Tractor Power for Implement Operation—Mechanical, Hydraulic, and Electrical: An Overview

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Abstract. *It is well understood that the main function of tractors is to provide drawbar power either through the single-point connection known as the drawbar or through the three-point hitch. Early tractors essentially replaced horses and other draft animals to do work. Also, over the years, tractors have been called upon to provide other forms of power transfer, for powering and for controlling implement functions. This Lecture looks at other power usages and requirements, focusing primarily on mechanical means such as the PTO, tractor hydraulic systems, and more recently through transfer of electrical power. A historical prospective is provided for each form of power. One of the themes developed is how tractor and implement manufacturers can exploit available tractor power to improve efficiencies of the tractor implement system that will be beneficial to the end user of the equipment. The advantages and disadvantages of each type of power transfer as well as relevant standards and current practices are discussed, as are some future trends.*

Keywords: *Agricultural machinery, Electrification, Farm equipment, Farm machinery, Hydraulics, Hydraulic equipment, Power take-offs, Power use.*

Introduction

The great increases in agricultural productivity over the last century can be related to mechanization, particularly the development of the tractor. The definition of an agricultural tractor is given in ASABE Standard S390.5 (2011) as:

> A traction machine, intended primarily for off-road usage, designed and advertised primarily to supply power to agricultural implements. An agricultural tractor propels itself and provides a tractive force in the direction of travel and may provide mechanical, hydraulic, and/or electrical power and/or control to agricultural implements to enable them to perform their intended functions.

The main function of tractors is to be interfaced with implements. Implements are generally towed by a drawbar or a three-point hitch at the rear of the tractor. Implements may be carried or pushed by a front three-point hitch. Implements may also be directly mounted to the tractor frame. Not only do tractors provide tractive effort to move the implements through the field, but they also power and control the implements.

The draft or tractive capability of tractors to do useful work has been covered earlier in this series of Distinguished Lectures. The phrase underlined in the above definition is the focus of this Lecture: the mechanical, hydraulic, and electrical power that tractors provide to implements and that enables increased productivity and versatility.

Originally, tractor-drawn implements emulated horse-drawn implements and only required that tractor power provide draft. Over time, implements have become more sophisticated with additional power requirements. Now, the tractor power that is usable for doing work must be balanced between the tractive requirements, the PTO power requirements, and the hydraulic-electrical power requirements. By properly understanding how the tractor power can be used, tractor-implement systems can be optimized.

Only part of the potential energy available in the fuel is available for useful work by the tractor. After the power losses through the cooling system, exhaust system, drivetrain losses, and rolling resistance, what power is left is available for useful work. There are implements available today that can have high draft requirements, high hydraulic flow requirements, and electrical requirements, potentially at the same time. All of these power requirements must be balanced and optimized because in the right circumstances the implement power requirements could exceed available tractor power.

This Lecture will give an overview of each of these technologies—mechanical, hydraulic, and electrical. One could argue that air compression and delivery should be included but we have chosen to leave that for later.

Historical Perspective

Steam traction engines preceded the development of the tractor. Early steam engines served to provide power to stationary equipment through belt drives. Both the engine and the implement were stationary. Early belt-driven implements included threshing machines and other crop processing machines. Later, flexibility improved by mounting the steam engine and implement on wheels so that they could be towed by horses from farm to farm. Self-propelled steam traction engines started appearing in the late 1870s; large ones were also used for primary tillage work. They grew in popularity until production stopped in the 1920s with the advent of tractors powered by internal combustion engines.

Figure 1. Tractor powering a belt-driven threshing machine from the 1920s.

Appearing on the market in the early 1900s, tractors served the same functions as the steam traction engines: to power threshers or to do tillage work. Figure 1 shows a typical threshing operation from the 1920s. Large steam engines and large tractors were instrumental in opening the prairies for cropping. However, the large size tended to limit their usage to tillage operations. Smaller tractors, when developed, were initially seen as replacing horses and doing much the same types of operations.

Manufacturers rated tractor performance by their drawbar power rating and their belt rating. A designation of "15-30" meant the tractor had 15 drawbar horsepower and 30 horsepower through the belt pulley. The state of Nebraska started requiring tractors being marketed in the state to be tested by a independent third party to verify performance claims. This was the start of the Nebraska Tractor Test Laboratory in Lincoln, Nebraska. Testing started in 1920 and included a drawbar performance test and a belt performance test. Belt horsepower testing continued to be conducted and reported until 1959. For example, the John Deere tractor model 720 included belt power ratings in the 1956 Nebraska test report while the John Deere 4010 Nebraska test report in 1960 included PTO power ratings.

Mechanical Power Interfaces: Power Take-Offs

Historical Perspective

Power take-offs or PTOs have been described by Mayhew and Hansen (2004) as being the most efficient way to transmit power from a tractor to an implement. PTOs were first installed on a tractor by IHC in 1918 and marketed in 1920. This gave IHC three ways to deliver useful power: drawbar, belt, and PTO. Agricultural machinery manufacturers quickly saw the benefits of having a PTO; this led to the development of the first ASAE PTO standard being published in 1927. It standardized the PTO in terms of speed, size and shape of the splines, and location of the PTO stub shaft. See Goering and Cedarquist (2004), Leffingwell (2000), and Baumheckel and Borghoff (1997) for discussions of the early PTO history. Engineering PTO drivelines is covered in other Distinguised Lectures, so are not discussed here.

The introduction of the PTO was key to increasing productivity in agriculture. As explained earlier, belt power required stationary operation. A PTO allowed power to be transmitted from the tractor to an implement, such as a mowing machine or binder, which could do work on a crop while moving. Corn pickers and hay balers were developed as well as pull-type combines. IHC as a manufacturer of tractors and crop processing machines was able to develop a system of machines that could be powered by the PTO.

Over the years there has been three configurations for PTO drive and control. The earliest configuration was the transmission-driven PTO. When the clutch was depressed, the PTO would stop, with obvious disadvantages. These were overcome by the "live" or continuously running PTO. The live PTO usually used a dual clutch or a separate hand clutch to allow the PTO driveline to continue operating at a constant speed even when the tractor stopped moving. This helped the tractor operator to adjust tractor travel speed in varying field conditions. In the mid-1940s, the Cockshutt tractor company became the first tractor manufacturer to market a tractor with a live PTO. Soon other manufacturers were offering it. John Deere began offering the live PTO in 1953 on the two-cylinder numbered series of tractors.

The third configuration is the independent PTO. Here, separate controls such as levers or switches control the engagement of the PTO; the function is completely independent of the traction clutch. Generally, with lever controls, the tractor operator can feather the PTO to start heavy loads. Electronically controlled clutches often have programmed modulation schemes that allow gradual clutch engagement over a set period of time. Sometimes these controls can have selectable engagement rates available through the tractor control screens. ASABE Standard S205.2 (listed in table 1) gives formal definitions of these three types of PTO configurations.

Figure 2 shows the advances offered by usage of PTO drivelines. In the picture on the left the hay or straw had to be brought from the field to a location where the stationary baler and tractor was set up to operate the baler with a belt drive. Think of the work to feed the stationary baler from the pile! Then the bales had to be moved to their final destination. A PTO allowed the baler to be pulled through the field avoiding the labor involved in piling the crop and feeding the stationary equipment. The tractor shown in the right picture has enhanced the baling operation with a live PTO; the operator could change gears easily to reduce the potential of plugging the baler.

We have talked about the transition from steam power to tractor power as enabling increases in productivity. The development of the PTO also allowed farmers to become more productive. The continuously running or live PTO further enhanced productivity. PTO powered equipment is almost taken for granted today.

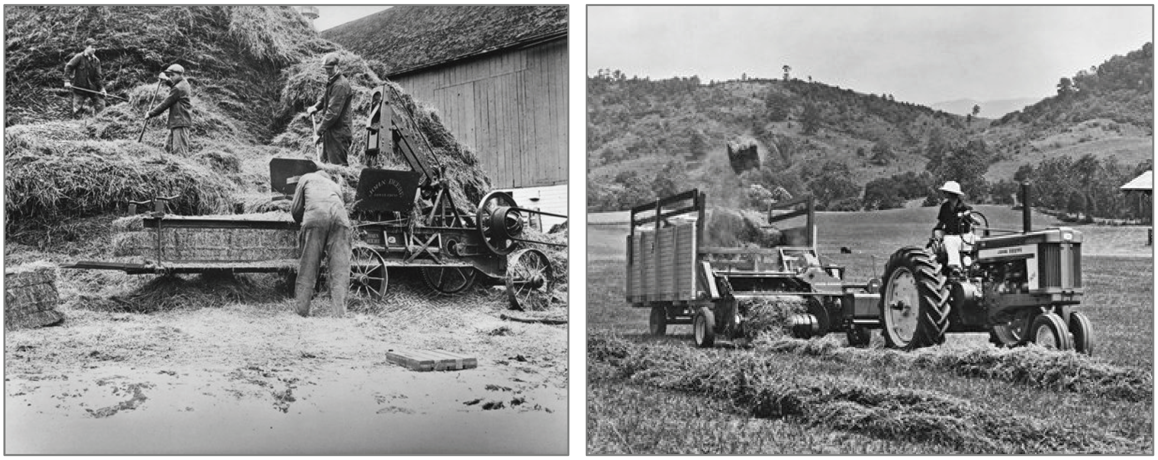

Figure 2. Baling operations before and after PTO availability.

Modern PTO Drivelines

Figure 3 is a simple PTO interface diagram that depicts how the tractor PTO system interfaces with the rest of the tractor and the implement. A few comments about the tractor system:

- All tractors that have a PTO will have an internal drivetrain arrangement that provides a specific speed ratio relationship between the engine and the PTO stub shaft.
- There will be internal gears, shafts, and bearings requiring lubrication flow.
- The internal system must be able to withstand the thrust forces imposed by the implement PTO driveline and must be able to withstand the torque fluctuations also imposed by the implement on the tractor drivetrain.
- There will be some sort of clutching system and there could be a PTO brake. Clutch capacity must be considered in regards to starting machines with high inertia.
- There are many types of operator controls that can be used to actuate the PTO such as mechanical systems or electrically controlled switches that activate the clutch valve.
- The PTO module may reside in a hitch frame at the rear of the tractor or in the rear differential case.
- External forces imposed by hitches or twisting motion of the tractor frame must be considered to ensure proper PTO module operation during all tractor operating conditions.
- Finally, depending on the sophistication of the system, there may be speed sensors, pressure sensors, or perhaps torque sensors to control the PTO system.

Standards Related to PTO Drivelines

Table 1 is a fairly complete listing of ASABE and ISO standards related to PTO driveline design. For tractor design, from the compact tractor to the largest four-wheel drive tractor, the standards listed in table 1 should be considered, because compliance to these industry standards is

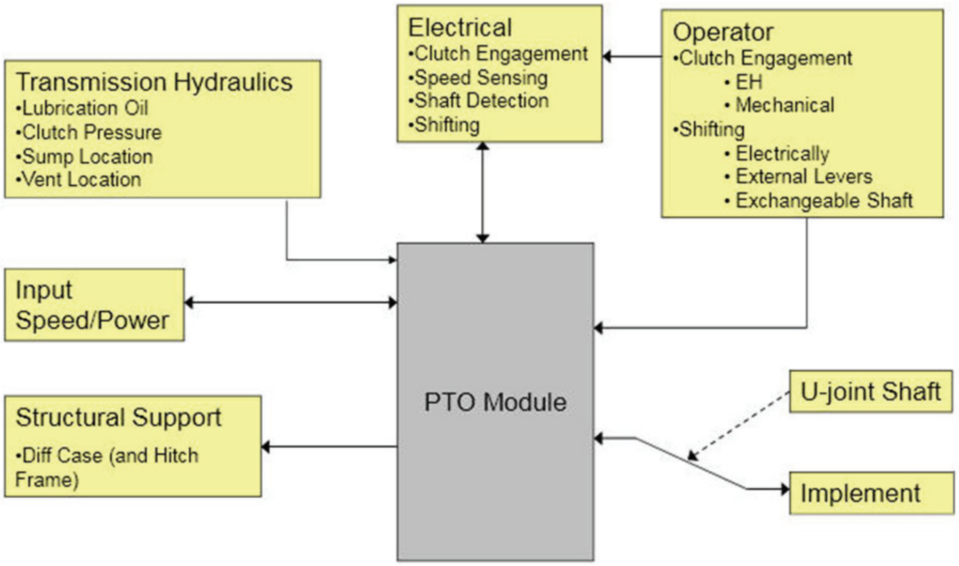

Figure 3. Tractor PTO interface diagram.

