General Comparison of Direct and Geared Drives for Control Applications

G. Dubrovskiy[1], A. Mikerov[2], V. Dzhankhotov[3] and J. Pyrhönen[4]
[1,2]SAINT PETERSBURG ELECTROTECHNICAL UNIVERSITY
[1,2]197376 Saint Petersburg, Russia
[3]GREENENERGY FINLAND
[3]53850 Lappeenranta, Finland
[4]LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
[4]53851 Lappeenranta, Finland
Tel.: [1]+7-965-019-2747
E-Mail: [1]GVDubrovskiy@ieee.org, [3]Valentin.Dzhankhotov@gef.fi

Acknowledgements

The authors are very grateful to Jussi Puranen for the article reviewing and useful comments about high-power drives.

Keywords

«Servo-drive», «Windgenerator systems», «Electrical drive».

Abstract

This paper considers basic criteria which should be taken into account when an electric drive designer selects between geared (GD) and direct drives (DD).

Introduction

In 1840 Robert Davidson has presented an electrical motor, which was installed directly to the locomotive wheels. This was the first electrical direct drive [1]. Later it was found that high-speed (1000-12000 rpm) machines are more suitable thanks to the lower weight and energy consumption. In the applications working at speeds below 1 revolution per sec (60 rpm), a gear between motor and load was introduced. Practically, the majority of the drives, manufactured in 20th century, were geared. The direct drives came back in the end of XX century, when new electrotechnical materials and electrical motors, called torque motors, were proposed [2, 3]. Now DDs are intensively used in different power and mechanical equipment, robots, airplane and ship control systems. For example, Fig. 1 demonstrates an airborne radar antenna with a permanent magnet torque motor.

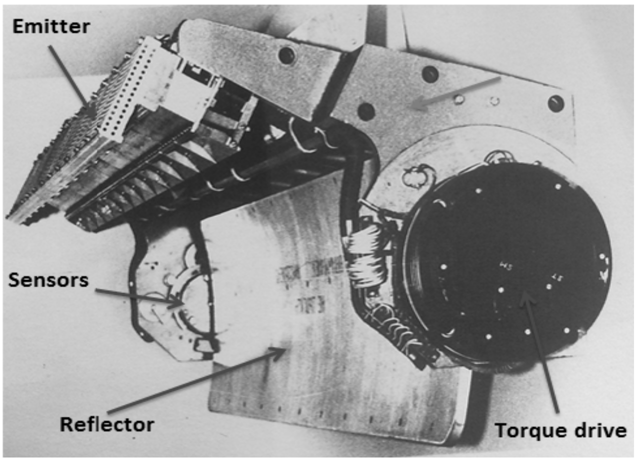

Fig. 1: Airborne antenna

A large area of the intensive progress of the DD is the wind power, due to the market trend of the turbine power increasing above 1.5 MW. A further development of the superconducting materials will expectedly bring even better DD solutions in the future.

Direct and geared drives are both designed to solve the same problem of a mechanical plant control however they have different characteristics and this paper analyses main differences between them.

Two approaches: direct and geared drives

For an electrical motor having a linear speed Ω_M versus torque T_M characteristic we can write

$$\frac{\Omega_M}{\Omega_{M.NL}} = 1 - \frac{T_M}{T_{M.St}}, \tag{1}$$

where $\Omega_{M.NL}$ is no-load speed, $T_{M.St}$ is starting torque.
For a DC motor,

$$\Omega_{M.NL} = U_a/K_E \text{ and } \; T_{M.St} = K_T \cdot I_a, \tag{2}$$

where K_E is the EMF coefficient, K_T is the torque coefficient, $K_E = K_T = K$, U_a and I_a are the armature voltage and current.
For a geared drive with the gear ratio i we can write:

$$\frac{\Omega_L \cdot (i \cdot K)}{U_a} = 1 - \frac{T_L}{I_{a.St} \cdot (i \cdot K)}, \tag{3}$$

where $T_L = i \cdot T_M$ is load torque, $\Omega_L = i \cdot \Omega_M$ is load speed, $I_{a.St}$ is starting current. Similar equation may be written for any BLDC or vector-controlled PMSM. For example, in a PMSM U_a and I_a are equivalent to the phase voltage and current.

Equation (3) indicates that there are two alternatives to provide needed load and torque (Ω_L, T_L) at given voltage and current (U_a, I_a): either by a gear with a ratio i or by a special construction of electrical machine, expressed by K.

It should be emphasized that GD and DD have different features, which is not evident from eq. (3). These features can be divided by two main groups: operation features and application features.

Comparison of operation features

Next operation features are important for comparison of the DD and GD:

- Their transfer functions;
- Control system errors;
- Speed ripples;
- Drive efficiency.

