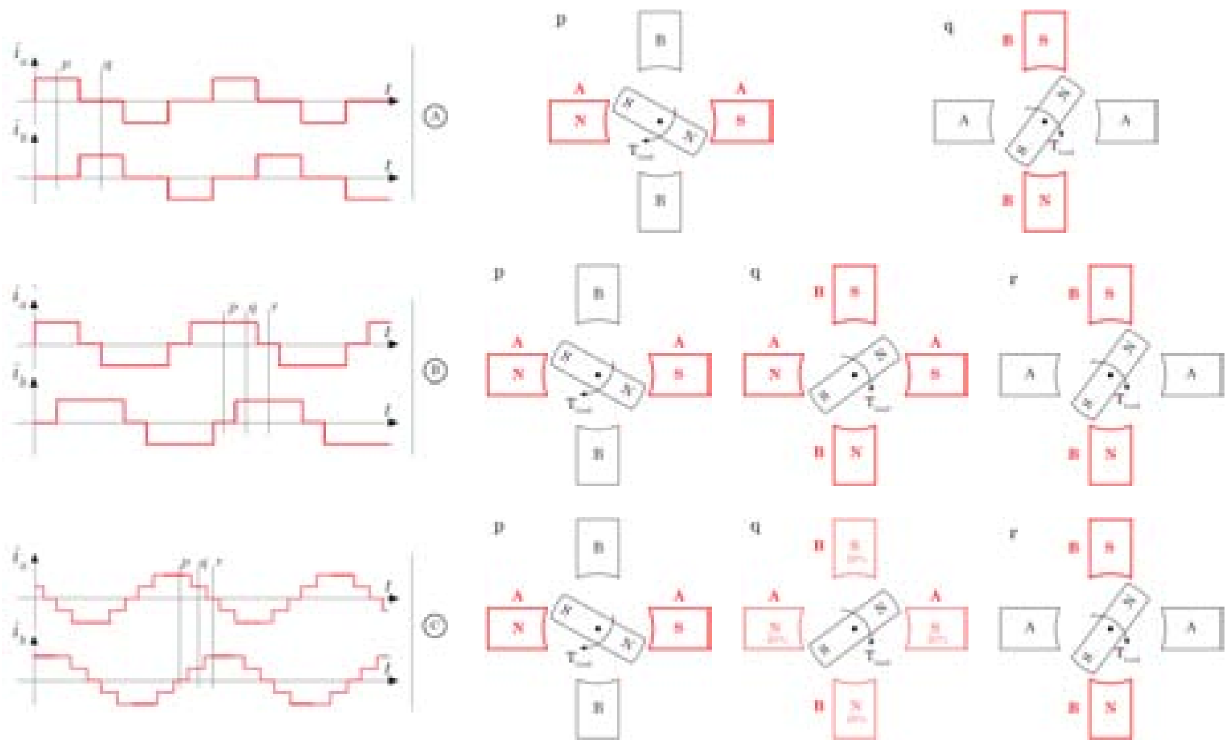

Figure 4. **Full-, half- and micro-stepping algorithms**

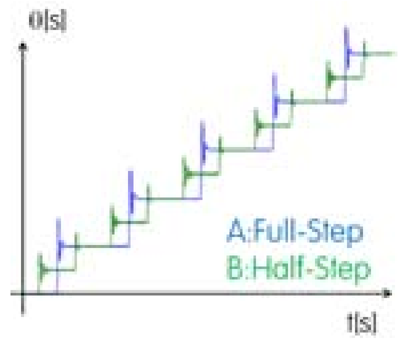

Figure 5. **Full- and Half step position profiles**

Vector Control

Fig. 6 illustrates the vector control principle. The flux vector Φ_R is fixed to the permanent magnet rotor. The vector control algorithm requires that the two phases can be excited simultaneously. The combination of the currents in phase A and B results in the stator current vector i_s.

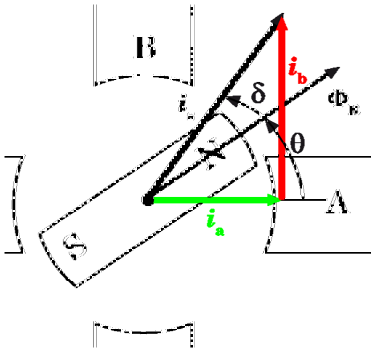

Figure 6. Vector Control torque generation

When neglecting reluctance and saturation effects, the torque can be written as:

$$T_{\text{motor}} = C_T . i_s . \sin(\bullet) \tag{2}$$

According to (2), the motor torque is proportional to the stator current amplitude and the sine of the load angle δ between the stator current vector $\boldsymbol{i_s}$ and the rotor flux vector $\boldsymbol{\Phi_R}$. The torque-current ratio is optimal when δ equals 90°. By applying a closed-loop controller, the load angle δ can be controlled in a stable way.