Table 1. Current ASABE and ISO standards* relevant for PTO design. Those for lawn and garden tractors, as well as those for specialized implements, are not listed.

Standard Number	Name
ASABE AD500-1	Agricultural tractors — Rear-mounted power take-off types 1, 2 and 3 — Part 1: General specifications, safety requirements, dimensions for master shield and clearance zone — Incorporating Corrigendum 1: October 2011
ASABE AD6489-3	Agricultural vehicles — Mechanical connections between towed and towing vehicles — Part 3: Tractor drawbar
ASABE AD8759-1**	Agricultural wheeled tractors — Front-mounted equipment — Part 1: Power take-off and three-point linkage
ASABE AD8759-2	Agricultural wheeled tractors — Front-mounted equipment — Part 2: Stationary equipment connection
ASABE AD26322-1	Tractors for agriculture and forestry — Safety — Part 1: Standard tractors
ASABE AD26322-2	Tractors for agriculture and forestry — Safety — Part 2: Narrow-track and small tractors
ASABE/ISO 500-2	Agricultural tractor — Rear-mounted power take-off types 1, 2 and 3 — Part 2: Narrow-track tractors, dimensions for master shield and clearance zone
ASABE/ISO 500-3	Agricultural tractors — Rear-mounted power take-off types 1, 2 and 3 — Part 3: Main PTO dimensions and spline dimensions, location of PTO
ASABE/ISO 24347	Agricultural Vehicles Mechanical Connections between Towed and Towing Vehicles Dimensions of Ball-type Coupling Device (80 mm)
ASABE S207.12	Operating Requirements for Tractors and Power Take-Off Driven Implements
ASABE S217.12	Three-Point Free-Link Attachment for Hitching Implements to Agricultural Wheel Tractors
ASABE S318.17	Safety for Agricultural Field Equipment
ASABE S331.5	Implement Power Take-Off Driveline Specifications
ASABE S604	Safety for Power Take-off (PTO), Implement Input Driveline (IID), Implement Input Connection (IIC), and Auxiliary Power Take-off (aux. PTO) for Agricultural Field Equipment
ASABE S205.2	Power Take-off Definitions and Terminology for Agricultural Tractors
ASABE S278.7	Agricultural wheeled tractors and implements — Three-point hitch couplers — Part 1: U-frame coupler
ISO 500-1	Agricultural tractors — Rear-mounted power take-off types 1, 2 and 3 — Part 1: General specifications, safety requirements, dimensions for master shield and clearance zone
ISO 500-1 CORR1	Agricultural tractors — Rear-mounted power take-off types 1, 2 and 3 — Part 1: General specifications, safety requirements, dimensions for master shield and clearance zone TECHNICAL CORRIGENDUM 1
ISO 500-2	Agricultural tractors — Rear-mounted power take-off types 1, 2 and 3 — Part 2: Narrow-track tractors, dimensions for master shield and clearance zone
ISO 500-3	Agricultural tractors — Rear-mounted power take-off types 1, 2 and 3 — Part 3: Main PTO dimensions and spline dimensions, location of PTO
ISO 730	Agricultural wheeled tractors — Rear-mounted three-point linkage — Categories 1N, 1, 2N, 2, 3N, 3, 4N and 4
ISO 5673-1	Agricultural tractors and machinery — Power take-off drive shafts and power-input connection — Part 1: General manufacturing and safety requirements
ISO 5673-2	Agricultural tractors and machinery — Power take-off drive shafts and power-input connection — Part 2: Specification for use of PTO drive shafts, and position and clearance of PTO drive line and PIC for various attachments
ISO 5674	Tractors and machinery for agriculture and forestry — Guards for power take-off (PTO) drive-shafts — Strength and wear tests and acceptance criteria
ISO 6489-1	Agricultural vehicles — Mechanical connections between towed and towing vehicles — Part 1: Dimensions of hitch-hooks
ISO 6489-2	Agricultural vehicles — Mechanical connections between towed and towing vehicles — Part 2: Specification for clevis coupling 40
ISO 6489-3	Agricultural vehicles — Mechanical connections between towed and towing vehicles — Part 3: Tractor drawbar
ISO 6489-4	Agricultural vehicles — Mechanical connections between towed and towing vehicles — Part 4: Dimensions of piton-type coupling
ISO 6489-5	Agricultural vehicles — Mechanical connections between towed and towing vehicles — Part 5: Specifications for non-swivel clevis couplings
ISO 8759-1	Agricultural wheeled tractors — Front-mounted equipment — Part 1: Power take-off and three-point linkage
ISO 8759-2	Agricultural wheeled tractors — Front-mounted equipment — Part 2: Stationary equipment connection
ISO 11001-1	Agricultural wheeled tractors and implements — Three-point hitch couplers — Part 1: U-frame coupler
ISO 11001-2	Agricultural wheeled tractors and implements — Three-point hitch couplers — Part 2: A-frame coupler
ISO 11001-3	Agricultural wheeled tractors and implements — Three-point hitch couplers — Part 3: Link coupler
ISO 24347	Agricultural vehicles — Mechanical connections between towed and towing vehicles — Dimensions of ball-type coupling device (80 mm)
ISO 26322-1	Tractors for agriculture and forestry — Safety — Part 1: Standard tractors
ISO 26322-2	Tractors for agriculture and forestry — Safety — Part 2: Narrow-track and small tractors

*ASABE Standards can be obtained from American Society of Agricultural and Biological Engineers, 2950 Niles Road, St. Joseph, MI 49085 or http://www.asabe.org/publications/publications-catalog/standards.aspx.
International Organization for Standards (ISO) can be obtained from American National Standards Institute (ANSI), ANSI Attn: Customer Service Department, 25 W 43rd Street, 4th Floor, New York, NY 10036 or http://www.iso.org/iso/home/store.htm.
** Under revision

the best way to ensure proper operation of PTO drivelines.

ASABE standards apply to North America and the ISO standards can be thought of as world-wide standards. The ASABE strategy related to standards has been to adopt the ISO standards either as written or with deviations. Mayhew (2008) discusses the advantages of harmonization of the ASABE and ISO standards, a continuing process. Included in table 1 are the standards that address drawbar and three-point hitch connections in North America as well as safety standards that may apply. Standards for tractor to implement connections used in other regions of the world are included for completeness. This listing does not include any national standards that may be in place in any other country.

PTO drivelines can be used to power implements in several ways: three-point hitch mounted implements, pull-type implements connected through a single-point connection, mounted implements to the tractor frame, and stationary implements. PTO drivelines used with three-point hitches primarily have to accommodate angular displacements in the vertical plane, although hitch sway can introduce angular displacements in the horizontal plane. Pull-type implements are usually connected to the tractor by the drawbar, although there are other connection types. A pull-type implement can change its orientation in all planes relative to the tractor. Frame-mounted or stationary implements have fixed relationships between the implement and tractor so generally the motions are small and are not as concerning as for the other configurations. Regardless of relative motion, a good PTO driveline should not collapse or pull apart during normal operation. So, PTO driveline designs allow for movement between the tractor and the implement in the yaw, pitch, and roll planes. Recommended relationships for tractor drawbar connections to PTO-driven implements are given in ISO 6489-3 and ASABE AD6489-3. Similar relationships for three-point hitches are covered in ASABE S217.12 and ISO 730. Good references for PTO driveline designs are given in an earlier Distinguished Lecture by Mayhew (1994). Also see Mayhew and Hansen (2004), Trojanowski (1979), and Reimer (1965) for more driveline design information.

PTO drivelines involve the use of cardan joints or, sometimes, constant velocity joints to aid in transmitting the rotational power from the tractor to the implement so that relative motion of the tractor and implement can be accommodated. There are also speed fluctuations in the drivelines and torque variations during PTO driveline operation. ASABE 331 gives some guidance as to the torsional capacity of different classes of drivelines and ASABE S207 gives guidance as to the allowable thrust loads that a PTO driveline can impose on the tractor PTO stub shaft.

One of the disadvantages of a PTO driveline is that there must be a open area from the tractor PTO stub shaft to the power input connection (PIC) on the implement for the driveline to pass (see ISO 5673-1 and ISO 5673-2). By virtue of being a rotating system there are hazards associated with the driveline. Table 1 includes standards for the fixed tractor PTO master shield and the rotating PTO driveline shielding. Thomas et al. (2003) discusses hazards and provides references to PTO driveline safety concerns. Figure 4 shows a typical PTO driveline, including the cardan joints, shielded by rotating guards. The only part of the driveline that is exposed is the splined end that slides over the tractor PTO stub shaft, which is area is covered by the tractor master shield.

Figure 4. PTO driveline on mower conditioner, showing shields.

Table 2 shows the current tractor PTO stub shaft sizes and speeds specified in ISO 500-1 and ASABE AD500-1. Goering et al. (2003) explains how the original 6 spline PTO was standardized at 540 rpm. In Europe, 35 mm shafts with 6 splines can also be used at 1000 rpm. Only the 540 rpm, 6 spline shafts are allowed in North America. In parts of Europe a common PTO spline in use is a 45 mm, 6 spline PTO stub shaft. This spline is not covered by the standards. The standards also specify that PTO drivelines should rotate in a clockwise direction (when looking at the tractor from the rear).

At this writing, ISO is balloting drafts of ISO 500-1 that include a new Type 4 PTO spline. This new spline would be a 57.5 mm OD shaft turning at 1300 rpm. The higher speed would allow for high power consuming applications. At least one tractor manufacturer in Europe has experimented with this new Type 4 PTO spline. One PTO driveline manufacturer also offers drivelines conforming to the new Type 4 specifications.

PTO Speeds

Table 3 shows the PTO speed options available for a current production tractor. Many countries, particularly in Europe, want to use tractors with multiple-speed PTOs. The reason is to provide different ratios between engine speed and the rated PTO speed. Commonly a 1000 rpm driveline speed will be obtained near or slightly below the rated engine speed. Providing 1000 rpm PTO speeds at a lower engine speed is seen as a way to lower fuel consumption in lower-power applications.

With the advent of electronically controlled engines and transmissions, many tractor manufacturers now offer a control scheme where the engine power level can be boosted,

Table 2. Current and proposed tractor PTO splines from ISO 500-1.

PTO Type	Nominal Diameter	Number and Type of Splines	Nominal PTO Rated Rotational Frequency, rpm	Recommended PTO power at rated engine speed, kW
1	35	6 straight splines	540	<65
			1000*	<110
2	35	21 involute splines	1000	<190
3	45	20 involute splines	1000	<300
4**	57.5	22 involute splines	1300	<450

* Not available in North America

** Proposed at this writing

Table 3. PTO speeds available for John Deere 7R tractors.

PTO Type	Spline (Shaft Diameter – Number of Teeth)	Speeds	Engine Speed at Rated PTO Speed			
			540	540E	1000	1000E
Type 1	35 – 6T	2	1958	--	1950	--
Type2	35 – 21T					
Type 3	45 – 20T					
Type 1	35 – 6T	3	1958	1723	1950	--
Type2	35 – 21T					
Type 3	45 – 20T					
Type 1	35 – 6T	3	--	1763	1967	1756
Type2	35 – 21T					
Type 3	45 – 20T					
Type 3	45 – 20T	1	--	--	1950	--

provided the PTO is engaged and loaded when the tractor is moving. The range of the boost in power output is in the range of 15 to 22 kW. The theory is to increase the tractor's power output for PTO operation so that the additional power is available to propel the tractor and implement through the field and still allow the PTO to operate closer to its full-load capability. These schemes to boost the engine power output rely on measuring the PTO clutch slippage or measuring the torque in the PTO driveline. The power management control schemes can also be used to boost tractor power during acceleration or deceleration events during transport operations. These control schemes could be used to boost power output during high flow requirements by the hydraulics systems.

