SYNCHRONIZATION AND EFFICIENCY ANALYSIS OF A DIRECT-DRIVE MULTI-MOTOR APPLICATION

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Keywords: Multi-motor synchronization, direct-drive, efficiency maps, PMSM

Abstract

This paper presents the results of a technical feasibility study concerning the direct-drive conversion of an existing four-axis wire processing machine. The objective is to obtain a considerable efficiency improvement, while maintaining equal speed and angle synchronization properties as the substituted gearbox mechanics. A control algorithm based on the method of 'electronic line shafting' is implemented and verified with simulations and experiments on a test setup. The controller emulates the inter-shaft state feedback of a physical gearbox resulting in comparable synchronization performance during load disturbances, acceleration and emergency stop conditions. The efficiency improvement potential is verified with measured efficiency maps of all drivetrain components. In the nominal operating point, the direct-drive machine outperforms the conventional machine with 14% due to the avoidance of gearbox losses and the application of highly efficient permanent magnet synchronous motor technology.

1 Introduction

In today's economic and ecologic reality of limited natural resources and increasing energy costs, reducing the total cost of ownership of motor driven systems in industrial applications is a key priority for creating a sustainable business model. Furthermore, cost containment and productivity improvement should also be considered in modern machine design. Electric motor driven systems account for approximately 70% of the total industrial electricity consumption worldwide, of which a large amount is wasted through inefficiency of the drivetrain components. Hence, the potential savings are large in terms of absolute figures when (re)designing the drivetrain of many machines. In doing so, all viable options should be explored to reduce losses. The largest gains are to be found in the mechanical components of the drivetrain, followed by electronic process control with a variable frequency drive instead of mechanical regulation. The application of high-efficiency motors should only be the third and last measure to implement. An interesting concept that goes even further, namely total elimination of mechanical transmission elements, is direct-drive. It offers promising potential for numerous industrial applications [1] using rotative or linear power transformations by means of mechanical components (gearboxes, belts, pulleys, chains, camshafts,...). By directly coupling power electronic controlled motors to the driven load, these mechanical components can be eliminated. This approach leads to an improvement of overall process efficiency, controllability and productivity. Furthermore, it results in a compact and straightforward machine design requiring less maintenance. In recent years, the breakthrough of permanent magnet synchronous motors (PMSM) able to provide high torque at low speed has further increased the interest in direct-drive machines [2]. Other benefits of these motors are the high power to volume ratio, high efficiency and excellent controllability over a wide operating range

Multi-axis machines in web or wire processing industries (paper, textile and metal) are particularly interesting for direct-drive conversion. These machines traditionally use mechanical components such as gearboxes or line shafts for power transformation and motion synchronization from a single driving motor to multiple output shafts.

This paper presents the results of a technical feasibility study concerning the direct-drive conversion of an existing four-axis gearbox-based wire processing machine (Figure 1). A number of technical challenges and considerations must be addressed in checking the feasibility of direct-drive for this application. First, suitable motors and drives must be found on the market able to deliver the required torques and speeds. Second, the attainable efficiencies of these motors are unknown or at least highly uncertain. Most manufacturers only provide values for the nominal operating point, which leaves the question how the motor will perform in other torque-speed regions. Finally, an electronic synchronization of the multiple machine shafts must be implemented in order to guarantee process continuity in case of load disturbances.

A research project was carried out to gain insight in the technical feasibility and efficiency improvement potential of direct-drive for this machine, addressing the previously mentioned items. A summary of the research findings can be found in this paper.

2 From gearbox to direct-drive

2.1 Experimental setup

In Figure 1, a schematic representation of the existing machine is shown. The four output shafts are connected to a speed-controlled 15 kW 6 pole induction motor M0 by means of a gearbox. The fixed gear ratios ensure that the resulting speeds of the shafts, and more importantly the speed ratios between them are in accordance with the demands of the process. Table 1 gives an overview of the load characteristics at each of the four machine shafts.

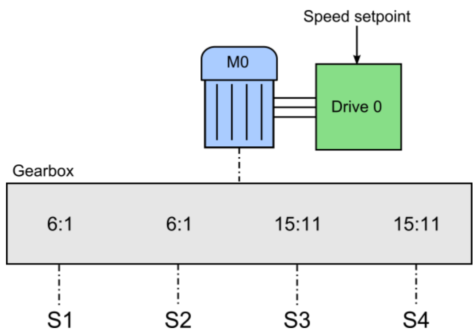

Figure 1: Conventional machine with gearbox.

