Variable Flow Vane Pump

The Hydraulic Solution for the Evolution of Electric Drives

Parker

ENGINEERING YOUR SUCCESS.

Variable Flow Vane Pump

The Hydraulic Solution for the Evolution of Electric Drives

Dr.-Ing. Gerd Scheffel *is industrial applications engineering manager for Parker in Kaarst, Germany. He holds a doctor's degree in hydraulics at Aachen University. He started his career as hydraulics engineering manager at Towler Hydraulics which was acquired by Parker in 1984. He served as general manager from 1989 to 2012 of the Hydraulic Controls Division and managing director of Parker Germany from 1991 to 2014.*

Dr.-Ing. Roland Bublitz *is industrial applications engineering manager for Parker in Kaarst, Germany. He holds a diploma and a PhD in mechanical engineering both from the RWTH Aachen University in Germany. He began his career at Parker in 2003 and worked previously as research assistant at the Institute for Fluid Power Drives and Controls at RWTH Aachen University.*

The variable-speed hydraulic pump, with its potential for energy savings, power density and temporary noise reduction, is currently the dominant pressure supply system in the media. It provides a clear example of how hydraulics can successfully participate in the evolution of electric drives.

Promotions for the variable-speed pump like to suggest that standalone individual drives are the future for hydraulics. Electrohydraulic actuators have their uses, of course, but it is important to remember that electric motors, and their converters, are what make electromechanical drives so costly. Each drive needs a fixed motor, which makes the drive large and expensive. If this principle is applied to hydraulics, it restricts the choice of appropriate pumps to those variants that are suitable for four-quadrant operation. This limits options and increases costs as well.

The multiple use of the electric motor in the central supply, together with the large range of suitable two-quadrant pumps (pumps in which the P- and T-attachments on the pump remain in place unchanged, regardless of the direction of flow; that is, the high pressure is always on P, and T is always connected to the tank), provide good economic arguments in favor of hydraulics as opposed to electromechanical systems. Because the central supply is connected to the drive with pipes and hoses – this is why hydraulic drives are often so compact – the power can be fed around any corner.

When marrying hydraulic pumps with electric motors, one has to take into account the behavior of each system, as determined by its construction type, with respect to its hydraulic, electrical and mechanical characteristics.

A variable hydraulic flow can be created with an adjustable-flow pump, a fixed-displacement pump on a variable-speed electric motor, or a combination of both: a variable-flow pump on a variable-speed electric motor (Figure 1).

Studies so far suggest that the last of these is the most energy-efficient combination, but also the most expensive. With smaller flow rates in particular, this expense cannot be justified, and it is preferable to adopt more economical solutions involving fixed-displacement pumps. The long-established option of a variable-flow pump on a constant-speed asynchronous motor is almost unanimously considered to be the benchmark solution.

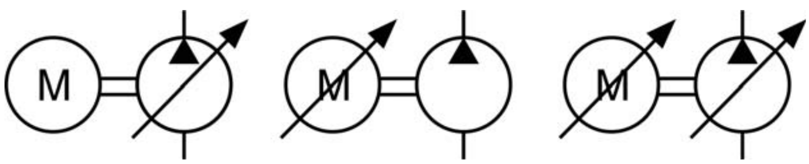


Figure 1: Options for varying flow rate

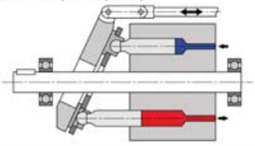
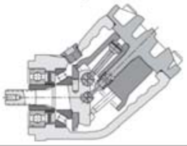
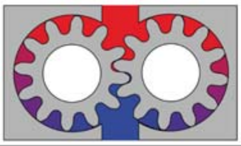
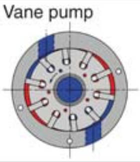
	Asynchronous motor	Asynchronous motor with drive	Synchronous motor with drive
			
Swash plate pump 	Output flow and pressure control, inexpensive, idling losses	Maximum energy efficiency, output flow and pressure control	Maximum energy efficiency, expensive, dynamics of the e-motor is only partially usable
Bent axis pump 	Maximum energy loss	Output flow and pressure control with low dynamics	Output flow and pressure control, elaborate mechanics
Internal gear pump 	Maximum energy loss	Output flow and pressure control with low dynamics	Output flow and pressure control, simple mechanics
External gear pump 	Maximum energy loss	Output flow and pressure control with low dynamics	Output flow and pressure control, moderate efficiency
Vane pump 	Maximum energy loss	Output flow and pressure control with low dynamics	Output flow and pressure control, simple mechanics, integrated + compact