Front PTOs

The primary function of a PTO is to transmit shaft (rotational) power to an implement. For a rear PTO, the implement may be connected to the tractor by the drawbar, rear hitch, or several other types of implement attachments. In addition, an implement might be a stationary item not attached to the tractor.

Over the last 20 years, there has been increasing interest and demand for front-mounted three-point hitches in combination with a front PTO on row crop tractors. The front PTO is used to provide power to a front-mounted implement, such as a front-mounted mower, snow blower, tiller, or fertilizer spreader. There are also stationary implement applications (augers, etc.). Figure 5 shows a typical front hitch and PTO that can be bolted onto a tractor.

The front PTO can be driven directly by the engine crankshaft, by the tractor transmission, or by other means, depending on the layout of the specific tractor. Many tractors have the front PTO driven by the engine crankshaft. A driveline runs forward from the front of the crankshaft, under the cooling package, to the front PTO gearbox. The cooling package being located relatively high and above the front axle allows for the driveline to pass under it, providing space for this style of front PTO. Other tractors may have a front PTO design driven by a shaft that runs through front axle differential case from the transmission to the front PTO clutch housing. Some tractors have a cooling package which is mounted low, below the front axle centerline and forward. There is very limited space in front of the crankshaft for any drive couplings and a gearbox to fit behind the cooling package. Packaging of the front PTO module becomes a major design exercise to place the front PTO stub shaft so that it is located in proper relation to the front hitch and to the front of the tractor.

Figure 5. Typical bolt-on front PTO and three-point hitch module.

Figure 6. A front-mounted mower conditioner is a typical application requiring a front PTO and a front hitch.

Front PTOs are almost always packaged with a front three-point hitch. ASABE AD8759-1 and ISO 8759-1 (table 1) are the main standards that make recommendations for the front hitch and PTO. These standards continue to evolve. Until recently, the standards recommended that the front PTO should rotate in a clockwise manner (when viewed from the front of the tractor). It was allowed by standard for a Type 1 PTO, which could have 1000 or 540 6 spline shafts, to turn in the counterclockwise direction. Recently, there has been pressure to allow all front PTOs to rotate in the counterclockwise direction. At this writing, ASABE is balloting changes to AD8759-1 which would require all front stub shafts to rotate in the counterclockwise direction. Also, AD8759-1 does not recommend that the 6 spline, 1000 rpm shaft speed be used in North America. This is in alignment with the anticipated direction that the ISO standard will adopt when updated. Also, there are discussions about the front PTO height and how to accommodate every tractor manufacturer’s preferred height so that the front PTO drivelines will work correctly without separating or collapsing during front hitch raising and lowering.

Regardless of front PTO drive type, mounting provisions are required to attach the PTO components to the vehicle. This typically involves machined features on a front support to allow a gearbox or other unit to be bolted to the chassis in the correct position. Newer designs tend to be more integrated into the front of the tractor, usually with dedicated features incorporated into the tractor front support for mounting the front hitch linkage, lift cylinders, and front PTO module.

A front PTO will require some level of lubrication for the drive components, clutches, and brakes. The design of the PTO itself will determine what, if any, external plumbing and components may be required for hydraulic oil. Some designs may utilize a separate oil system that is not tied into the main tractor hydraulics. These systems will usually require a separate cooler and filter which must be packaged and connected with oil lines or hoses. Other front PTO designs may use a more integrated lube/cooling strategy and may not require additional coolers or filters. However, they will still likely require some external plumbing to tie them into the main hydraulic system.

There are several shielding requirements for front PTOs. The most prominent is the PTO master shield which covers the output shaft. ISO 8759-1 (table 1) defines the dimensions for the front PTO master shield for each type of PTO output. If multiple output shaft options are offered, the master shield should be designed for the largest type. Master shields have typically been designed as sheet metal components to satisfy requirements for strength in case the shield is used as a step. This is the recommendation given in ASABE AD8759-1. An alternative design uses the surrounding structure of the front hitch to create the master shield without requiring a separate part. However, building the shield features as part of a large cast or fabricated structure can make changes more difficult and costly after the tooling has been built.

Some tractors have used a flexible rubber or plastic master shield. This can be allowed depending on the design of the surrounding tractor components. In general, flexible shields have been avoided where the shield protrudes enough to possibly be used as a step. If a flexible shield is considered, the material chosen must resist sag and must be capable of withstanding the various environmental factors it may encounter (oil, UV, fuel, freezing, heat, etc.). This design is not recommended by ASABE AD8759-1 since there is a high probability that the front master shield would be used as a step.

Figure 6 shows a front hitch and front PTO application that is becoming very common. A mower conditioner mounted to the front of the tractor offers another machine form option compared to a dedicated windrower.

Hydraulic Power Interface

Historical Perspective

The first usage of hydraulics on farm tractors was to replace manually raising and lowering implements. This innovation gave the operator the ability to easily control the implement while moving, rather than trying to man-handle the adjustment levers while in motion. The safer alternative was to stop, dismount from the tractor, make the adjustment, remount the tractor, and continue operation—but this did not always occur.

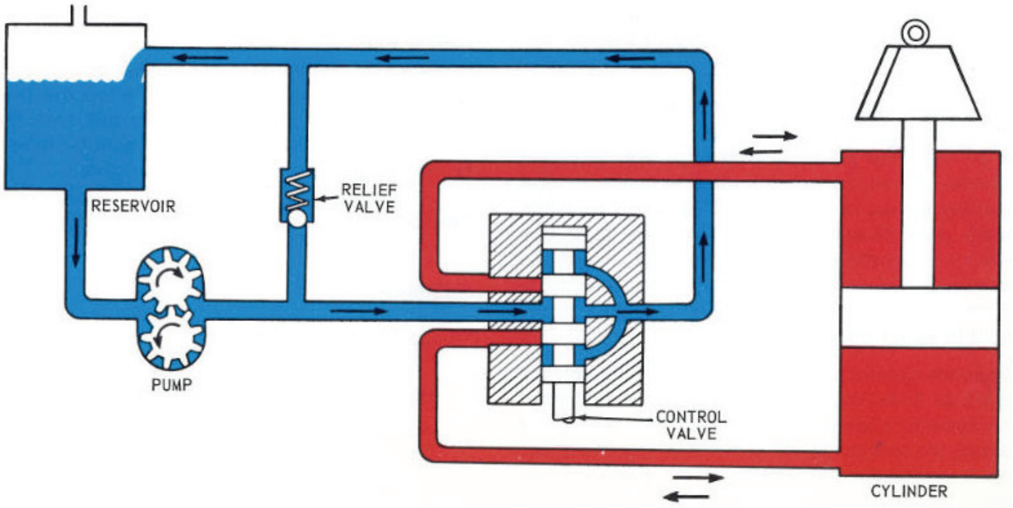

Figure 7. Open-circuit hydraulic system.

Hydraulics improved productivity by removing down time and also by improving field operations. When soil conditions varied, the operator could make implement depth adjustments so as to not kill the tractor engine. Also, when the tractor encountered soft soil the operator could make implement depth adjustments while moving, which reduced the risk the tractor would get stuck.

Like most innovations, the first developments were crude by current standards. Open-center gear pump or vane pump circuits were used. The pressures were low, less than 6900 kPa (1000 psi). The John Deere model H tractor hydraulic system had a 3800 kPa (555 psi) working pressure, while the John Deere model B tractor had a 4200 kPa (610 psi) working pressure with a flow of 0.49 L/s (7.7 gpm) (John Deere, 1952).

At first, pumps were not driven using “live” shafts; if the operator stepped on the clutch pedal, the power to the pump would be disconnected, similar to the way early PTOs operated. There were times when the operator needed to stop the tractor but would have preferred to continue raising the implement. Eventually, designs evolved so that the hydraulic pump was driven by a live shaft. This made hydraulic power available whenever the engine was running, regardless of whether or not the clutch pedal was depressed. This was an improvement which advanced the versatility of the tractor and implements.

The usual means of using hydraulics to control implement raising and lowering was and still remains the hydraulic cylinder. The cylinder replaced the long levers and linkages with mechanical advantage used previously. The first cylinders were “single acting,” meaning that a control valve on the tractor would direct oil into the head end of the cylinder causing the rod to extend from the barrel using a single hydraulic line from the tractor. This change in device length coupled with the linkages of the implement would raise the implement. The volume in the rod side of the cylinder contained air and was vented to atmosphere. When the implement was lowered, the control valve would redirect the oil from the cylinder head side back into the tractor hydraulic sump. This arrangement required that gravity assist in pushing the oil back into the tractor using force developed from the dropping weight of the implement. The shortcoming of this arrangement is that there are times when it is desirable to retract the cylinder length beyond what gravity would assist, such as picking up the wheels to add weight to aid getting an implement into the ground.

The complexity of the control valve on the tractor progressively increased with two lines being run from the tractor to the hydraulic cylinder to actuate a double-acting cylinder. Depending upon how the control valve was positioned, oil would push into the cylinder head end and oil in the rod end would return to the tractor sump from the rod end, rather than simply being vented to the atmosphere. If the directional valve was repositioned, oil could be directed to the rod end to collapse the cylinder while pushing oil out of the head end (fig. 7).

If an open-center system is working to push oil at the relief setting, the area under the pressure flow curve is the amount of hydraulic power being generated. The flow is fixed because of the pump being fixed displacement and is usually proportional to engine speed (fig. 8).

When the open-center system is not working, the control valve is in neutral. The flow remains fixed and proportional to engine speed. However, the pressure at the which the pump produces flow is determined by the restrictions of the oil to circulate back to the reservoir. During this period, hydraulic power consumption decreases (fig. 9).

The usage of open-center hydraulic systems continues to this day, mostly with gear pumps. The advantage of using such a system is that it is cost effective for a tractor that is largely used for drawbar power. The downside is that from an efficiency point of view better systems have evolved. In spite of the disadvantages, the power density of the open-center systems has increased such that pressures are capable of the 20,500 kPa (3000 psi) range that more sophisticated systems use (ISO, 1994; ASABE Standards, 2008). Typically, the open-center system is used on the smaller tractors in developing parts of the world.

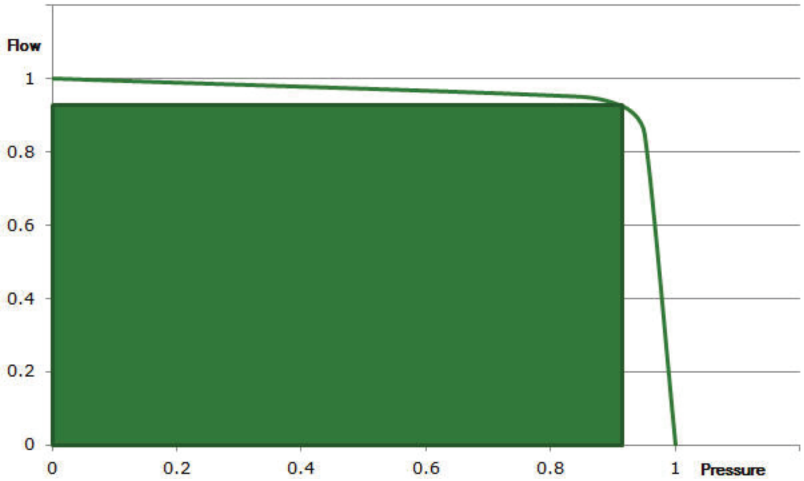

Figure 8. Open-center pressure flow curve.

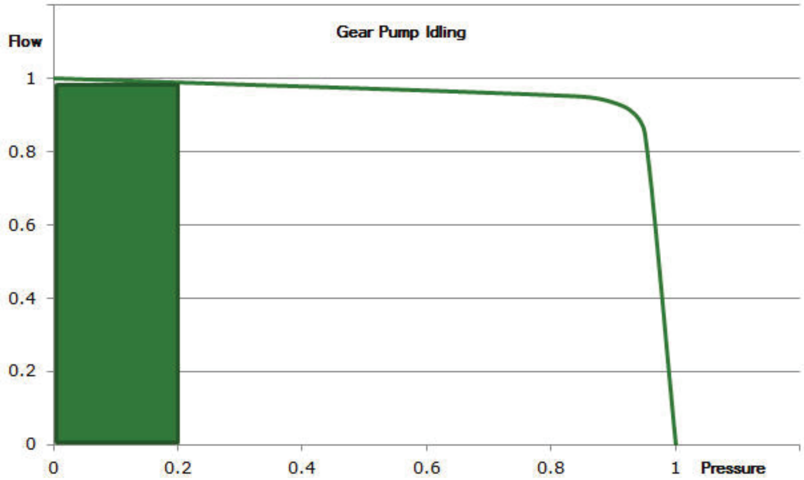

Figure 9. Open-center pressure flow curve, rest.