The implementation of this vector control algorithm is illustrated in Fig. 7. The set-point currents i_a^* and i_b^* are computed in order to have a load angle δ close to 90°. The current amplitude i_s results in the required torque.

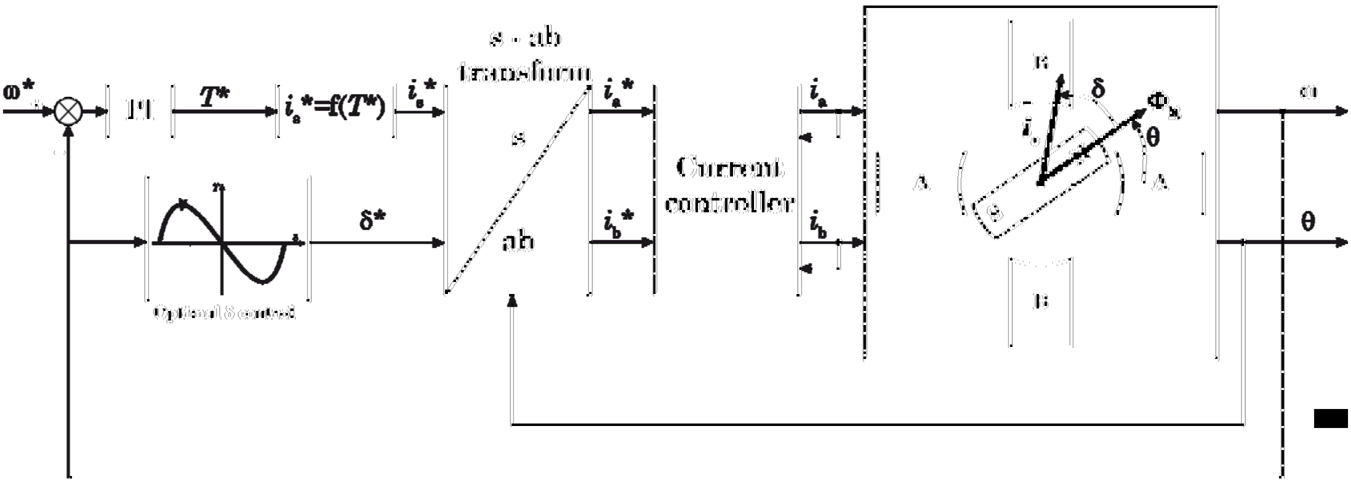

Figure 7. Vector Control implementation

Efficiency of a stepping motor

The efficiency of a stepping motor is given as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{mech}}{P_{mech} + P_{loss}} \qquad (3)$$

The electric power supplied to the drive is converted into useful mechanical power as well as some electrical and mechanical losses. In general, the losses appearing in electric machines are copper losses, iron losses, friction and windage losses, and the stray load losses [6]. In a small stepping motor it is reasonable to assume that the iron losses, friction losses and stray load losses are negligible compared to the copper losses. Since the cooling is natural there are no windage losses. When only taking into account the copper losses the calculated efficiency will be a little higher compared to the measured efficiency.

Copper losses

For the representation of the copper losses the r.m.s.-value of the phase current is used. The actual phase current is discontinuous (Fig. 4). The r.m.s.-value results in an equivalent dc-current generating the same copper losses as the discontinuous phase current. The copper losses in a phase, using the r.m.s.-current value are given by:

$$P_c = I_{ph,rms}^2 \cdot R_{ph} \qquad (4)$$

The r.m.s. current is defined as:

$$I_{ph,rms} = \sqrt{\frac{1}{T}\int_0^T i_{ph}^2(t)dt} \qquad (5)$$

For the full- and half- stepping, the r.m.s. current can be written as:

$$I_{ph,rms} = I_{peak} \cdot \sqrt{D} \qquad (6)$$

Where D is the duty cycle (D=0.5 for full-step and D=0.75 for half-step).