Figure 2: Combinations of electric motors and hydraulic pumps

Characteristics of electric machines

Among electric motors, the asynchronous motor was essentially designed to permit an automatic start without electronics on a three-phase supply. As a result of the motor's construction, it couples relatively loosely with the rotating field (slow speed-change), and rotates at a speed determined by the number of poles in the stator and the mains frequency; e.g., at 3,000 rpm with a 50 Hz 2-pole supply, at 1,500 rpm with a 4-pole supply, and at 1,000 rpm with a 6-pole supply. If a frequency converter is installed, the rotation speed of the asynchronous motor can be adjusted from zero to almost double the rated speed attainable on the grid without a converter. Above the rated speed, however, in the so-called field-weakening range, motor torque decreases quadratic with the rotation speed. Whether the lower rotation speed can be used depends on the type of engine cooling. In self-cooled engines, cooling capacity decreases with rotation speed (the fan turns at the speed of the motor). To achieve a very low rotation speed over a longer period of time, therefore, external cooling (a self-propelled fan) is necessary. For cost reasons, asynchronous motors generally come without sensors; that is, they operate without speed feedback. If the motor is to be operated at rotation speeds under 50 rpm, however, the use of speed feedback is recommended. There are also asynchronous motors that are designed differently from IEC or 'standard' motors in order to achieve better dynamics with a smaller rotor diameter (the 'main spindle drive' design). These motors have a rectangular flange and are longer at the same power rating. Many of these motors are fitted with encoder feedback, and are therefore also known as asynchronous servo motors.

The synchronous motor cannot run by itself on a three-phase supply, and needs a frequency converter to do so. The rotor is fitted with permanent magnets, and is therefore coupled very firmly with the rotating field of the stator. The speed range is often greater than with standard asynchronous motors, and the dynamics are considerably better. Because no induction is needed in the rotor, power dissipation is lower, thus reducing heating of the motor.

Electric motors can achieve considerably higher rotation speeds than most hydraulic pumps. When choosing a motor, therefore, it is important to consider the usability of the rotation speed. The rotation speed of hydraulic pumps is restricted by noise characteristics, centrifugal forces and suction capacity. These restrictions are particularly clear with electric drives on a 60 Hz grid and with diesel drives. Small pumps reach their limits at around 3,000 rpm, and large pumps at around 2,000 rpm, if they are self-primed.

Pumps with adjustable rotation speed

An adjustable pump can vary the flow rate very quickly; e.g., by adjusting the pivoting angle at a fixed rotation speed. With a fixed-displacement pump on a variable-speed electric motor, the rotation speed of the electric motor unit as a whole must be adjusted with a hydraulic pump coupled with the motor. The torque, which will change very quickly as a result of this adjustment, must be transmitted through all hydraulic components of the pump that lie in the power flux (Figure 2).

Pumps with an adjustable rotation speed must satisfy requirements and operating conditions that do not arise under operating conditions with a fixed drive speed. An axial piston pump of the swashplate type is ill-equipped for a rapid change in speed: the torque is transferred in the motor via the oscillating pistons through short contact lines to the piston barrel. This restricts the rotation adjustment speed, and hence the dynamics. Thus, the high dynamics of a synchronous motor cannot be used, because the mechanical components of the hydraulic pump cannot transfer them. For this reason, pivot-adjustable piston pumps, both with fixed and with variable rotation, mostly run on a cheaper asynchronous motor, and the dynamics are created by adjusting the pump.