During the early development of agricultural tractor hydraulics, tractors and implements were relatively small and simple. A single hydraulic cylinder could handle the job. Since different implements could be pulled by the same tractor, the normal operation was to have a single cylinder permanently attached to the tractor. The cylinder was installed on the implement while being used and removed when the implement was disconnected from the tractor (fig. 10).

The earliest tractors had the cylinder hoses thread directly into the tractor valve housing. Then breakaway couplers

Figure 10. Tractor pulling implement, using cylinders permanently attached to the tractor.

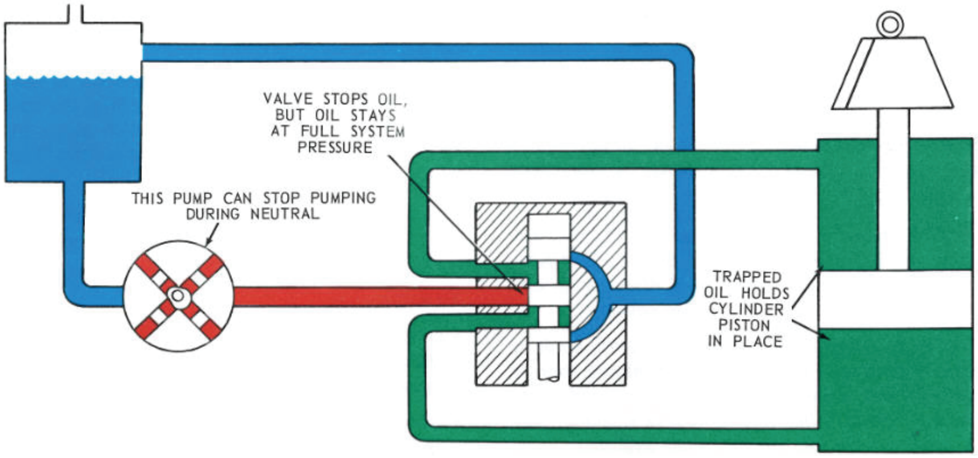

Figure 11. Closed-center hydraulic system.

were developed to uncouple the cylinder hoses from the tractor in the event the tractor pulled away from the implement and the cylinder had not been removed from the implement. This is not the recommended way to uncouple the hoses, but it did minimize damage to the hydraulic hoses and reduced the amount of oil lost and the corresponding mess. The operator could simply reconnect the cylinder hoses to the tractor and resume operation.

As tractors and implements grew in size, the need arose for multiple cylinders. This reduced the utility of keeping the cylinder with the tractor. The trend was to permanently locate cylinders (with all the required plumbing and hoses) on the implement, rather than with the tractor, and to utilize the couplers that had been developed. Similarly, it became necessary to fold large implements or do something to rearrange them to facilitate open road transport. A relatively easy approach was to have a separate, folding hydraulic circuit. This again utilized cylinders with dedicated plumbing permanently mounted on the implement. The coupler pair used for the folding would typically be separate from the coupler pair used for lift.

Increased hydraulic usage drove the evolution of hydraulic system designs with greater power density and improved efficiency. Larger systems moved from the open-center pumps to closed-center piston pumps. Piston pumps would destroke or stop pumping oil when the demand was not there (fig. 11).

For John Deere, the “New Generation of Power” tractors were introduced in 1960 with pressure-compensated, radial piston pumps. The system pressure was increased to 15,500 kPa (2250 psi) (fig. 12).

With this closed-center system and the radial piston pump, the pumps ran at a constant pressure but the piston displacements would vary depending upon the flow required. If the pump tried to deliver too much flow, the pressure would exceed 15,500 kPa and the compensator would

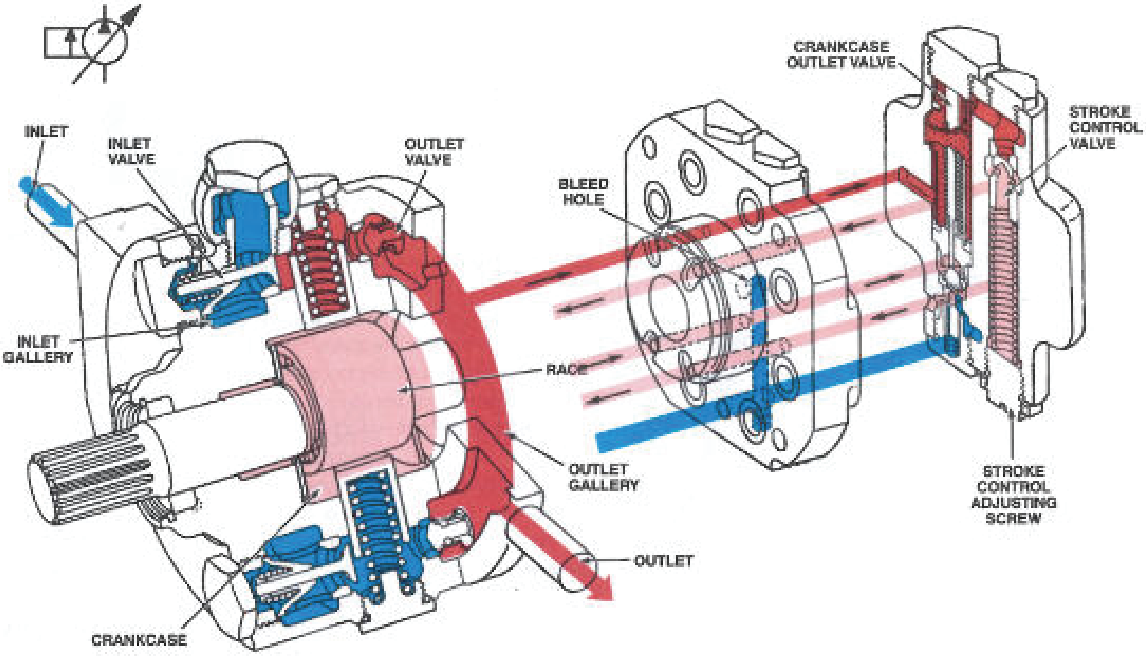

Figure 12. Radial piston pump, exploded view.

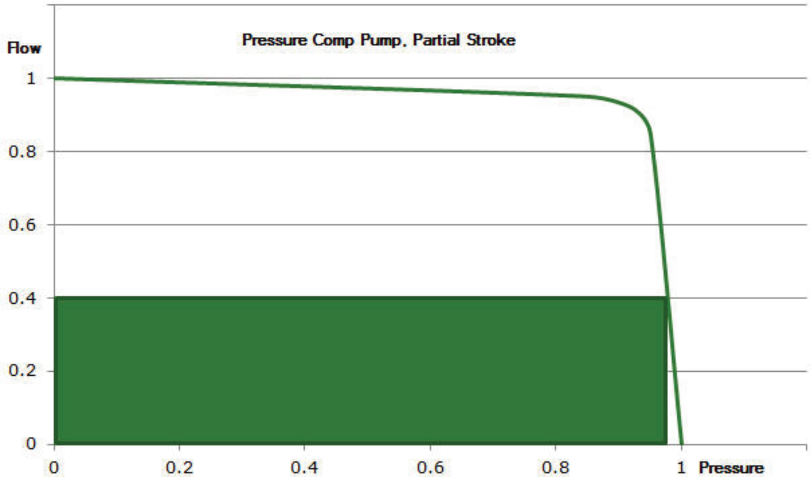

Figure 13. Radial piston pump pressure flow curve.

destroke the pump so that the pistons would push less flow. If not enough flow was delivered the pressure would drop and the pump would go into stroke to restore the constant 15,500 kPa output. By matching the flow to the demand the amount of excess heat generated in the system was reduced.

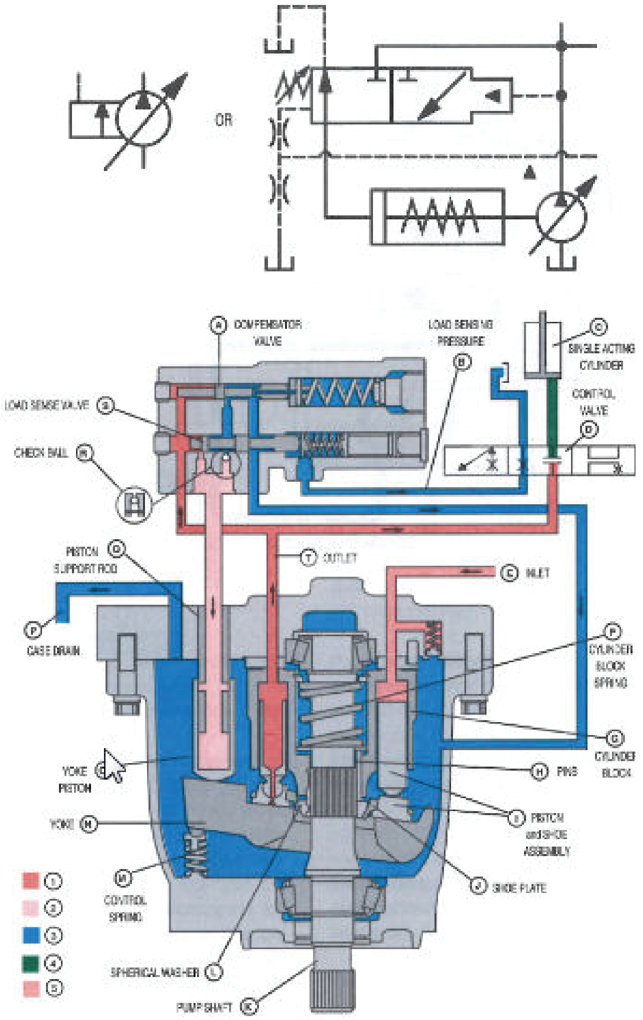

Figure 14. Axial piston pump, exploded view.

The radial piston pump curve shows that the pump is always producing at the maximum pressure the pump is able to produce for the demanded flow. The hydraulic power is the area under the curve which the hydraulic system is using. The flow rises and falls depends upon the demand (fig. 13).

Other companies, both OEMs and original component manufacturers, began developing commercially viable axial piston pumps. Today, the axial piston pump is the mainstay of the closed-center hydraulic system (fig. 14).

In the 1980s hydraulic pressure available to implements increased again. This time, per standard, the upper limit was set to 20,500 kPa (3000 psi) (ISO 1994; ASABE Standards, 2008). Part of the motivation of limiting the pressure with the standard is to protect the implements. An operator is free to connect whatever implement wanted to the tractor. If the implement is an older piece of equipment it may not have been adequately designed to handle the pressure. Implement damage or unsafe situations may occur.

System Considerations

There is a difference between wanting to protect the implements and knowing the capabilities of the on-board tractor system. For self-contained, on-board hydraulic systems the ISO standard has no upper limit on the hydraulic pressure. This increases the power density of the hydraulic system further than if it was subject to the same 20,500 kPa limitation. It is presumed that the system is designed to handle the pressure. An example of such a system is a hydrostatic propulsion system where the pressures can reach 50,000 kPa (7250 psi).