Shaft	Motor	Torque [Nm]	Speed [RPM]	Power [kW]
S1	M1	100	250	2.6
S2	M1	100	250	2.6
S3	M2	35	1100	4
S4	M2	35	1100	4

Table 1: Load characteristics.

The machine has two slow shafts (S1 and S2) with high torque demand and two fast shafts (S3 and S4) with lower torque but higher power demand. According to the direct-drive principle, the gearbox is replaced by power electronic controlled motors directly coupled to each shaft as shown in Figure 2.

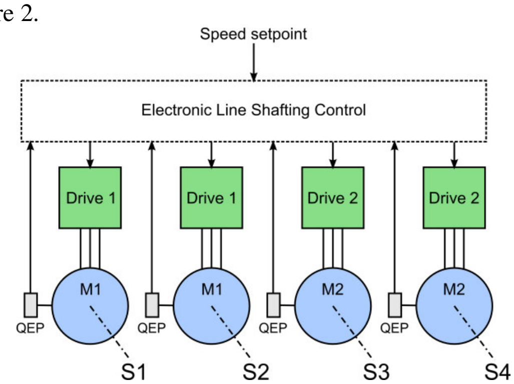

Figure 2: Direct-drive machine.

Two types of PMSMs were selected based on the shaft operating point. A slow running air-cooled motor M1 for S1 and S2 with a high pole pair number, concentrated stator windings and high power density NdFeB permanent magnets at the surface of the rotor (Figure 3). This type of high pole pair design, generally called a 'torque motor', generates maximum torque at relatively low speed and is specifically intended for direct-drive purposes. For the fast shafts S3 and S4, a PMSM with interior rotor NdFeB magnets and a more conventional lower number of pole pairs is selected. Figure 4 shows this 11 kW standard frame synchronous motor M2 with an IE4 'super premium efficiency' class label. All motors are equipped with 1024 pulses per revolution encoders for closed loop vector control and connected to variable frequency drives of 6.6 and 17 kVA. More properties of both motors are given in appendix.

The drives are interfaced with the Triphase Rapid Prototyping Platform[1], a Matlab/Simulink® based real-time control system allowing seamless switching between offline simulation mode and real-time testing of the control algorithm on the actual hardware. Both motors M1 and M2 are mounted on a test bench including a controllable brake, torque transducer, speed measurement and power analyzers for accurate loading and efficiency determination.

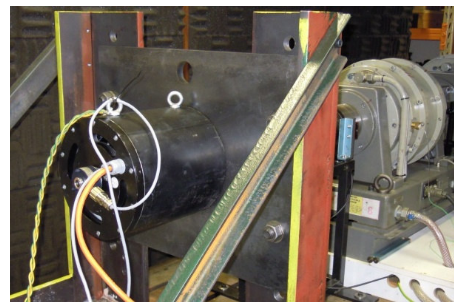

Figure 3: Motor M1

Figure 4: Motor M2

2.2 Multi-motor synchronization algorithms

Multi-motor synchronization techniques are necessary when a process requires true speed and angle synchronization between at least two axes. Several methods [3] have been developed and were successfully implemented in applications like paper machines, weaving looms and offset printers. Master-slave configuration is the simplest control topology. The output speed of the master serves as the speed reference for the slaves. Any disturbances applied to the master are reflected and followed by the slaves, but disturbances in the slaves will not be reflected back to the master or to any other slave. This makes it unsuitable for the machine discussed in this paper. Cross coupling and relative coupling strategies [3] offer good synchronization but are restricted to two motors. Electronic line shafting, often referred to as virtual line shafting, appears to be the best solution for multi-motor speed and angle synchronization control. It was originally proposed for sectional paper machine drives in [4] and [5]. Virtual line

[1] http://www.triphase.be

shafting (VLS) is based on emulating and even further enhancing the inter-shaft state feedback inherent to physical line shaft or gearbox driven mechanical systems. Figure 5 shows the block diagram of the VLS controller for two motors (expandable to more motors) with small adaptations compared to reference [4].