The r.m.s. current for the micro-stepping control depends on the number of micro-steps. For the micro-stepping profile of Fig. 4c, wich uses 4 micro-steps, the r.m.s. current is:

$$I_{ph,rms} = 0.74.I_{peak} \qquad (7)$$

The open-loop full-, half- and micro-stepping algorithms uses known current setpoints to drive the motor. On the other hand the closed loop vector control algorithm will continuously adapt the current setpoint. Therefore a theoretical calculation of the efficiency will only be performed for the full-, half- and micro-stepping algorithms.

Theoretical efficiency

Taking into account that the stepping motor has two phases, the theoretical efficiency assuming only copper losses can be written as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{mech}}{P_{mech} + \left(I_{ph,rms}^{2} \cdot R_{ph}\right) \cdot 2} \qquad (8)$$

The peak current I_{peak} for the analyzed motor is for both full and half step 5.7 A, and equals the nominal current of the motor. Each stator phase has a resistance of 0.65• . With these specifications the efficiency can be mapped in an ISO efficiency curve (Fig. 8). The contour lines indicate a variation of 2,5% and the vertical color bar on the right side represents the efficiency ranging from 0 to 80%. The maps are limited by the physical torque and speed limits of the motor indicated in Fig. 3. The strange and rough form of the curve which limits the maps is determined by experiments and is explained by the vibrations and resonances typical for the stepping motor movement.

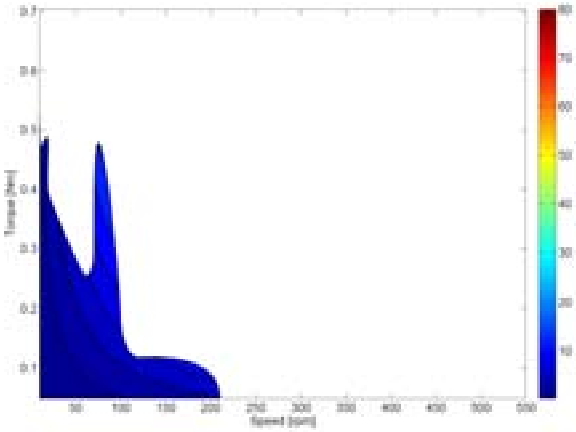

Figure 8. Theoretical efficiency (%) curve for a stepping motor in full step

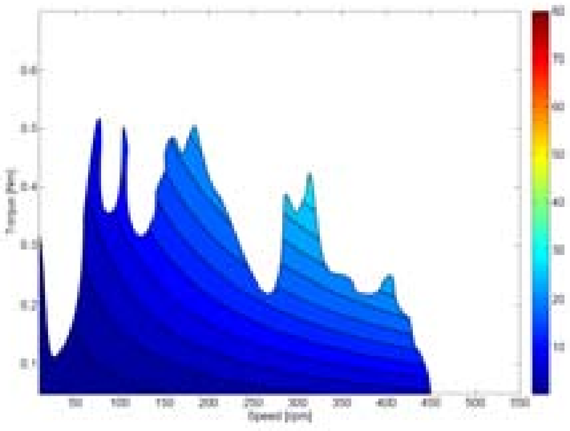

Figure 9. Theoretical efficiency (%) curve for a stepping motor in half step.

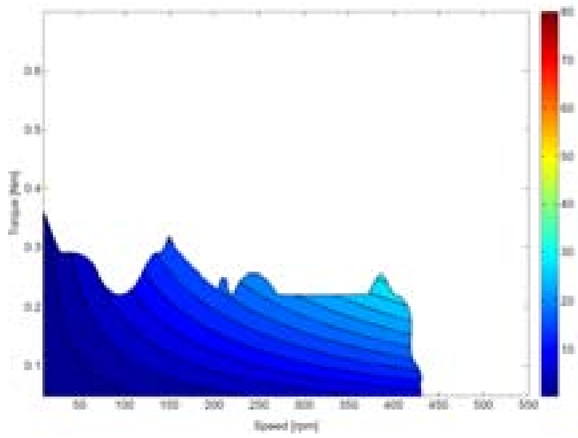

Figure 10. Theoretical efficiency (%) curve for a stepping motor in micro stepping.

As shown in Figs. 8-10 the efficiency of the stepping motor is very low. This is due to the high current, the relatively high phase resistance of the small motor and the poor torque/current ratio. Due to the higher duty cycle, the half step control results in a lower efficiency.