Transfer functions. DD and GD usually have different transfer functions, DD's time constants are usually much higher. DD's electromechanical time constant is large due to the load mounted directly on the motor shaft (the load inertia, applied to the motor's shaft, is inversely proportional to the squared gear ratio). Due to the larger copper volume DD's electromagnetic time constant is usually higher as well. As follows from (3), DD requires higher value of the coefficient K, which can be defined as

$$K = p \cdot w \cdot \Phi, \tag{4}$$

where p is the number of pole pairs, w is the number of turns in the phase of the PMSM, Φ is the rotor magnetic flux. Typically, increasing of p, w, Φ results in enlargement of the motor dimensions and copper volume. As shown in [4], a torque motor electromagnetic time constant is proportional to the winding copper volume.

Control system errors include dynamic errors (due to a reference input speed and acceleration), torque errors (due to a load torque) and errors induced by a mechanical gear. Typically, in a direct servodrive, torque errors prevail over dynamic errors and in a geared servo drive vice versa. Mechanical gear contributes in a number of negative phenomena, such as backlashes, kinematic errors, mechanical resonances, unstable friction, which worsen a control system stability and accuracy. It is practically impossible to achieve a geared servodrive error less than one angle minute, whereas for a direct servodrive such an error can be as low as a fraction of the angle second. That is why the DD is practically unbeatable choice for the high-precision low-speed control systems. However, its controller design method is different compared to a GD one.

Speed ripple. A relative magnitude of a drive speed ripple may be defined as [5, 6]

$$\delta\Omega = \frac{\Delta T_M}{h \cdot (J_{rot} \cdot i^2 + J_{load}) \cdot \Omega_{load}^2}, \tag{5}$$

where ΔT_M is an absolute value of the motor torque ripple, h is the lowest harmonic number of the torque ripple over the angle, J_{load} is the load (and gearbox) inertia, J_{rot} is the motor rotor inertia, T_{load} - the load torque.

Passing to the motor values

$$\Delta T = T_{M,St} \cdot \delta T;\ \tau_M = \tau_{M.0}\left(1 + \frac{J_{load}}{J_{rot} \cdot i^2}\right);\ \tau_{M.0} = \frac{J_{rot} \cdot \Omega_{M.NL}}{T_{M.St}},\ \text{and}\ \ \Omega_{NL} \approx\ \Omega_{load} \cdot i, \tag{6}$$

where τ_M and $\tau_{M.0}$ are, respectively, electromechanical time constant of the motor with and without a load.

Taking (6) into account, we can write (5) as follows

$$\delta\Omega = \frac{\delta T}{h \cdot \tau_M \cdot \Omega_{load} \cdot i}. \tag{7}$$

Hence, speed ripple depends on the load to motor inertia ratio. If $J_{load} \ll J_{rot} \cdot i^2$

$$\delta\Omega = \frac{\delta T}{h \cdot \tau_{M.0} \cdot \Omega_{load} \cdot i} \tag{8}$$

and GD's speed ripple is lower than speed ripple of the DD, because $i \geq 1$. Here we assume that for both drives time constants $\tau_{M.0}$ are similar.

Vice versa, if $J_{load} \gg J_{rot} \cdot i^2$

$$\delta\Omega = \frac{\delta T}{h \cdot \tau_{M.0} \cdot \Omega_{load}} \cdot \frac{J_{rot}}{J_{load}} \cdot\ i, \tag{9}$$

the GD's speed ripple is higher for $i \geq 1$ and, hence, the DD is preferable.

Drive efficiency. For an ideal motor with the linear speed versus torque characteristic and without additional losses, motor efficiency is zero for the starting point and tends to 100% for the no-load speed. Typically, for a servodrive rated torque is near 0.25 of starting torque and hence here the efficiency is about 75%. Main additional losses are steel losses due to high armature current frequency, which is proportional to the pole pairs. In a DD this frequency normally remains low even for high number of poles. For example, for 10 rpm and p = 60 the current frequency is just 10 Hz, which does not contribute to the iron losses significantly. In a GD with a high-speed motor this frequency is much higher. Besides, we should consider aerodynamic loses and friction in bearings and mechanical gear. For example, for a worm gear the efficiency may be less than 50% [7]. Therefore, we can see that DD efficiency is higher. The drawback of the DD drives is that, in order to obtain the highest efficiency, we should design a new torque motor for every new load specified. In case of GD, several standard motors can be selected, matching their characteristics with the load by an appropriate gearbox.

Comparison of application features

These features are important for customers:

- Weight and size;
- Service life and reliability;
- Vibrations and audible noise;
- Cost;
- Motor selection procedure.