The main parts are a speed controlled virtual line shaft drive and the torque controlled physical motor drives which get their reference from the virtual output shafts. For reasons of simplicity, the line shaft is assumed to be infinitely stiff and only the output shaft stiffness and damping properties are taken into account in the controller. The physical line shaft drive, or in our case the drive at the gearbox input shaft, can be considered as the master setting the position references to the output shafts of the gearbox. In order to track this reference, a proportional-differential (PD) controller is used. For zero steady state position error between the shafts [6], an integral action (I) can be added to this controller. Notice however that this is not in accordance to the physical behavior of a gearbox. The resulting torque references of the drives are scaled with the gear ratio and fed back to the virtual line shaft which in turn will slow down or speed up according to the load torque disturbance at the motor shafts. If a motor is subjected to a torque peak and starts to fall behind on the line shaft position reference, the increased torque reference is immediately reflected back to the virtual line shaft drive which will droop momentarily (Figure 6). This causes all other drives to decelerate too and keep synchronized to the slowest motor in the system.

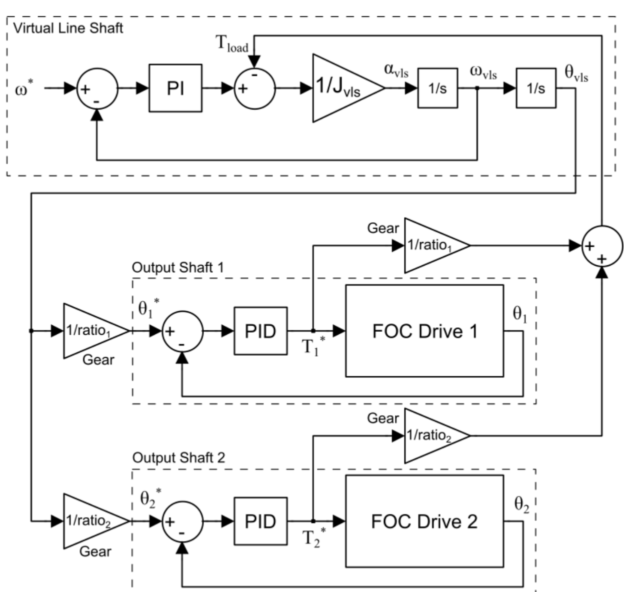

Figure 5: VLS control scheme for a two-motor test setup.

3 Synchronization controller implementation

Reference [7] gives an extensive overview of points of interest for commissioning a VLS drive. This paragraph provides a summary together with the equations that were used to tune the controllers.

3.1 Virtual line shaft inertia

The first and most important controller parameter is the virtual line shaft inertia J_{vls}. As in physical systems, it represents an energy buffer which influences the effects of sectional torque disturbances. A large value of J_{vls} will result in minimal speed droop of the line shaft, but it also means that high incremental torque capacity is required from the motors to remain synchronized with the master reference during a load disturbance. Hence, a good value for J_{vls} is a tradeoff between allowable synchronous droop and maximum torque ratings of the sectional drives [7]. A good starting point however, is to set J_{vls} equal to the largest moment of inertia in the system [6].

3.2 Motor torque controllers

The torque (current) of the motors is controlled by a field oriented control (FOC) loop with a maximum torque per ampere strategy to exploit the reluctance torque present in M2. The current controllers are tuned to obtain an optimum damping for fast torque response. The closed loop transfer function can be approximated by a first order system with an equivalent time constant τ_{equiv}= 1.1 milliseconds.

3.3 Virtual line shaft speed controller

The virtual line shaft speed PI-controller is tuned by choosing a cut-off frequency ω_c and phase margin φ_{rvls} according to the desired dynamic response and damping/stability. The phase margin should be around 65º for optimal damping and the cut-off frequency should be at least 10 to 20 times lower than the torque controller bandwidth $1/\tau_{equiv}$. The PI-controller integral time constant τ_{ivls} and proportional gain K_{vls} are calculated with equations (1) and (2) respectively.

$$\tau_{ivls} = \frac{\tan \varphi_{rvls}}{\omega_c} \tag{1}$$

$$K_{vls} = \frac{J_{vls}\omega_c \tan \varphi_{rvls}}{\sec \varphi_{rvls}} \tag{2}$$