The hydraulic system which supplies power to the implement can operate at pressures greater than 20,500 kPa, but when the hydraulic power crosses to the implement it must be reduced to the maximum 20,500 kPa level. Reasons for desiring the increased pressure could be for increased steering capacity with a single-pump system. Smaller, higher-pressure cylinders could be used for increased power density. For systems with a single hydraulic pump, often a priority valve is used to insure that control systems with steering and brakes get first availability of the

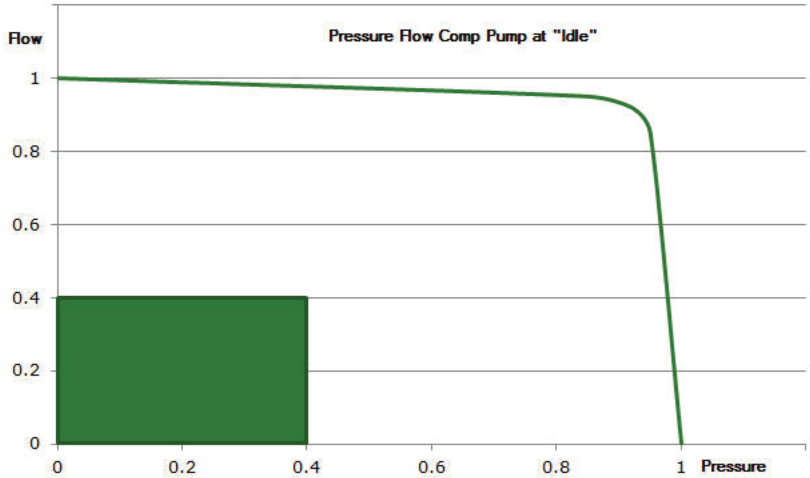

Figure 15. Flow curve for pressure-flow compensated pump pressure.

oil. Once the steering and brakes are satisfied, the secondary uses (implements) are supplied. What is diverted to the implement from the secondary circuit needs to have its pressure reduced.

One of the problems with reducing pressure to an implement is the size of the pressure reducing valve required to handle the flow typically going to the implement. Stability issues can occur with such a valve. Reducing the oil pressure also generates heat, which conflicts with the power improvements newer systems foster.

Such newer systems are both pressure and flow compensated to improve the overall efficiency. The pump goes into stroke to develop the required flow. A third line, a load-sense line, is added to the pressure and return lines. It signals the pump to tell it what pressure is required to perform its function. When a remote control valve is involved, the load-sense connection is picked up internally in the valve and the load-sense line runs from the valve to the pump. When power beyond is used, the load-sense line runs from the implement to the pump and is typically resolved, i.e., hydraulic logic selects the highest pressure requirement among the remote control valve sections and power beyond. The control valve or compensator then takes the load-sense signal and adds to it some pre-specified differential pressure to insure there is adequate margin to complete the job. Margin is the pressure differential between the hydraulic load and the output pressure of the pump. The margin that is added varies by application. The idea is to keep the margin as low as possible to minimize power losses, but high enough to provide adequate speed of response.

The result is that neither the pressure nor the flow is at the maximum limits unless both are required. This further reduces power losses compared to fixed-displacement pumps, which are always at the maximum flow conditions, or to pressure-compensated piston pumps, which are always at the maximum pressure condition. The result is further improvement in reducing unnecessary hydraulic power generation (see fig. 15).

If a single pump needs to satisfy two hydraulic functions at the same time with different pressure and flow requirements, there are inefficiencies. The pump will produce flow that is the sum of the total requirements. The pressure developed by the pump will be at the maximum required to satisfy all the functions. The result is that the pressure difference required for the function with lower demand generates extra heat and results in additional power loss. First, engine power would go into generating the additional hydraulic power. Then, additional power is required to power the fan to dissipate heat resulting from system inefficiencies.

As a goal, the amount of power thrown away at the cooler in a well designed system should not be greater than 15% of the maximum pump corner power. Corner power is the condition where maximum hydraulic power is produced. Hydraulic power is the product of the pump pressure and the flow the pump produces. For example, see figure 16. The green area represents the hydraulic power consumed by hydraulic function one. The yellow area represents the hydraulic power consumed by hydraulic function two. The red area is the hydraulic power wasted. When multiple functions are supplied with a single pump, the hydraulic power curve is the rectangular area of maximum pressure and total flow under the pressure-flow curve and encompasses both usable and unusable power.

Further optimization of such systems can be done as the systems grow in size. One way is to subdivide the system using different pumps with specialized system functions. In this way each system can operate at the pressure and flow demanded by that system (fig. 17). For example, one system could handle steering and brakes at an elevated pressure as an on-board system, while the pump that handles the implement would be limited to 20,500 kPa. (ISO, 1994; ASABE Standards, 2008). An additional benefit of having separate pumps is that the priority valve can be eliminated. Recall that the function of a priority valve is to direct flow so that critical control functions (steering, brakes) have access to oil before secondary functions. When the steering and brake functions are on their own pump, the priority valve can be eliminated.

There can also be benefits to having multiple systems

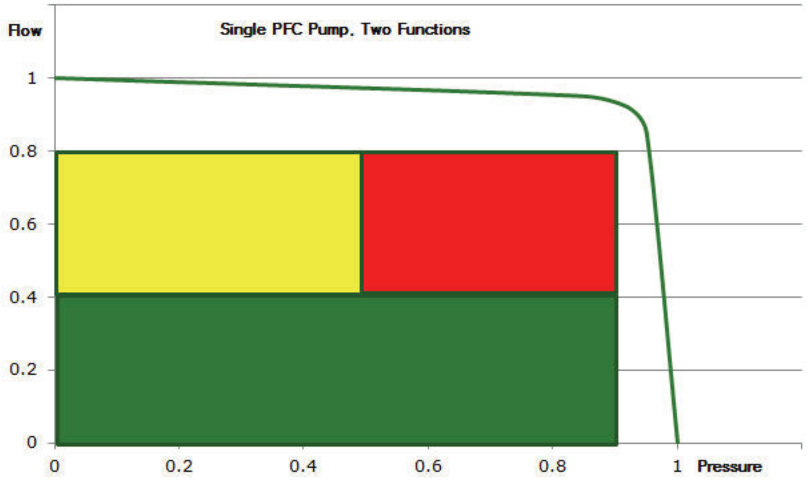

Figure 16. Pressure flow curve, single pump, dual functions.

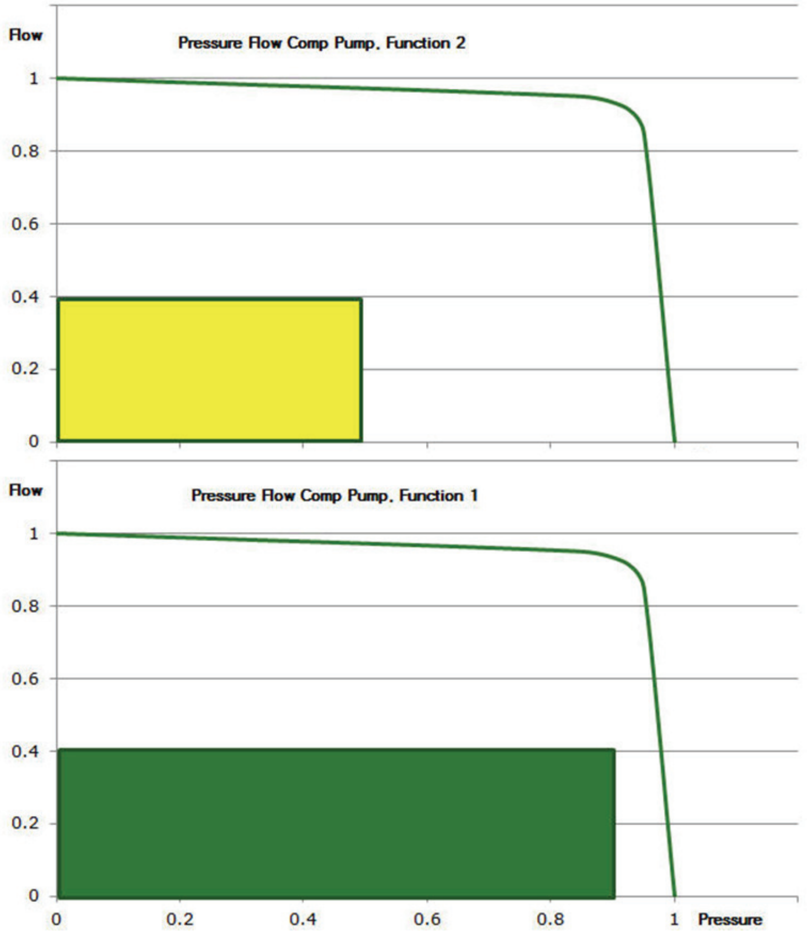

Figure 17. Pressure flow curve, dual pump, dual functions.

supply hydraulic power to an implement. A number of different tractor manufacturers utilize such multiple systems. One example is an air seeder (fig. 18) that uses hydraulic down pressure. One pump supplies pressure at or near the 20,500 kPa limit to push the openers down, but the flow demands are low. A second pump supplies the hydraulic motors which drive the fan(s). These motors typically operate at a lower pressure, for example 14,000 kPa, with whatever flow is required to turn the motor. If a single pump were to supply hydraulic power for down pressure as well as to the hydraulic motor, that pump would have to operate at the maximum pressure and total flow conditions. The result would be a total system mismatch with hydraulic power needing to be dissipated as heat.

Figure 18. An air seeder, which benefits from multiple hydraulic systems.

Remote Control Valves

The directional control valve on the tractor, also known as the remote control valve or selective control valve (SCV), guides and controls the hydraulic power to the implement. As the systems have evolved, so has this valve. Originally, such valves were little more than a three-way, three-position valve. As time progressed, valves evolved into complex multi-way, multi-position valves to include functions such as float, which permits oil to move freely back and forth from one side of a hydraulic function to another (such as a hydraulic cylinder) with minimal resistance. These valves can have a regeneration position which takes returning rod side cylinder flow (which is of an amount less than the head side flow required due to cylinder area ratio differences) and combines with the pump flow. This helps with system speed and efficiency during cylinder extension by not requiring the pump to produce as much flow (fig. 19).

Another feature is detent. This holds the valve in a fixed position while the function operates, rather than requiring the operator to continuously hold the controller. The valve control mechanism could be a lever for mechanical actuation or a paddle pot for electronic actuation. The detent operation could be continuous, which is a requirement for hydraulic motor control. For mechanical systems the control lever or mechanism could reset to neutral if a pressure spike is encountered, such as when a cylinder hits the end of travel. With an electrical system there could be a timer that returns the valve to neutral after a specified time interval.

Two common methods of directing flow through a remote control valve are to use a spool valve or a poppet valve. Nearly all tractor remote valves are spool valves. For poppets, the benefits include the ability to independently control flow (effective orifice diameter) out of the valve and return (which comes back into the valve). Also, poppets are relatively insensitive to contamination and can generally attain a zero leak interface. A shortcoming of poppets is that tailoring the metering curve is more difficult than with a spool valve. There is a large area opening with a short travel resulting in potential valve instability associated with the flow forces acting on the poppet geometry.

Typically a spool valve ties the inlet and outlet functions together. There are arrangements where functions are placed on separate spools, but this removes some of the attractiveness of spool valves compared to poppet valves. A

Figure 19. Remote control valve on a tractor.

spool valve has the ability to tailor the metering curve with notches to the spool land. Shortcomings of spool valves are that contamination may be a problem with binding of the spool. Also, leakage past the spool due to the inherent clearance between the spool and bore may be important. This may be addressed by additional check valves.

Fluid Conveyance

Probably the most common coupler size to connect a tractor with an implement has been the 0.5” ISO coupler (ISO, 2008; ASABE Standards, 2009). The tractor contains the female half of the coupler and the implement the male half of the coupler. To handle increased flows some applications have moved to 0.75” ISO couplers (ISO, 2008) (fig. 20). Another means by which some coupler restriction has been reduced is usage of flush-faced couplers in place of the ISO couplers (ISO, 2006). Currently, usage of the flush-faced couplers has limited applications.

Transfer of the hydraulic fluid has evolved as the complexity of systems has evolved. When hydraulic systems first were developed, pipe threads were used for connections between hoses and lines (ISO, 2012b). Eventually, 37° flare connections were developed for increasing pressures. (SAE, 2012a,b; ISO, 2007a). The metal-to-metal seals of the flare connectors provided an increased positive seal. In the 1980s O-ring face seals were developed for even further improvements in sealing. (ISO, 2005a). Another plumbing alternative that has been around for a long time, but typically has found usage with industrial equipment, is the four-bolt flange connection. There are code 61 four-bolt flange connections for 27,500 kPa (4000 psi) and below, and code 62 connections for 27,500 kPa (4000 psi) and above (SAE, 1993). All of these connections—pipe threads, flare, O-ring, face seal, and four-bolt—are used today in various capacities. Users need to be aware of their capabilites and limitations.