These results are interesting as it identifies the copper losses as the main reason for the low efficiency. Although the efficiency will be measured exactly in the following paragraph, this theoretical approach is interesting to understand the principle of the energy efficiency of a stepping motor.

However, from paragraph II, it follows that the desired torque can be achieved with a smaller current. By reducing the current the losses can be heavily reduced in some operating areas.

Measurements

The dedicated test rig, used to measure the efficiencies is illustrated in Fig. 11. To calculate the efficiency, the current i_{dc} and voltage v_{dc} at the dc-bus of the stepping motor drive and the shaft torque and speed are measured (Fig. 12). The advantage of this approach is that the total amount of power, necessary to drive the motor can be measured. The switching losses are also included in this measurement.

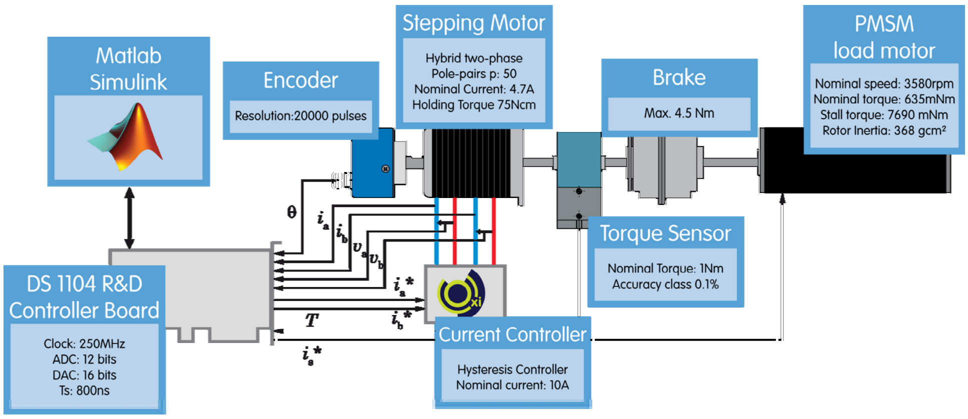

Figure 11. Test Rig

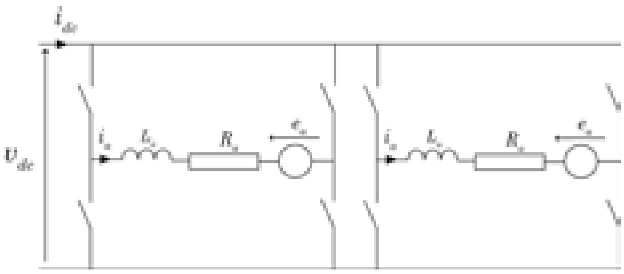

Figure 12. Electric scheme and measurements

The power delivered to the motor can be calculated as:

$$P_{in} = \frac{1}{T}\int_0^T v_{dc} \cdot i_{dc} dt \qquad (9)$$

Then the measured efficiency is computed by:

$$\eta = \frac{P_{mech}}{P_{in}} \qquad (10)$$

The mechanical power can be noted as:

$$P_{mech} = T \cdot \omega \qquad (11)$$

The torque T is measured by the torque sensor present at the test rig, the rotational speed ω is known as the speed set point is known.

Measurements are made at 55 different speed values and for 25 different load torque values resulting in a matrix of 1375 measurement points. The rotor speed is chosen in a way that resonance is avoided [7].

Nominal current

First, the motor is driven with nominal current. The ISO efficiency curves for full, half and micro stepping are shown in Figs. 14-16. The overall efficiency is lower than expected in the theoretical approach, especially at higher speeds. The maximum deviation between the theoretically calculated and measured efficiency is 3.5%. This can be due to iron losses, friction losses and stray load losses. Furthermore, the currents generated by the drive are not exactly square wave. As a result, (6) is an approximation of the computed r.m.s.-value of the current.

Fig. 13 shows the currents in a single phase for different speeds. This figure shows that current overshoot and oscillation occur when the current converges to zero. These oscillations increase the r.m.s.-value of the current. At low speeds, this ripple can be neglected as its duration is small compared to the excitation time t_{step}. However, at higher speeds it becomes more important. The increased r.m.s.-current produces higher copper losses compared to the theoretical approximation. Optimization of the current control algorithm could reduce these additional losses.