Weight and size. As it follows from (4), in order to increase the motor coefficient *K* number of poles, winding turns and magnet might should be enlarged, which causes extra dimensions (especially outer diameter of the machine), weight and cost. As an example, Table 1 presents two torque motors, designed for operation at similar output mechanical powers, but different speeds [8]. We can see that the weight of the high-speed GD motor is about 1/50th of the weight of the low-speed DD motor. Of course, this difference is eliminated by a gear; however, GD may obviously provide compact and low-weight solutions, which is especially relevant for the remotely installed high-power applications. This simplifies and cheapens the logistics, installation and maintenance procedures.

Table I

Drive type	Motor type	Operation under maximum output power			Outer diameter, mm	Weight, kg
		Power, W	Speed, RPM	Torque, Nm		
DD	DBMV185-16-0,04	13.3	15	8.6	185	5.5
GD	DBMV50-0,025-3	13.4	1700	0.075	50	0.12

In addition, an increased amount of the rare-earth magnets in high torque motors makes rotor insertion into the stator technologically difficult and expensive.

All these observations are valid also, e.g. in wind turbines with GD and DD. An example is FusionDrive produced by The Switch, which has also efficiency advantage when compared to the DD [9]. It is indicated in [10] that the weight of the wind turbine equipped with DD is approximately 25% higher than the weight of the GD.

Service life and reliability. Since DD is structurally same as GD, except it does not contain a gearbox, reliability of DD is significantly higher. A typical service life of a gearbox is 30,000 hours at its best [11], or less than 3.5 years of the continuous operation. Service life of the application is typically 20-30 years, which indicates the need in rather frequent gearbox replacement. In addition, downtime due to the gearbox failures is one of the highest between the components of the whole drive. It has been reported in [12] that, for a typical wind turbine, 1/5th of the overall downtime is related to the gearbox failures. This fact diminishes the cost advantage of the GD, at least in terms of mean time to repair [13].

Vibrations and audible noise. Each drive's mechanical component tends to vibrate. Thus, roughly speaking, GD is noisier than DD. However, in practice audible noise level depends on a number of different factors, which is extremely difficult to take into account. This is especially relevant for the modern systems fed by the frequency converters, where pulse-width modulation (PWM) principle is utilized. PWM pattern contains a set of high-order components [14-16], which may amplify resonance in the mechanical parts. Furthermore, a complex of constructive features (such as eccentricities and machine parts manufacturing quality, a number of slots, a number of pole pairs, gear and bearing type, etc.) make audible noise individual for every application. It may be roughly assumed that GD is noisier due to the higher motor rotational speed. As an additional part, gearbox in GD contributes to the audible noise and vibrations.

Cost. Costs include initial investments and long-term maintenance expenses. Due to the larger dimensions of DD's motors and its relatively expensive material DD's initial price is typically higher than the price of the GD. It must be, however, noted that precise and reliable gearboxes are very expensive as well. Bearing of DD can be much more expensive than one of GD, however, DD can sometimes use the bearing of the load, whereas GDs typically contain a number of bearings, including bearings of the gearbox. Besides DD systems require fewer transducers because one precise common transducer is able to substitute two or three angle and speed GD transducers.

Finally, gearbox reliability is low, it requires frequent maintenances, (e.g. lubrication), which increases the overall price of the GD. Interrupts in a drive operation may also mean essential lay-up expenses. Generally speaking, final cost highly depends on the application specific and comprehensive answer cannot be given in such a preliminary guideline. Reportedly [10], in wind turbines DD produces initial cost increase to 30%; GD is more profitable up to 1.5-3 MW range, whereas DD is implemented at larger powers.

Motor selection procedure. Different techniques are used when selecting a motor for a DD and a GD. For a GD motor is selected in accordance with the required maximum output power, whereas for a DD motor is selected in accordance with the maximum required torque [17].

The required maximum output power for the GD motor can be found as [17-19]:

$$P_{required} = (1.2 \ldots 1.5) T_{required} \Omega_L; \quad T_{required} = \frac{T_L}{\eta} + J_{load} \varepsilon_{load}\,; \tag{10}$$

$$k_{sm} = \frac{T_{M.St}}{T_{required}}; \quad P_{max} = \frac{k_{sm}^2}{4(k_{sm}-1)} P_{required}, \tag{11}$$

where k_{sm} is smoothness factor, η is gear efficiency, ε_{load} is load angular acceleration, $T_{required}$ is required torque.

The starting torque for the DD motor can be calculated as follows [17-19]:

$$T_{M.St} \geq k_{sm} T_{required}; \quad T_{required} = T_L + (J_{load} + J_{rot}) \varepsilon_{load}, \tag{12}$$

where T_L is load torque.