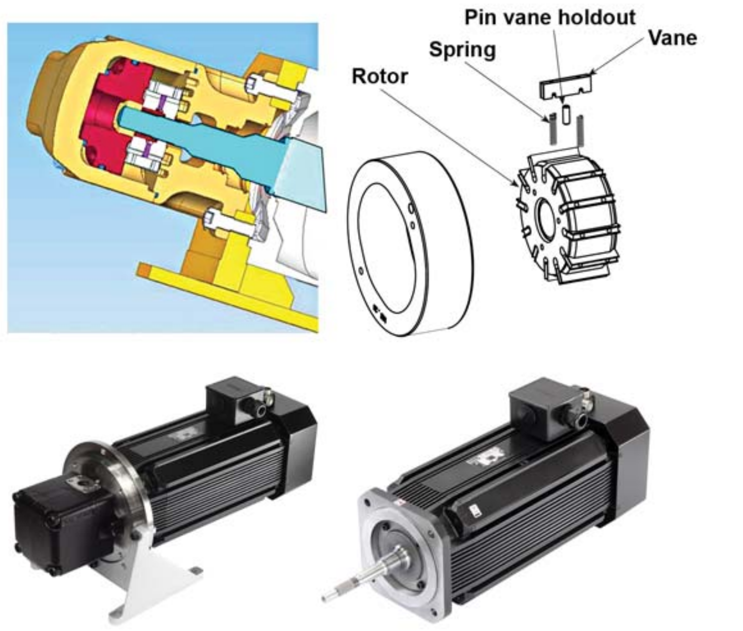


Figure 3: Integrated vane pump on a synchronous motor

The alternative to the swashplate piston motor is the fixed-displacement bent-axis piston motor. The shaft torque in some designs is transferred to the piston barrel through mechanical coupling; e.g., through two gears in mesh. The pistons move without being subject to shear forces, and this design is therefore very suitable for rapid speed change. This machine shows particular mechanical robustness when the motor is in operation, as it operates with rotation speeds of up to 14,000 rpm.

The internal gear pump, which currently dominates the field in variable-speed pumps, has two interlocking gears in mesh. This is useful for transferring a rapid speed change, such as the kind that occurs in pressure control, between the rotating/moving parts in a mechanically sound way.

Just like the internal gear pump, the external gear pump is very well-suited to rapid speed changes on a synchronous motor. Because of its larger pressurized surfaces, however, it is less favorable in the resulting bearing forces it creates, which reduce the maximum pressure and create a higher level of friction, particularly at low rotation speeds. There are numerous pumps on the market that have helical gears for noise-related reasons.

Advantages of vane pumps

Another pump that is very suitable for internally transferring the varying levels of torque is the vane pump. In this pump, large-surface vanes occupy slots in the rotor. The torque is transferred not through linear contact, but through full-area contact of the vane with the rotor, which makes this design particularly robust. The hydraulically balanced vanes, which are pressed onto the external curved path by centrifugal force, are also spring-loaded, which ensures contact with the external curved path even at lowest rotation speeds. Two opposing pump chambers balance the hydraulic load fully, so bearings are not needed to carry the load, but only to guide the shaft. As a result, the pump rotor can also be operated directly from the extended shaft end of an electric motor. This means that the shaft bearing, the bell housing and the coupling are not required, which results in a firmer coupling of the pump with the electric motor. This not only shortens the overall length of the unit as a whole, but also reduces its inertia and prevents torsional vibrations as a result of the elasticity of the coupling, which permits a high level of dynamics. The vane pump is suitable for various fluids, as it has no roller- or ball-bearings in the liquid. Because of the bearing-free installation of the pump cartridge, in cases of repair it can easily be replaced with a built-in pump by loosening the four screws on the cover (Figure 3).

The use of variable-speed pumps enables control of flow rate and pressure directly through the pump rotation speed. Pressure control, in particular, imposes different requirements on the pumps. Thus, depending on the application, it may be necessary to set the working pressure between low and no initial flow volume for a period of time. In this state, the pumps heat up because of internal leakage. The smaller the internal leakage of the pump, the longer the dwell time of the pump before a critical temperature is reached in the pump. Once this temperature is reached, the lubrication properties of the hydraulic medium are no longer sufficient to separate the moving parts of the pump, and this results in a mechanical failure. The two most important requirements for variable-speed pumps are the ability to transfer high torques, and low internal leakage.

Internal leakage includes not just leakage in the displacement space, but also all other oil flows inside the pump, because such flows also cause losses and, in the case of pressure control, heating of the pump.

Adjustable swashplate piston pumps must feed the hydrostatic bearings of the piston shoe and supply the control unit for adjusting the swashplate with pilot oil. These additional oil flows lead to a reduction in the efficiency of the machine, which operates with such low losses in the displacement space.