Pipe threads would leak fluid around the spiraling threads. Various tapes and compounds on the threads address the leakage issue by forming a barrier, but increasing pressure pushed the ability of the tape and compounds to resist the fluid.

One of the problems with the 37° flare connectors is that since the seal is metal to metal, the connection can be unforgiving. If the metal surface where the connection is made gets damaged, the only way to address leakage is to replace the damaged piece. Additionally, if the connection is loosened and retorqued, the potential for damage increases significantly. This could include out-of-round surfaces so the seal is not complete. If a leak starts and is not fixed early, erosion of the metal at the seal can occur.

Figure 20. Male 0.5” and 0.75” ISO hydraulic coupler tips.

The benefit of using the face-seal connections is that a replaceable O-ring provides the sealing connection. Connections which are hand tight can often provide sealing for some period of time. The potential downside of the face-seal fitting is the hydraulic restriction that occurs through the fitting itself.

Four-bolt flanges provide the benefit of being able to complete the connections by tightening four bolts (there is also a two-bolt variation) with a lower torque than what is required with a single connection with a face seal. Also, the flow restriction through the four-bolt flange connection is less because the throttling through the fitting itself is not present. For agricultural applications, the four-bolt connection is generally overkill relative to pressure capability, and thus can create cost penalties.

Fluid conveyance is typically through either metallic (usually steel) lines or flexible rubberized hoses. Lines are specified by the outside diameter; hoses are specified by the inside diameter. For lines the wall thickness is important for determining the resistance of the fluid to the conveyance. Hose technology has evolved to improve reliability including varying layers of fiber or metallic braiding. The outer cover of hoses has evolved to address exterior abrasion.

To assist designers with properly sizing hydraulic lines and hoses some rules of thumb have been developed using fluid velocity as the indicator of resistance. The key is to not be too small as to cause excessive pressure drop and power losses. Being too large generates excess costs and potential difficulty in routing the larger lines and hoses. Some fluid velocity recommendations for sizing lines and hoses are as follows:

Suction: 0.6-1.2 m/s (2-4 ft/s)
Return: 3-4.5 m/s (10-15 ft/s)
Medium pressure: 4.5-6.1 m/s (15-20 ft/s)
High pressure: 6.1-7.6 m/s (20-25 ft/s)

These guidelines have evolved through internal experience at Deere in conjunction with tubing and hose suppliers. These recommendations apply to hydraulic flow in general, both on the tractor and on the implement.

Power Beyond

An option to using the tractor remote control valve is a “power beyond” connection. Power beyond is a direct connection between the pump and the implement around the remote control valve. Reasons for using power beyond include not having enough remote control valve connections, the inability of the remote control valve to provide satisfactory control, and that the individual remote control valves restrict flow too much. Power beyond coupler sizes have recommendations per standard so that they do not become significant performance inhibitors (ISO, 2005b).

Using power beyond requires that some sort of control valve be part of the implement. An example of where this may be beneficial is when the tractor has mechanical control valves, but the control on the implement utilizes electrohydraulics. Essentially, the implement requires a valve with a higher level of sophistication and control than the tractor is able to provide.

Matching Components

In order to optimally perform, the hydraulics on the implement need to be matched with the hydraulics on the tractor. Oftentimes with hydraulic cylinders this may not be a big deal because the time actually required to lift is short. However, sometimes reaction time is important or negatively noticeable.

More often, matching hydraulics is more important with continuous-flow applications. Hydraulic motors on planters and air seeders are such applications. One problem is that there are many different combinations of tractors and implements which makes it extremely difficult to match directly.

To accomplish this matching, an impedance-matching device is required. Impedance involves a flow or through variable and a pushing or across variable and their relationship to one another. These impedance variables occur in pairs such as pressure-flow, torque-speed, and voltage-current. The output impedance of a component is always a downward sloping curve similar to what has been shown on the pressure-flow diagrams. The input impedance to the next component is always an upward sloping curve when superimposed on the pressure flow diagram (fig. 21).

For an automobile, to match the output impedance of an engine with the input impedance of the driveline and wheels which actually move the auto, a transmission provides the impedance match. After all, the impedance of the engine and the driveline depend upon the engine speed and vehicle speed, respectively.

For a hydraulic system we have the output impedance of the hydraulic pump and the input impedance of the hydraulic motors. Again, the impedance depends upon the pump speed (flow rate) and the motor speed. In this case, the pump compensator and remote control valve provides the impedance matching.

Hydraulic motors on a planter or air seeder are sized to provide the appropriate amount of air flow. Typically, components are available in predetermined size increments for component suppliers. The remote control valve provides improvements in the matching. This is compounded when combined with using two pump systems to divide the duties of the system, as discussed above.

Future Trends

Tractors and implements are growing in size and equipment designers and customers are finding ways to use the increased power. At the moment, the hydraulic pressure to the implement is limited by standard at 20,500 kPa (3000 psi). However, there may be a point where there is an increase in the permissible pressure level. The question is to the level of protection required for implements.

The other hydraulic power parameter is hydraulic flow. This can and probably will continue to increase. Usage of split systems, i.e., multiple hydraulic pumps operating at different pressures, seems to be a trend. From a cost point of view, larger pumps are less cost effective because of lower production volumes. Smaller pumps tend to be more cost effective and are able to produce hydraulic power with reduced losses by more closely matching the system needs.

Increasingly, implements are being developed which have valves and feedback devices with their own control logic. Using ISO BUS, the implement communicates with the tractor integrating the implement and tractor control.

Electrical Power Interface

Introduction

In the last decade the agricultural industry has seen increasing levels of precision farming and automated equipment operation. Conventional tractor power interfaces, mechanical or hydraulic, are increasingly controlled and automated to provide increased value to the farmers' operations.

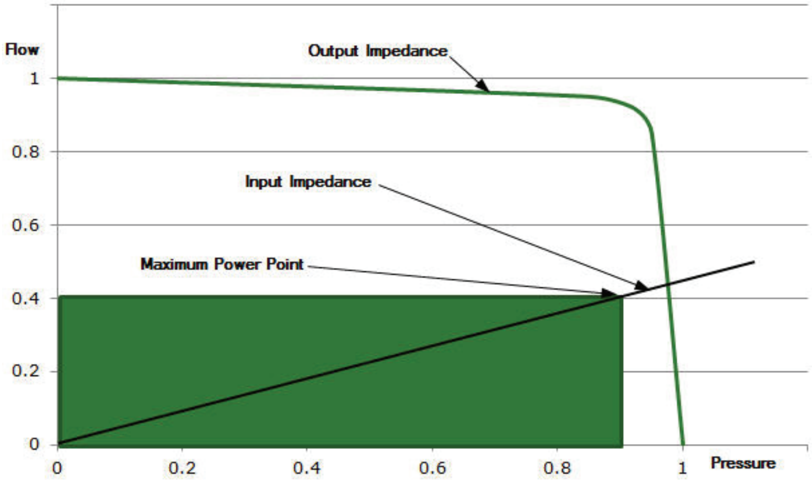

Figure 21. Impedance-matching hydraulic components.

Figure 22. Farmall 450 with IH ElectrAll, 1954.

Figure 23. Type plate, Electrall.

Figure 24. PTO-driven generator, retrofit power generation device.

Compared to mechanical (PTO) and hydraulic interfaces, the transfer of electric power has the potential to improve controllability (control of torque or speed) of an implement drive and to simplify the power distribution on the implement.

Electric Drive System

A first approach was initiated about 60 years ago, in 1954 when IH introduced the IH Farmall 450 with an integrated electric power generator called the IH ElectrAll system (fig. 22). The generator provided up to 10 kW of electric power, available for an agricultural implement, e.g. a square baler, or even as an uninterruptable power supply.

To arrive at a reasonable power level was the increase of voltage (208 V 3~AC) and the design of the generator for, in these days, a relatively high rotational speed of 3600 rpm (fig. 23). The building block set IH introduced even contained a retrofit solution to generate electric power via a PTO-driven machine (fig. 24).

The ElectrAll system demonstrated some benefits in respect to power distribution, but ultimately it was not successful in the marketplace. Without the appropriate power electronics (consider these “inverters” to represent “electric control valves”) and the complementing advantage of electric drives, increased controllability was not yet realized.

The breakthrough for electric drive systems with increased controllability was triggered by the availability of high power density transistors, called IGBTs (isolated gate bipolar transistors). Available since the late 1980s, IGBTs are the backbone of inverters. Broad application in industrial automation was followed by automotive volume products starting in the early 2000s.

In the meantime, electrification technology has been adapted for off-road equipment. John Deere introduced the 7430/7530 EPremium tractors with high voltage engine auxiliaries to the public in 2007. The 7430/7530 EPremium was the first series tractor of its kind, representing a new way of power generation and distribution: an on-board, integrated high voltage power generation system.

Electric Systems on Tractors

Legacy Systems on Ag Equipment

The common electric systems on self-propelled agricultural equipment are based on a alternator-type power source. In order to ensure a start of the combustion engine, a 12 V battery is applied to power a starter, which is an electric motor applying torque via a gear set to the engine’s flywheel. Standard alternators are belt driven with a gear ratio typically I = 3:1 to 5:1 relative to the combustion engine’s speed, and are usually air-cooled machines with a current rating of 90 to 200 A. Given their output voltage is 14 V (14 V are needed to charge 12 V lead acid batteries), the power output can be calculated as

$$P = V \times I$$

where

P = electric power output of the alternator, W

V = terminal voltage of the alternator, V

I = output current of the alternator, A

That leads to an alternator output power of 1260 to 2800 W. The alternator provides power to all on-board electrical

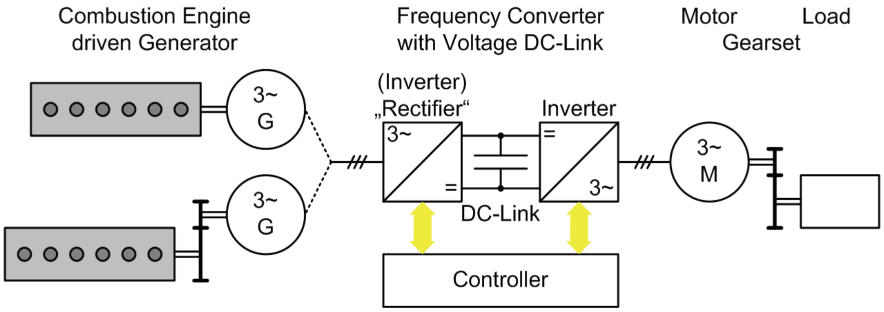

Figure 25. Schematic of an electric drive system.

loads, lights, electronic control units, etc.

If power is to be provided to agricultural implements on a 12 V level, ISO 1724 connectors (see ISO, 2003), the standard interface for lights, and the ISOBUS connector (see ISO, 2007b) are used. This combination of a CAN-based data interface and a 60 A capable power interface are used for power transfer.

The overall power available for implements out of the legacy 12 V system is basically limited by the capabilities of alternators and the electric current required. Since the electric current drives the conductor size and therefore weight, it also drives the space and costs of an electric drive system.

Voltage Levels

Basically for mobile machinery applications two voltage classes are considered:

- Class A: <50 VAC, <75 VDC, also covering 12 V systems; and
- Class B: 50 to 1000 VAC; 75 to1500 VDC.

Class B voltage regulations are covered by the "low voltage directive" (EU, 2006). Since the term "low voltage" defined relative to cross-country power lines is easily misunderstood, the automotive industry commonly uses the term HV ("higher voltage") to characterize systems beyond the common 12 V and 24 V on-board systems.

Electric Drive System Architecture

In mobile applications, electric generators are commonly powered by combustion engines. The generator is either mechanically linked to the crankshaft directly or powered through a transmission (fig. 25).

In order to compensate for changes in rotational speed and therefore in output voltage and frequency of the generator, a first inverter is applied. Just using a passive rectifier, the common approach in an industrial inverter being powered out of a "rigid" (voltage and frequency are "rigid" = constant) grid, would end in a variable DC-link voltage, a function of engine rpm. Out of this DC-link, a second inverter that is dedicated to the load is applied to power the electric motor. This motor is driving a load either directly or via a transmission or gear set.