3.4 Output shaft position controllers

The output shaft PID-controllers provide a torque set point to the FOC drives and should be tuned for fast and oscillation-free tracking of the position reference from the virtual line shaft. Similar to a physical gearbox, the proportional action represents the stiffness of the output shaft and the corresponding angular windup. A differential action provides the necessary damping which can be set to values that are considerably higher compared to a physical gearbox. Since angle synchronization with zero steady state position error between the machine shafts is required, an integral part is also added to the controller. Parameter calculation is done by symmetrical optimization starting from the desired phase margin φ_{rM}. With equation (3) the differential time constant τ_{dM} can be calculated. For a critically damped system ($\varphi_{rM} = 65$ º) this results in $\tau_{dM} \approx 20\tau_{equiv}$. The proportional gain K_M resulting from symmetrical optimization is given by equation (4) with J_M the sectional drive and load inertia. Depending on the desired angle error correction response the integral time constant τ_{iM} is free to determine, but should be larger than τ_{dM} to avoid instability.

$$\varphi_{rM} = \tan^{-1}\sqrt{\frac{\tau_{dM}}{\tau_{equiv}}} - \tan^{-1}\sqrt{\frac{\tau_{equiv}}{\tau_{dM}}} \qquad (3)$$

$$K_M = \frac{J_M}{\tau_{dM}\sqrt{\tau_{dM}\tau_{equiv}}} \qquad (4)$$

3.5 Simulation results

Figure 6 shows the response of the system (two fast axes S3 and S4) when S3 (Motor 1) is subjected to a load disturbance of 35 to 70 Nm. The tuning parameters are φ_{rvls}=75°, ω_c=1/(20τ_{equiv}), J_{vls}=1.5J_M, φ_{rM}=55° and τ_{iM}=5τ_{dM}.

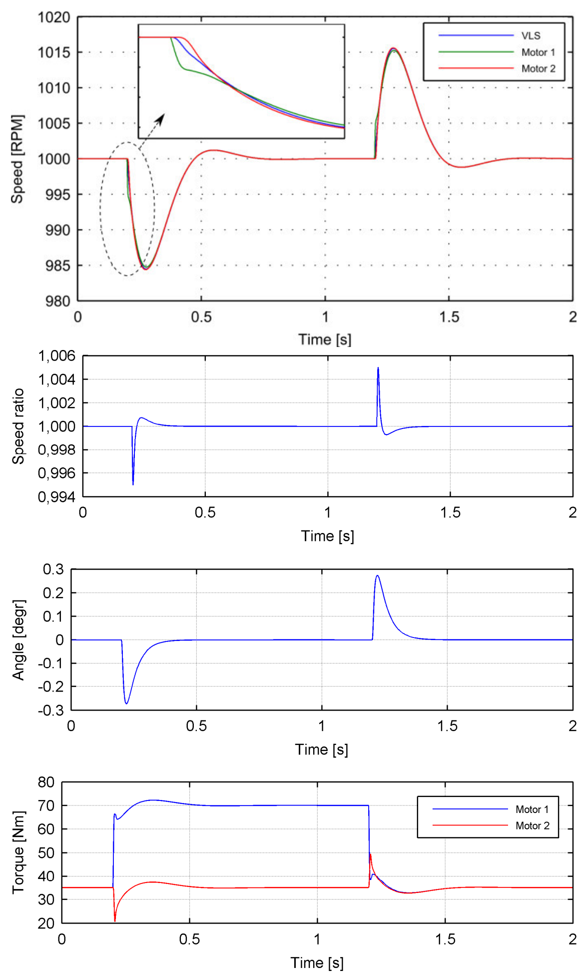

Figure 6: Simulation: System response during a torque step of 35 to70 Nm on motor 1.

The load disturbance causes motor 1 to slow down, but is immediately followed by the VLS and hence also motor 2. A fast tracking of the VLS reference assures a very short transient with a small angle error between both shafts. This error is forced back to zero by the integral part of the controller. Thanks to the droop of the VLS speed, the incremental torque needed to maintain synchronism is small (no torque overshoot).

4 Experimental results

A number of experiments were conducted on the test setup to verify if the synchronization performance is sufficient for the process. In other words, the speed ratio between the fast motor M2 and the slow motor M1 must be maintained at 4.4 and the normalized angle error (θ_{M2}-4.4θ_{M1}) equal to zero. The tuning parameters for the experiments are φ_{rvls}=88.5°, ω_c=1/(12τ_{equiv}), J_{vls}=J_M, φ_{rM}=55° and τ_{iM}=5τ_{dM}.
The controller performed good under heavy load disturbances (Figure 7) with negligible speed ratio and angle deviations. Synchronism is also an important requirement during the start up phase of the process. Figure 8 shows how both motors track the VLS reference in order to stay perfectly synchronized when starting up under heavy load conditions. Also during an emergency stop (Figure 9) the synchronism must be maintained to prevent process failure and a long machine downtime. The VLS controller also passed this test successfully.