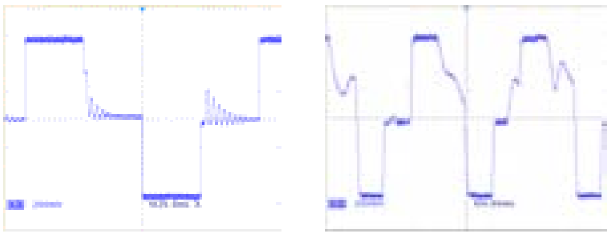

Figure 13. Current in one phase at 7 rpm (left) and at 77 rpm (right) (100mV/A)

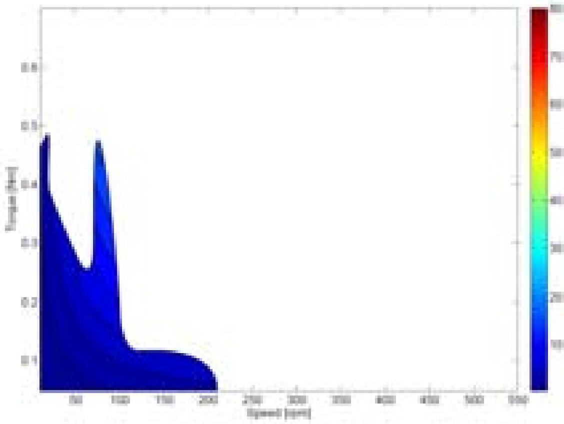

Figure 14. Measured efficiency (%) curve for stepping motor in full step

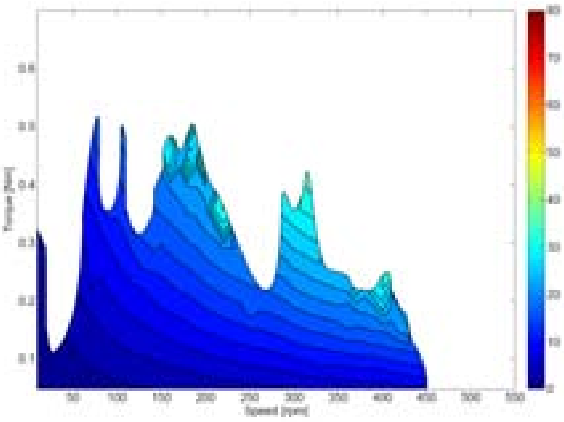

Figure 15. Measured efficiency (%) curve for stepping motor in half step

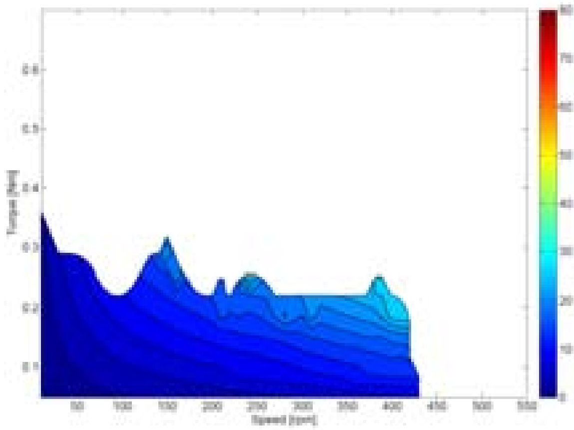

Figure 16. Measured efficiency (%) curve for stepping motor in micro step

Current reduction

To measure the efficiency at more optimal current levels, the current for every torque/speed operating point is reduced as low as possible, meaning the lowest current at which the motor is still able to perform the movement at the setpoint speed. Of course, this implies that there is no margin for acceleration or torque disturbances. This maximum current reduction is determined by equation (1) and the constraint illustrated in Fig. 3 and explained earlier.

Measurement results are shown in Figs. 17-19.

The impact of current reduction on the efficiency is maximized at half the maximum speed and torque. At low speed there is also a significant current reduction, but the losses stay relatively high compared to the useful mechanical power, resulting in a low efficiency. As shown in Fig. 2, at high speed, the torques must be high enough to accelerate the machine. As a result the margin for current reduction is low. This also holds for high load torques.

As mentioned before, the current reduction can be higher at half- and micro-stepping, as the necessary acceleration torque is smaller.

Indeed, in Figs.18 and 19 the area of the current reduction is much larger resulting in a higher efficiency increase. Figs. 18 and 19 show better efficiencies than Fig. 17. From Figs. 14, 15, 17 and 18 it follows that the half-step drive methodology will only result in a higher efficiency if the current reduction is applied.