John Deere 7430/7530 EPremium

In everyday language the terms electric "motor" and "generator" are used to describe the specific application of an electric machine. Electric machines have the particular advantage of being operational in either positive or negative direction while providing accelerating or braking torque. Basically, the electric machine's design itself is independent of its actual application. It's just converting electric current into torque or vice versa—a reason that calling both generators and motors electric "machines," as

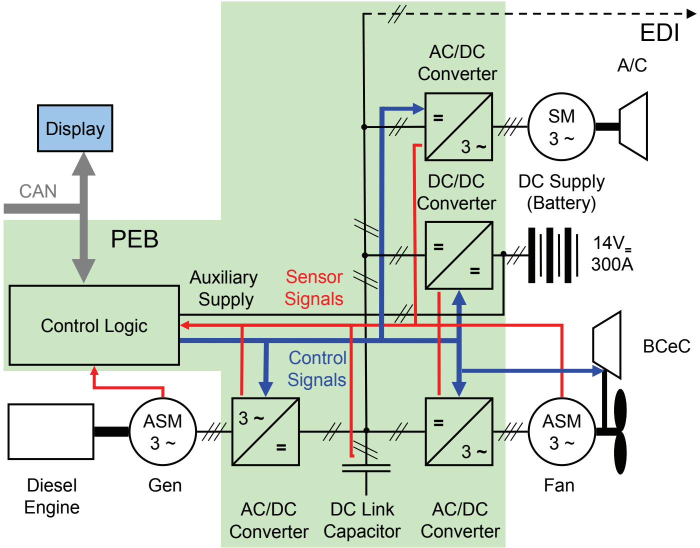

Figure 26. John Deere 7430/7530 EPremium, overview.

Figure 27. Flywheel mount AC induction generator.

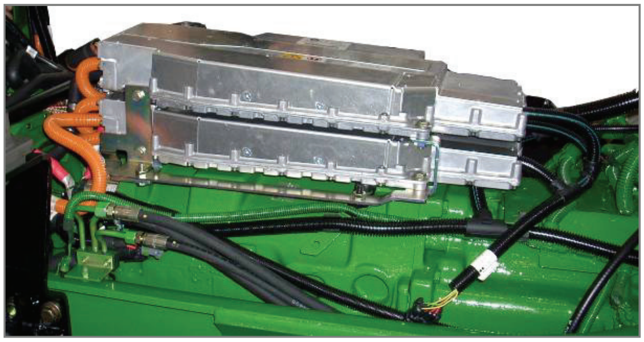

Figure 28. Power electronics that control and process the electric power on the EPremium.

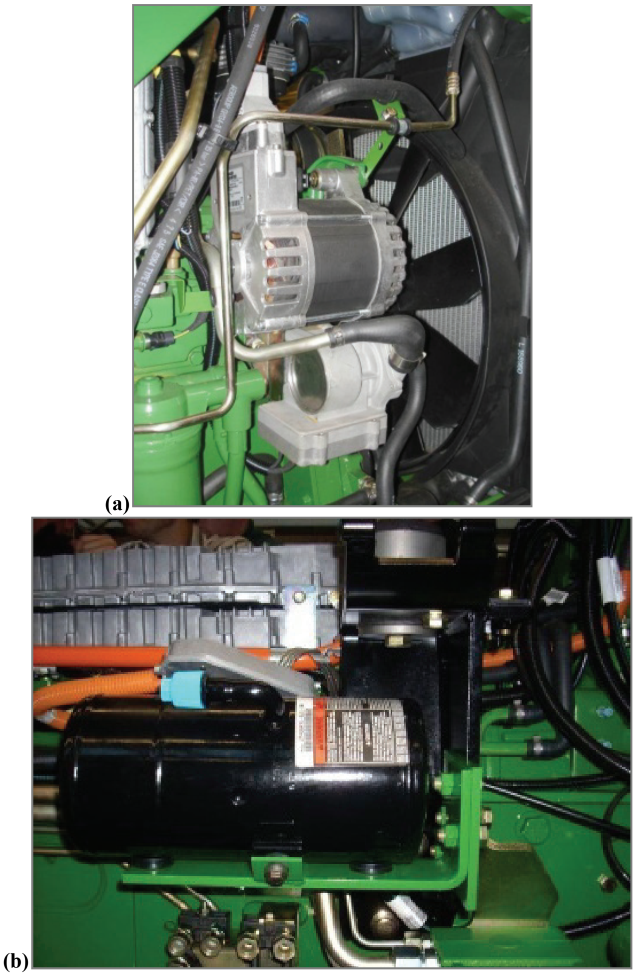

Figure 29. Electric drive components on the EPremium: (a) 10 kW fan motor and (b) electric motor for the air conditioning compressor.

done within this Lecture, is appropriate. An electric machine is actually a simple torque source, using the Lorentz or the reluctance effect, or both, to produce torque in its air gap. The torque itself depends on the current in the coil windings of the machine and the surface area of its air gap.

In 2007 John Deere introduced the first agricultural tractor having HV engine auxiliaries, the 7430/7530 EPremium (fig. 26). On these tractors a 20 kW AC induction generator is mounted directly to the engine flywheel.

Whereas the flywheel-mount generator (fig. 27) produces 20 kW at 1800 rpm rotational speed, the electric motor for the radiator fan operates at 10,000 rpm rated speed and drives the fan via a belt drive with a maximum of 10 kW. The variability of the radiator fan drive controls its power consumption to the level required.

Shown below are a few electrified devices on the EPremium. Figure 28 shows the power electronics that control and process the electric power. Figure 29 shows the 10 kW fan motor and electric motor for the air conditioning compressor.

Machine Torque Speed Curve

A good understanding of any electric machine includes knowing its torque speed characteristics. In figure 30, an AC electric machine is used as an example to illustrate the basic torque speed curve.

First, the rated output power is defined as the product of rated torque and rated speed. The electric machine torque increases as a function of electric current. Below the rated speed, the electric machine can deliver torque up to its rated value. Specifically, at or near zero speed, the electric machine can already output rated torque. When maintaining rated torque, the electric machine output power increases linearly with the speed.

Going above rated speed, the electric machine reaches a constant power region. In this region, the output power does not change while the torque capability decreases with the speed. The width of this constant power region depends on machine type and machine design. It needs to match the requirement of the specific application.

Beyond the corner point, where constant power cannot be supported anymore, the electric machine torque capability drops faster than the increase in speed. Also, the electric machine has an inherent speed limit that is mainly determined by the mechanical strength of its parts. Operating beyond this point may compromise the its mechanical integrity.

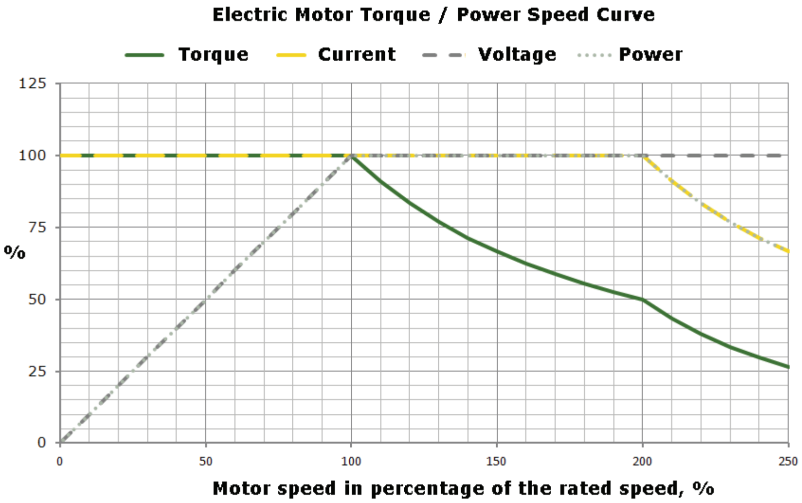

Figure 30. Electric motor (machine) torque speed/power curve.

Overview of the Tractor-Implement Electrification System

A tractor-implement electrification system (see fig. 31) consists of components of both tractor and implement. Included on the tractor are the generator, controllers needed for the generator and the implement motors (rectifier and inverters), cooling circuits for these electric components, harnesses, and an appropriate power interface. Key components on the implement side include the implement job controller, implement motor(s), high voltage interface plug(s), and the means to preprocess raw electric load information and signals, depending on the system configuration.

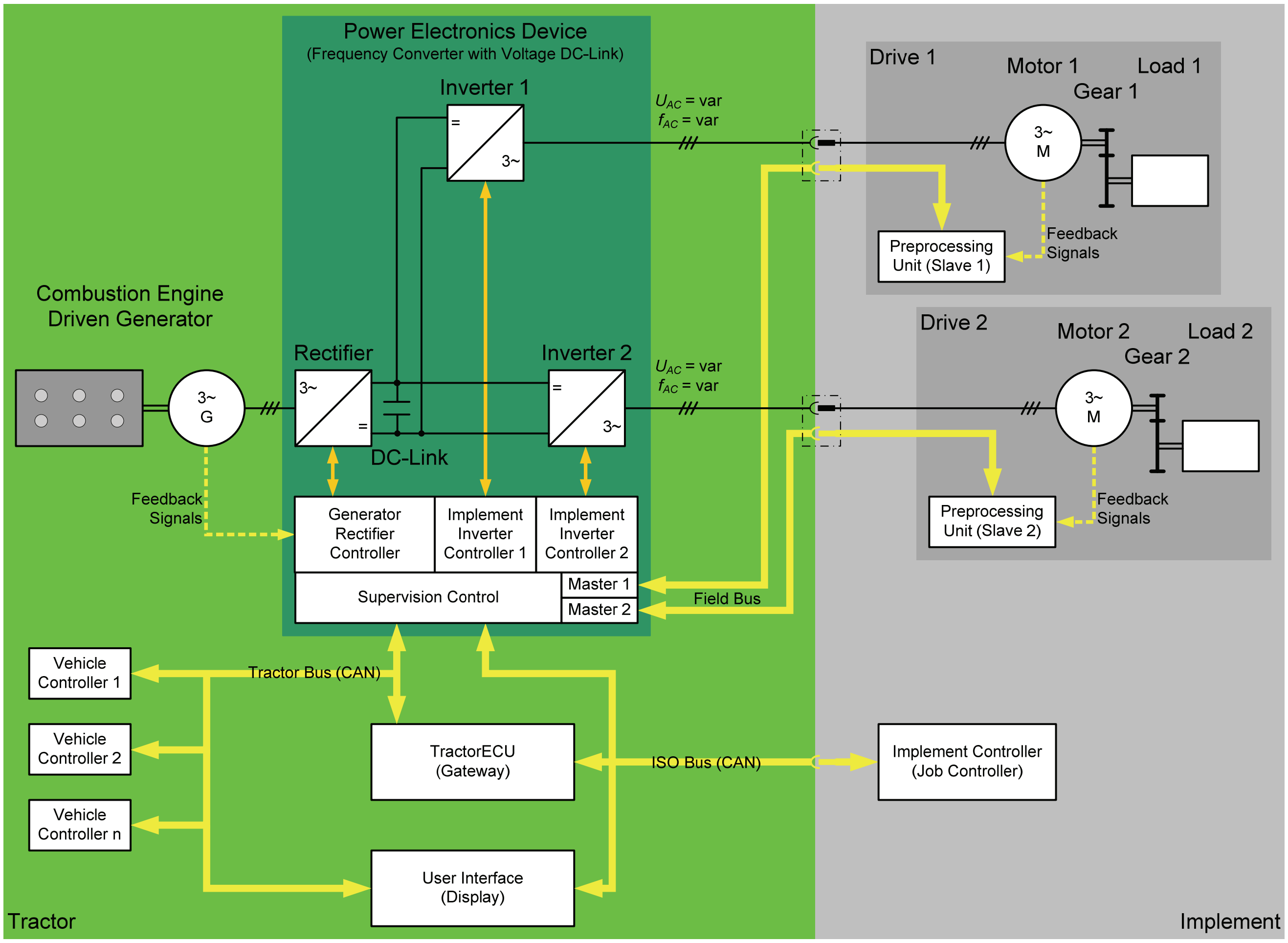

Figure 31. System block diagram of tractor-implement electrification.