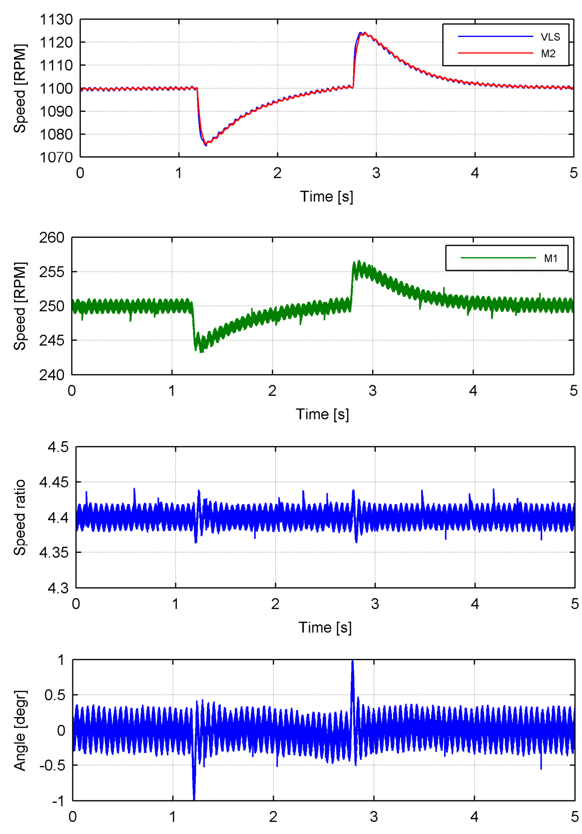

Figure 7: Experiment: System response during a torque step of 40-80 Nm on M2 and constant torque 100 Nm on M1.

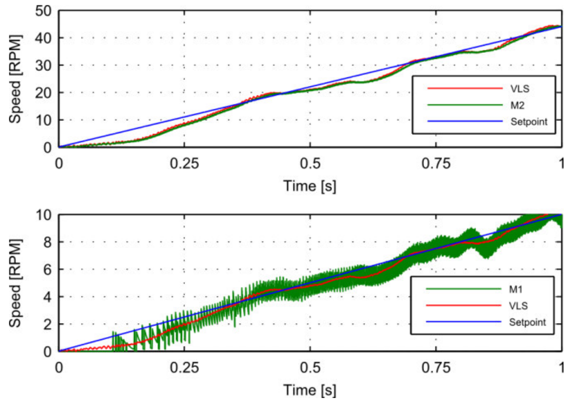

Figure 8: Experiment: System response during start up under loaded condition (M1: 100Nm, M2: 35Nm).

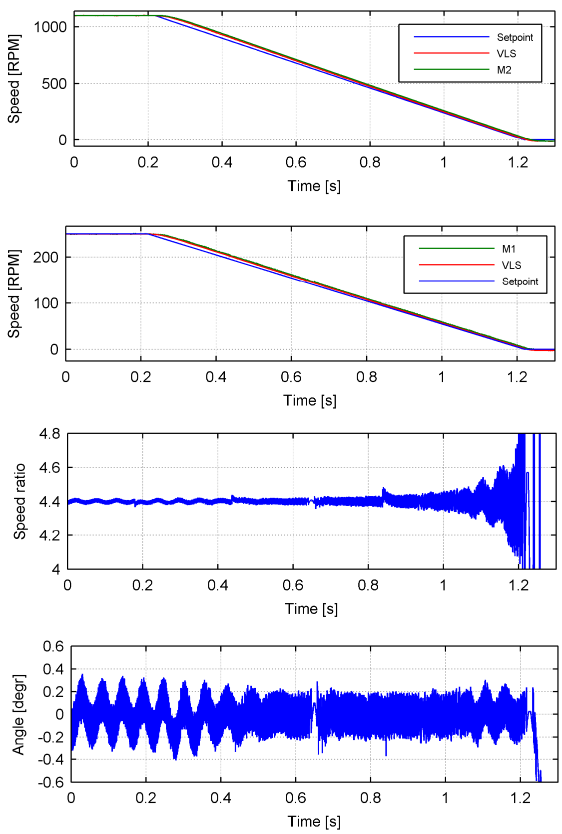

Figure 9: Experiment: System response during a one-second emergency stop.