E.g. for half-step control at 120rpm and with a load torque of 0.1173 Nm the efficiency is only 4.6%. While the full-step control efficiency at that point is 6.9%. By reducing the current to 15% of the nominal current, the half-step efficiency can be increased up to 45.3%. Due to the smaller possible current reduction at full-step, the full-step efficiency can only be optimized up to 10.1%. At this particular point the micro-stepping efficiency is 5.4% at nominal current and 48.7% for a reduced current.

Vector Control

The vector control principle is based on the optimization of the torque/current ratio. Measurements illustrated in Fig. 20 prove that this approach increases the efficiency to a more optimal level. At lower torques and speed set points the efficiency is still low due to the low useful mechanical power. However at the largest part of the map, the efficiency varies around 45%. Compared to the efficiencies, obtained with half- and micro-stepping control at minimized current, the gain in efficiency can be as high as 62% by using the vector control algorithm.

Thanks to the vector control structure this optimized torque/current ratio does not affect the dynamic behavior and margin for torque or speed set point disturbances. Furthermore Fig. 20 clearly shows that the area in which the stepping motor is able to deliver torque at a certain speed set point is much larger compared to the full- half and micro-stepping control thanks to the smoother movement obtained by the vector control principle.

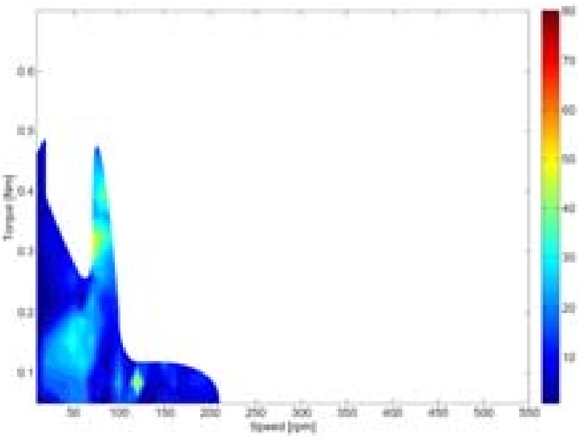

Figure 17. Measured efficiency (%) curve for a stepping motor with full-step control and with current reduction

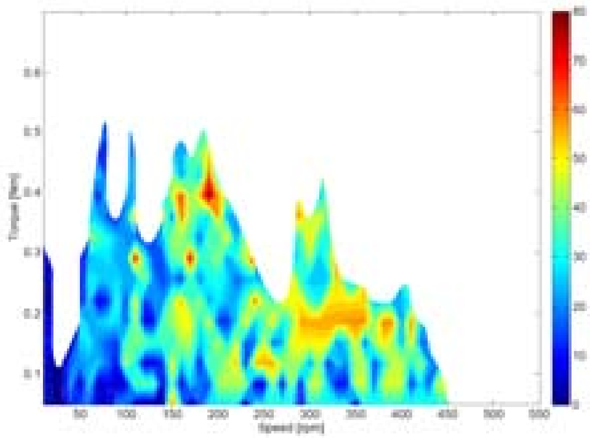

Figure 18. Measured efficiency curve (%) for a stepping motor with half-step control and current reduction

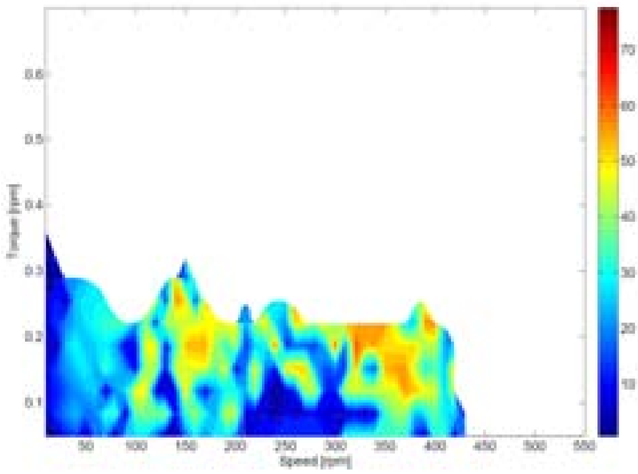

Figure 19. Measured efficiency curve (%) for a stepping motor with micro-stepping control and current reduction