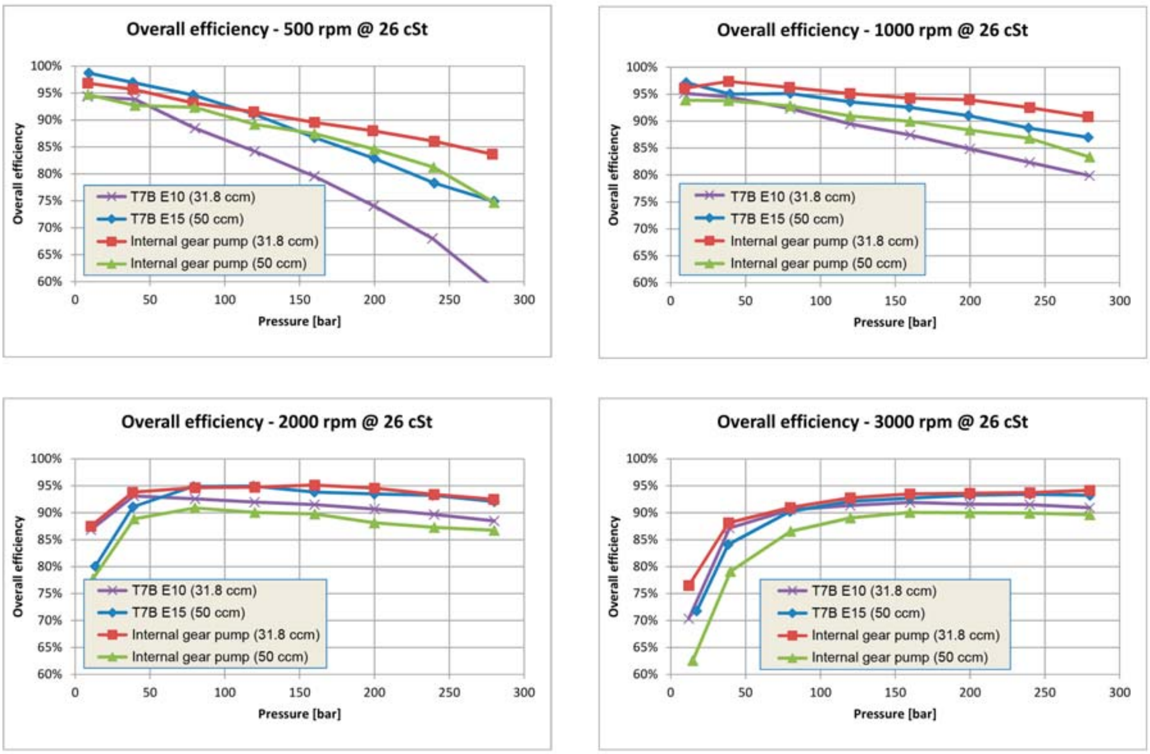


Figure 4: Overall efficiency of the T7B vane pump and internal gear pump of 32 ccm and 50 ccm

The fixed-displacement bent-axis machine has the advantage over the swashplate machine, in variable-speed operation, that the pistons are supported on the bearing by spherical balls. This reduces the supply to the hydrostatic bearings, and because it operates constantly, it has no control unit that needs to be supplied. This machine has very high efficiency. On the other hand, its construction costs are high.

Internal leakage mainly depends on the length and height of the sealing gaps of the displacement spaces. In this sense, piston machines have a clear advantage, because a round piston in a round hole can be manufactured with very narrow tolerances. Pistons with a larger diameter and a longer piston stroke create larger displacement volumes. There is a proportional relation between leakage and displacement.

Toothed flanks or vanes vary in their suitability for sealing the cross-sectional displacement space, and the side flanks of the gears or vane rotors are also difficult to seal without creating large frictional forces. There is more leakage at these points than with piston machines. Gear pumps, both with external and internal gear teeth, are manufactured with different gear sizes, and the displacement volumes within a construction size are defined by different gear widths. There is a proportional relation between leakage and displacement. In pressure-compensated designs for internal gear pumps, the sealing gap at the tooth tip reduces as pressure increases. This increases volumetric efficiency, but also increases mechanical losses.

Vane pumps are manufactured with different rotor diameters, and within a construction size the displacement volumes are defined by the profile of the stroke ring. In this construction type, the lengths of sealing gaps remain almost constant. Internal leakage only varies slightly as a result of the differences in vane stroke size. Thus, the pump with the largest displacement volumes, which has the largest vane stroke, has almost the same internal leakage as the pump with the smallest. There is a proportional relation between leakage and displacement volumes across the range, but this declines within a given construction size, thus increasing the efficiency. The most effective combinations are almost as good as the most effective internal gear pumps (Figure 4).