Conclusion

Selection of the type of the drive, geared or direct, is a compromise between many factors, such as application nature, performance, overall expenses during the whole service life, etc. Overall expenses of the GD and DD can be assumed equal. Geared drive has an advantage in the lower ripple at low-inertia loads, efficiency, compactness and lower weight. Direct drive is more precise and stable, has no backlash and more rigid, produce lower amount of audible noise, has longer service life and more reliable.

References

[1] D. Mackie, "Prospects of electromagnetism as a prime mover," *The practical mechanic and engineer's magazine*, vol. 2, pp. 48-52, 1843.

[2] H. U. Wurgler, "The World's First Gearless Mill Drive," *IEEE Trans. Ind. and General Appl.*, vol. IGA-6, no. 5, pp. 524-527, Sept./Oct. 1970.

[3] ABB company website. *Gearless Mill Drives* [Online]. Available: http://www.abb.com/industries/db0003db002806/0b4087643b17ef1dc1257475004eb57b.aspx. [Accessed: May 9, 2014].

[4] A. Mikerov, "Brushless DC Torque Motors Quality Level Indexes for Servo-drive Applications," *Proceedings of the IEEE Conference EUROCON 2009*, St. Petersburg, Russia, May 18-23, pp. 827-834, 2009.

[5] A. Mikerov and Y. Belenkiy, *Brushless Torque Drive for Multifunctional Control Systems*, Energoatomizdat, Moscow, 1991(in Russian).

[6] G. Dubrovskiy, "Control Systems Direct Drive," B.Sc. thesis, Control Systems Dept., SPbETU "LETI", St. Petersburg, Russia, 2013 (in Russian).

[7] B. Stoeber and J. Schumacher. (2000, Jul. 1). *Gear efficiency — key to lower drive cost* [Online]. Avalable: http://machinedesign.com/mechanical-drives/gear-efficiency-key-lower-drive-cost. [Accessed: May 9, 2014].

[8] LEPSE company website. *Main DGMV line torque motors characteristics* [Online]. Available: http://www.lepse.com/products/novye_izdeliya.php. [Accessed: May 9, 2014]. (in Russian).

[9] The Switch company website. *FusionDrive® – Smartest gear and generator combination* [Online]. Available: http://www.theswitch.com/wind-power-2/fusiondrive/. [Accessed: May 9, 2014].

[10] "Fundamental and Advanced Topics in Wind Power," *InTech*, Editor R. Carriveau, p. 191, July 2011.

[11] Neugart company website. (2005, May 3). *Neugart extends the service life of their planetary gearboxes* [Online]. Available: http://www.neugart.de/index.php/gb/Latest/News/Arsiv/2005/node_457. [Accessed: May 9, 2014].

[12] J. Ribrant and L. M.Bertling, "Survey of Failures in Wind Power Systems With Focus on Swedish Wind Power Plants During 1997-2005," *IEEE Trans. on Energy Conversion*, vol. 22, no. 1, pp. 167–173, Mar. 2007.

[13] P. J. Tavnet, G. J. W. Van Busseland and F.Spinato, "Machine and Converter Reliabilities in Wind Turbines," *The 3rd IET International Conference on Power Electronics*, *Machines and Drives*, Dublin, Ireland, April 4-6, pp.127-130, 2006.

[14] V. Dzhankhotov, J. Pyrhönen, P. Silventoinen, M. Kuisma, T. Minav, "A New Passive Hybrid Air-Core Foil Filter for Modern Power Drives," *IEEE Trans. Ind. Electron*. vol. 58. no. 5. pp. 1757–1762, May 2011.

[15] V. Dzhankhotov, J. Pyrhönen, P. Silventoinen, M. Kuisma, "Hybrid *LC* Filter Electrical Design Considerations," *IEEE Trans. Ind. Electron.*, vol. 59, no. 2, pp. 762-768, Feb 2012.

[16] V. Dzhankhotov and J. Pyrhönen, "Passive *LC* filter design considerations for motor applications," *IEEE Trans*. *Ind*. *Electron*. vol. 60, no. 10, pp. 4253-4259, Oct. 2013.

[17] A. Mikerov, "Torque motor selection for a Direct or Geared Drive," *Control Engineering Russia*, vol. 40, pp. 14-19, 2012 (in Russian).

[18] A. Mikerov and Y. Belenkiy, *Selection and Parameter Programming of Brushless Torque Drive*, LDNTP, St. Petersburg, Russia, 1990, pp. 16-17 (in Russian).

[19] G. Dubrovskiy, "Main Direct Drive versus Geared Drive Features," Proceedings of the 2014 IEEE NW Russia Young Researchers in Electrical and Electronic Engineering Conference (ElConRusNW'2014), St. Petersburg, Russia, Feb. 3-4, pp. 105-110, 2014.