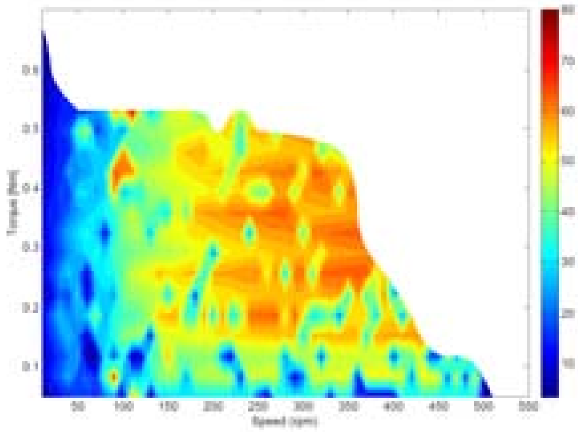

Figure 20. Measured efficiency curve (%) for a stepping motor with vector control

Conclusions

For both full-, half- and micro-step control of a two-phase hybrid stepping motor a detailed overview of the efficiency is given by using ISO-efficiency curves. These curves are obtained by a theoretical approach and through measurements.

The bulk of the stepping motor applications are driven in open loop, with maximum current to avoid step loss. These drive strategies result in very poor efficiency. To increase the efficiency the current can be reduced. The possible current reduction depends on the operating point in the torque-current area. The efficiency can be seriously increased, up to 9 times better, by this current reduction approach, which is achievable on most basic stepping motor drives.

To perform the measurements the current level was reduced until step loss occurs. An algorithm which predicts the possible current reduction could be implemented based on the mechanical equation (1). Solving this non-linear differential equation would result in a high computational cost and should be performed offline. Therefore and alternative approach is considered using a vector control algorithm.

This vector control algorithm not only increases the efficiency (sometimes up to 62%) but also results in a much larger area in which the system is able to deliver a certain torque at a particular speed set point. Furthermore, the current reduction approach used for full-, half and micro-stepping implies that there is no margin left for torque or speed disturbances. However, the dynamic behavior and margin for torque and speed set point disturbances is not influenced by optimizing the torque/current ratio using the vector control algorithm.

It has to be mentioned that all the algorithms mentioned in this paper can be implemented without any additional hardware cost, apart from the controller. When a sensor less algorithm is used, even the vector control algorithm can be implemented without using a mechanical position or speed sensor.

As the total number of stepping motors installed worldwide is enormous, it is interesting to optimize the energy-efficiency of these systems. Moreover, a current reduction of 85% as mentioned in this paper, will reduce the heat production of the system, which is quadratic to the current.

References

[1] S. Derammelaere, B. Vervisch, J. Cottyn, B. Vanwalleghem, K. Stockman, F. De Belie, L. Vandevelde, P. Cox, G. Van den Abeele, *“ISO Efficiency Curves of a -Two-Phase Hybrid Stepping Motor”*, in Industry Applications Conference, IAS Annual Meeting, 2010.

[2] S. Williamson, M. Lukic, A. Emadi, *"Comprehensive drive train efficiency analysis of hybrid electric and fuel cell vehicles based on motor-controller efficiency modeling*," IEEE TRANSACTIONS ON POWER ELECTRONICS, vol. 21, pp. 730-740, MAY 2006.

[3] C. B. Rasmussen, H.R. Andersen, E. Ritchie, J.K. Pedersen, *"Design and efficiency comparison of electric motors for low power variable speed drives with focus on permanent magnet motors,*" in Electrical Machines and Drives, 1995. Seventh International Conference on (Conf. Publ. No. 412), 1995, pp. 428-432.

[4] S. Derammelaere, B. Vervisch, J. Cottyn, K. Stockman, F. De Belie, L. Vandevelde, P. Cox, G. Van den Abeele*, “Sensitivity analysis of a linear model for a vector controlled hybrid stepping motor”*, The XIV International Conference on Electrical Machines, Rome, 2010.

[5] C. Kuert, M. Jufer, Y. Perriard, *"New method for dynamic modeling of hybrid stepping motors,*" in Industry Applications Conference, 2002. 37th IAS Annual Meeting. Conference Record of the, 2002, pp. 6-12 vol.1.

[6] V. Raulin, A. Radun, L. Husain*, "Modeling of losses in switched reluctance machines*," IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, vol. 40, pp. 1560-1569, NOV-DEC 2004.

[7] M. Bodson, J.S. Sato, S.R. Silver, *"Spontaneous speed reversals in stepper motors,"* IEEE Transactions on Control Systems Technology, vol. 14, pp. 369-373, Mar 2006.