The lengths of sealing gaps are roughly the same in internal gear and vane pumps, and thus both types of pumps exhibit very similar leakage rates up to medium pressures. In terms of energy efficiency of the system, efficiency is crucial at high rotation speeds and pressures, because this is where the most energy is used. At small rotation speeds, efficiency is important for the pump itself, because in pressure-holding operation the pump is barely able to dissipate heat. In the absence of flow, only internal leaking is pumped. The T7E15 pump is of the same construction size as the T7E10, but has the largest vane stroke and hence is better in terms of efficiency. At identical displacement volumes, the pump has to turn faster the greater the leakage is. Internal gear and vane pumps are equivalent; at higher pressures, the vane pump has to turn somewhat faster (Table 1).

Because this heat cannot be dissipated without a drain port (which is normally dispreferred with fixed-displacement pumps in order to simplify installation), the maximum pressure-holding time up to the heating limit is a function of leakage. A higher level of leakage means a shorter pressure-holding time in the ab-

		T7B E10	Internal gear pump with 31.8 ccm
	p [bar]	n [l/min]	n [l/min]
η_{vol} = 0 %	280	290	110
	240	220	85
	200	140	80
	160	100	70
η_{vol} = 10 %	280	320	120
	240	230	95
	200	150	80
	160	110	70
η_{vol} = 20 %	280	330	120
	240	240	100
	200	170	90
	160	120	80
η_{vol} = 30 %	280	350	140
	240	260	110
	200	190	100
	160	130	90

Table 1: Comparison of rotation speeds in pressure-holding operation depending on volume of efficiency of a vane pump and an internal gear pump of 31.8 ccm

sence of flow. However, a higher level of leakage also entails a higher rotation speed and thus a lower pressure pulsation. If the pressure-holding time that can be achieved is not sufficient for the application, a small amount of flow to eliminate the dissipation loss of the pump will extend this time considerably. For the most part, leakage will provide sufficient flow for the connected device to achieve sufficiently long pressure-holding times for the application (Table 2).

T7B E15	Q_{out} [l/min]	p [bar]	t [s]
η_{vol} = 0 %	0.00	280	9
	0.00	240	43
	0.00	200	101
	0.00	160	418
η_{vol} = 10 %	1.44	280	42
	0.83	240	62
	0.58	200	122
	0.45	160	447
η_{vol} = 20 %	3.24	280	57
	1.87	240	92
	1.30	200	> 600
	1.00	160	> 600
η_{vol} = 30 %	5.57	280	> 600
	3.21	240	> 600
	2.22	200	> 600
	1.73	160	> 600

Table 2: Pressure-holding time (T ≤ 90 °C, HLP32) of a vane pump of 50 ccm depending on volume of efficiency

Compact and robust

The trend towards variable flow rates is forcing manufacturers of fixed-displacement pumps to adapt their products for variable-speed operation. In the future, a wider range of designs is to be expected on the market. A variable-flow vane pump is already available as an additional option alongside more established products. This pump is quieter than a piston machine and has a considerably simpler design. The vane pump is comparable in terms of hydraulic efficiency and noise characteristics, and, at medium pressure at no flow condition, it has almost the same pressure-holding times as an internal gear pump. With respect to the pressure-holding times of fixed-displacement pumps in general, it should be noted that, in practice, the need for pilot oil and the leakages of the components of the total hydraulic system, impose no restrictions. The vane pump is the only pump that can run on the extended shaft of the electric motor, which makes this integrated solution uniquely compact and robust.

Bibliography

[1] H. Murrenhoff, Grundlagen der Fluidtechnik, Band 1: Hydraulik, 6. Auflage, 2011

[2] R. Bublitz, K. Roosen, Energetic optimization of variable speed pump systems, 9. Internationales Fluidtechnisches Kolloquium, Aachen, 2014

[3] T. Neubert, J. Wolff, S. Helduser, H. Spath, Untersuchung elektrischer Antriebssysteme am Beispiel von Hydraulikpumpen; Antriebstechnik 43 Nr. 1, 2004

[4] I. Rühlicke, Elektrohydraulische Antriebssysteme mit drehzahlveränderbarer Pumpe, Dissertation, Technische Universität Dresden, 1997

Parker Hannifin Manufacturing
Germany GmbH & Co. KG
Hydraulics Group Europe
phone + 49 (0)2131 513-0
www.parker.com