5 Efficiency analysis

From an economic and ecologic point of view the main advantage of direct-drive over a conventional geared solution is the potential gain in overall efficiency. This advantage however comes at a certain cost. For a successful business case the energy cost savings over time should be in proportion to the additional purchase cost of direct-drive technology in order to result in a feasible payback period. To make such a preliminary assessment of cost versus savings, the efficiency of the conventional machine should be benchmarked together with a good estimation of the efficiency of a future direct-drive alternative. However, making this estimation is a difficult task because the efficiency values provided by motor manufacturers are highly uncertain and often only specified for the nominal operating point which leaves the question of how the motor will perform in the actual process. Therefore, the efficiency of all drivetrain components (motors, drives and gearbox) was measured in this project.

The existing internationally accepted test protocols IEC 60034-2-1 and IEEE 112 for the determination of grid-connected induction motor efficiency are composed in such a way that the results are reproducible and reasonably accurate but are not applicable as such for VSDs, including PMSM. This problem was addresses in a previous publication [8] presenting a test setup and procedure to characterize (by means of an efficiency map) the motor and variable frequency drive efficiency over the entire operating range with reasonable accuracy (+-0.5%). The measured efficiency maps of both direct-drive motors M1 and M2 with an indication of the process operating point are shown in Figure 10 and 11. Similar maps were recorded for the power electronic converters (not shown). The same procedure was repeated for the conventional machine drivetrain, including the gearbox, induction motor M0 and converter.

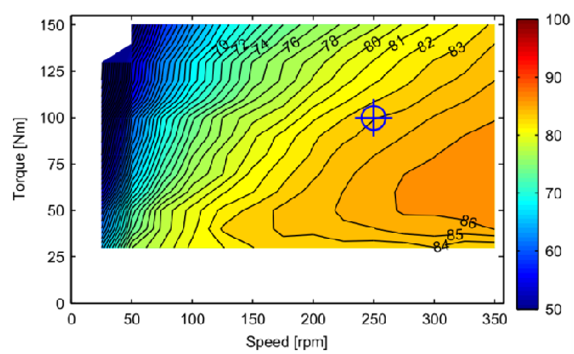

Figure 10: Motor efficiency map of M1.

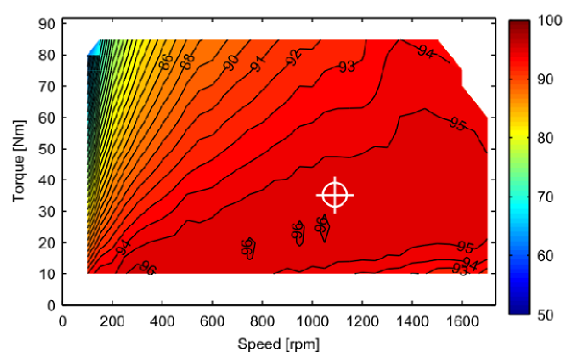

Figure 11: Motor efficiency map of M2.

Projecting the process operating points (Table 1) on these maps, gives the following results. Table 2 and Figure 12 show that the direct-drive machine outperforms the conventional machine by 14% which comes down to a power loss reduction of 2939 W. The savings are mainly due to the avoidance of gearbox losses and the application of highly efficient permanent magnet motors. It should however be noticed that the efficiency of the low speed direct-drive motor M1 is relatively poor, which was partially to be expected due to the high number of poles.

	Conventional	Direct-drive	
Efficiency [%]	M0	M1	M2
Motor	88.3	84.0	95.6
Drive	97.3	95.7	96.3
Gearbox	85.0	/	/
Total	**73.0**	**87.1**	

Table 2: Direct drive versus conventional machine efficiency.

Absolute energy cost savings depend on the usage of the machine and electricity price and should be assessed with the correct figures. In order to get a first idea of the order of magnitude, consider a fictive case of €0.08 per kWh and a usage factor of 90%. Then the yearly energy consumption cost drops from €11486 to €9632, a saving of €1854.

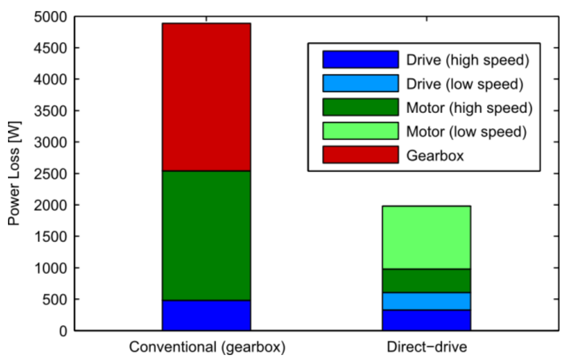

Figure 12: Loss breakdown conventional versus. direct-drive.

6 Conclusion

A technical feasibility study on direct-drive technology for the replacement of mechanical transmission components in a multi-axis wire processing machine was presented. The focus of this paper was on the efficiency and synchronization performance of a direct-drive machine compared to a conventional machine with a gearbox. A synchronization algorithm based on the electronic line shafting method was implemented in Simulink® and the equations for adequate tuning of the controller parameters were discussed briefly. Simulation and experimental results on a test setup demonstrated nearly perfect angle and speed synchronization performance during load disturbances, startup and emergency stop situations. The efficiency of the machine was assessed by means of measured efficiency maps of all the drivetrain components. Due to the avoidance of mechanical losses and the application of highly efficient PMSM drives, the direct-drive machine has an efficiency advantage of 14% over the conventional gearbox machine.

The main conclusion is that, from a technical point of view, direct-drive was proven to be successful for this type of machine. However, in order to make a full business case, other feasibility factors such as cost, maintenance and reliability should be addressed too. Furthermore, a sensorless control of the motor drives in the final design is highly desirable because of cost and reliability advantages.

Appendix

	M1	M2	
Rated Power	3.8	11	[kW]
Rated Torque	103	70	[Nm]
Rated Speed	360	1500	[RPM]
Rated Line Voltage	400	400	[V]
Rated Line Current	6.19	20.2	[A]
Rated Efficiency	/	93.6	[%]
Pole pairs	22	3	[/]
Phase Inductance Ld	11.4	10	[mH]
Phase Inductance Lq	11.4	19	[mH]
Phase Voltage Constant	591.9	245	[V/kRPM]
Phase Resistance	2	0.336	[Ohm]
Rotor Inertia	0.045	0.0543	[kgm2]

Table 3: Properties of M1 and M2.

References

[1] T. Haring, K. Forman, T. Huhtanen, and M. Zawadzki, "Direct drive - opening a new era in many applications," in *Conference Record of the 2003 Annual Pulp and Paper Industry Technical Conference.*, 2003, pp. 171–179.

[2] S. Evon and R. Schiferl, "Direct-drive induction motors: using an induction motor as an alternative to a motor with reducer," *Industry Applications Magazine, IEEE*, vol. 11, no. 4, pp. 45-51, 2005.

[3] F. J. Perez-Pinal, C. Nunez, R. Alvarez, and I. Cervantes, "Comparison of Multi-motor Synchronization Techniques," in *30th Annual Conference of IEEE Industrial Electronics Society, IECON 2004*, 2004, vol. 2, pp. 1670-1675.

[4] M. A. Valenzuela and R. D. Lorenz, "Electronic Line-Shafting Control for Paper Machine Drives," *IEEE Transactions on Industry Applications*, vol. 37, no. 1, pp. 158-164, 2001.

[5] R. G. Anderson, A. J. Meyer, M. A. Valenzuela, and R. D. Lorenz, "Web Machine Coordinated Motion Control via Electronic Line-Shafting," *IEEE Transactions on Industry Applications*, vol. 37, no. 1, pp. 247-254, 2001.

[6] F. J. Perez-Pinal, "Improvement of the Electronic Line-Shafting," in *Power Electronics Specialists Conference, PESC 04, IEEE 35th Annual*, 2004, pp. 3260-3265.

[7] M. A. Valenzuela and R. D. Lorenz, "Startup and Commissioning Procedures for Electronically Line-Shafted Paper Machine Drives," *IEEE Transactions on Industry Applications*, vol. 38, no. 4, pp. 966-973, Jul. 2002.

[8] W. Deprez et al., "Iso Efficiency Contours as a Concept to Characterize Variable Speed Drive Efficiency," in *Electrical Machines (ICEM), 2010 XIX International Conference on*, 2010, pp. 1–6.