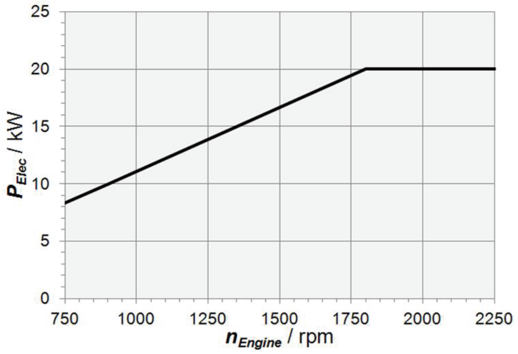

Figure 32. Power available to implements vs. engine speed.

ISOBUS class III capability (see ISO, 2011) on implements is required in order to ensure that both ISOBUS function-level features and electric-drive features are available on the tractor-implement system.

Power Generation

The rest of this Lecture will introduce the John Deere 6210RE system, detailing its power generation, controller architecture and communication, connector and harnesses. An overview of electrified implements and field experience with the 6210RE tractor is also presented.

The currently used generator is designed to provide up to 20 kW of electric power in collaboration with the DC-link control at a level of 700 V. The engine flywheel mounted electric machine is a 3~AC squirrel-cage induction machine, already proven with the 7430/7530 EPremium series. The power (fig.32) available depends on the demand of external implement loads continuously in the field.

The rated voltage of the power-generating electric machine is 480 VAC, actively rectified by an inverter (power electronics system) to the 700 VDC of the DC-link. Out of this DC-link either a corresponding DC-load or another inverter can be fed with electric power. On the 6210RE, an inverter was chosen to provide the most flexibility in respect to the implement's electric architecture.

The implement applications introduced in this Lecture take advantage of the AC closed-loop capability of the 6210RE system, using the tractor-integrated power-conditioning device, the inverter, to control the electric machine's operation and therefore the actual application. The 6210RE tractor architecture also allows the support of AC open-loop systems or even pure DC loads. The flywheel-mounted electric machine and the power electronics are liquid cooled, using a dedicated coolant circuit.

Implement Drive Control

Meeting the needs of the first applications, closed-loop control with two operational modes appeared to be most versatile: torque and speed control mode for permanent magnet synchronous machines (PMSM), and an electric machine type with high torque density and low power losses. Additional modes (such as AC open loop, DC, or 230 V/400 V at 50 Hz to support the needs of an uninterruptable power supply) are not maintained with the system introduction, but can be upgraded by software. Other types of electric machines can be supported with dedicated control software in the future.

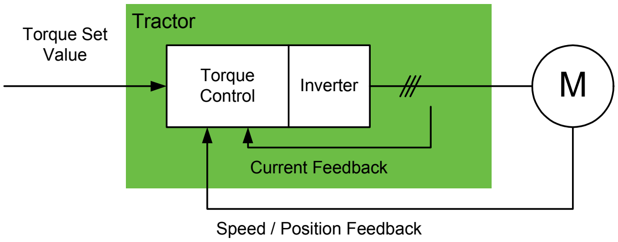

Figure 33. Closed-loop torque control.

The communication is based on specifications available from IEC61800-7-201 (IEC, 2007). Therefore, the interface provides a wide range of parameters to set up the tractor-located electric machine control by the implement-located job controller through the ISOBUS. The implement controller also sends the command values to the drive control and receives needed feedback signals such as actual speed or actual torque. These feedback values and their accuracy and repeatability enable the implement controller to provide special features—such as mass-flow control on a spreader—to the customer.

In order to realize an efficient closed-loop control, feedback values from the implement load (such as speed or position of the PMSM) are needed. Therefore, interface-integrated, real-time, field-bus capable contacts are used in conjunction with an appropriate Ethernet-base bus system.

Torque Control Mode

The torque control (current control) provides the potential for, e.g., traction applications (fig. 33). The commanded torque, sent through the ISOBUS, is processed within the control and will be limited in regards to slope and maximum torque. Other physical parameters of the load are necessary as well, to set up sufficient control with load-specific default parameters. Nevertheless, the implement controller is able to modify independently the torque controller's proportional gain and reset time. For a sufficient closed-loop machine control, position feedback as well the actual current of the PMSM is needed with a high repetition rate.

Speed Control Mode

The speed control (fig. 34) provides the potential for a wide range of applications, such as fertilizer spreaders or rakes. The commanded speed is processed similarly to the commanded torque within the speed control loop. Compared to conventional drive systems (by cardan shafts or hydraulics) the electric drive enables an easy change of the rotational direction without additional effort, just by sending the related speed command. Via ISOBUS, the acceleration and deceleration ratios, as well minimum and maximum speed, are set for control. Load-dependent default values for the controller parameters (gain and reset time) are provided. Also, specially tuned parameters can be sent by the implement controller. The output of the speed controller is the input of the subordinated torque control (see above). The controller supports the process control on

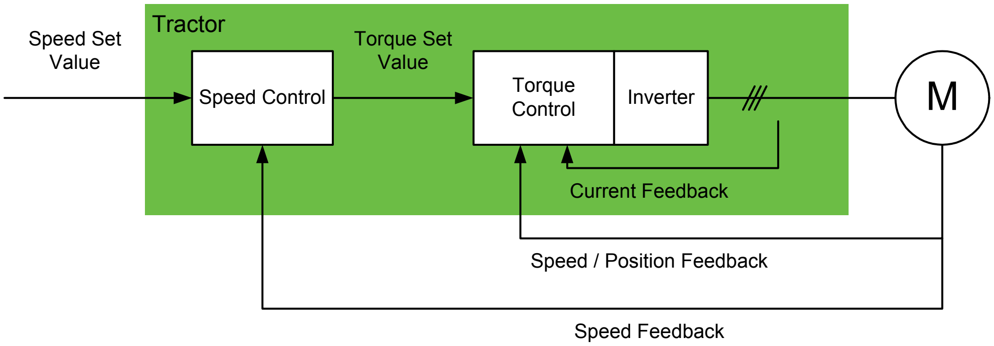

Figure 34. Closed loop speed control.

board the implement by sending feedback values as status information of the load. This feedback is generated without extra sensors, e.g., torque transducers.

Within the 6210RE architecture a torque feedback is available based on inverter internal current measurement. Measurements show that the accuracy and repeatability of the torque feedback in correlation with a calibration routine meets or exceeds the limits of common solutions (fig. 35). In the given example, 6210RE torque feedback processed with a calibration routine leads to final torque estimation accuracy close to 0.1 Nm, with good repeatability at different load conditions.

The internal speed feedback of the load (measured at the electric machine directly or calculated by processing the position feedback) is forwarded via ISOBUS to the process control within the implement controller, too.

Protection and Safety Measures

Given a voltage level higher than the common 12 V or 24 V systems, appropriate protection measures have to be provided. Despite tractor-specific guidelines and standards not being available regarding high voltage systems, standards or final drafts exist for comparable systems in other industries, e.g. ISO 6469 (ISO, 2011) or ECE-R100 (UN/ECE, 2011) represent a starting point.

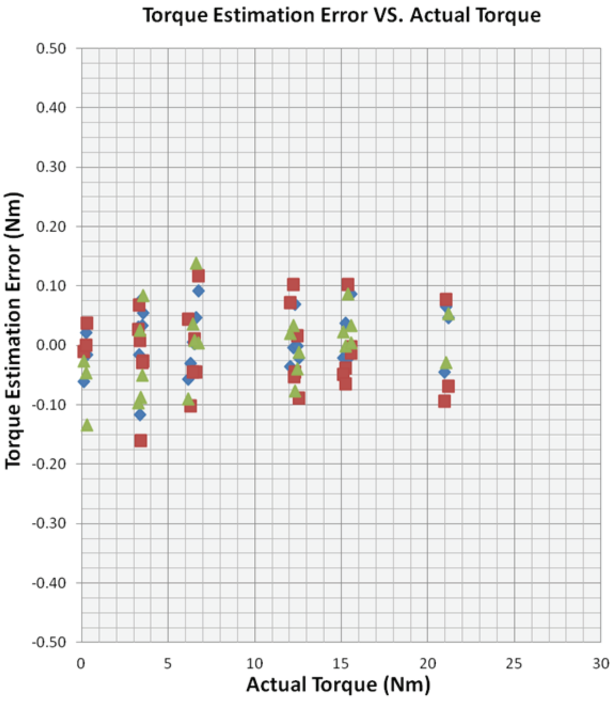

Figure 35. Torque feedback. Different colors represent measurement taken at different operating conditions, e.g., speed.

The 6210RE system incorporates several common protection measures. First, all high voltage cables are adequately insulated and can easily be recognized given their orange color. Also, the power electronics are covered by a solid housing installed between cabin and transmission, a remote location hard to access without intention. The same applies to the engine-mounted generator, which is only accessible after dismounting the cab or disassembling the engine. Another safety feature is that the system does not contain relevant energy storage at higher voltage levels; in particular there is no high voltage battery. Therefore, the system is de-energized when the engine is off.

The high voltage electric system is realized as an IT system (see IEC 60364-4-41; IEC, 2005), comparable to the proven state of the art in automotive hybrid product. An IT system is a configuration where live parts are isolated from the environment, particularly from the chassis. Each relevant conductive part of the system—which is no live part—is connected to the protective equipotential bonding conductor. The complete system establishes at least protection class IP67 (see IEC 60529; IEC, 2001). Exceptions are open, non-connected implement connectors. According to ECE R100 (UN/ECE, 2011), they are designed to meet IPxxB, being touch proof. Finally, the usage of the high-speed field bus is not limited to control purposes. It is also used for identification of the actual load present per connector. The system will only accept connected authorized loads, otherwise the related output will not be energized.

Power Interface

The new high voltage electric power interface complements existing mechanical and hydraulic interfaces. The interface is designed according to the latest status discussed within the AEF (Agricultural Electronics Foundation).

It supports both DC and three phase AC electric power transfer, with maximum operating voltage of 750 VDC or 480 VAC. The power contacts can support up to 200 A current, and beyond depending on the environment conditions.

Figure 36. The high voltage electric power interface.

Figure 37. Implement applications in the field.

Equipotential bonding conductor pins are provided on these interfaces, to allow easy connections between tractors and implements. Several other pins are available for 12/24 V power transfer and signal communications. Among them is a shielded four-pin interface compliant with the high-speed field bus. In the 6210RE design, this bus is used to transmit implement load information, such as electric machine position and temperature, to the tractor.

On the 6210RE, two independently controlled receptacles are provided (fig. 36). Each of the two is capable of providing up to 20 kW of electric power, until the total generator power is reached. Because the power contacts on the interface are rated for much higher current and power, the connector interfaces themselves do not need to be changed for future increases in tractor electric power.

Implements and Field Experience

Several companies have started development of electric implements and presented their machines at various events. Extensive field evaluation of the 6210RE tractor with implements is ongoing, in order to test and refine the electrified tractor-implement system. This allows validation of improved control with enhanced precision and productivity, with reduction in input and operation cost. Figure 37 shows a few electrified implements: a fertilizer spreader, trailer, and rake.

Conclusions

This Lecture began with a historical perspective of how mechanization improved the productivity of farmers, starting with steam engines, which transferred power through a belt to a threshing machine, to early tractors and the development of PTOs. The PTO enabled crop-processing machines to be powered via the PTO while moving through the field. Continuous, "live" PTOs allowed greater flexibility and control.

Hydraulics led to increased productivity of tractor-implement systems by allowing greater design flexibility and control, even with complex implements. Hydraulic flow can be used to operate multiple cylinders and to power hydraulic motors. With the advent of the CAN bus controls and power beyonds, implements are increasingly using smart valves and providing new options for implement controls and configurations. Matching tractor and implement systems reduces energy waste.

In the same way, electrical power systems are leading to increased options for controlling implements and allowing power to be sent to remote regions of the implement, where there may not be space to route hydraulic lines.

While electrical systems are the newest of the technologies, there likely will be need for PTOs and hydraulics for many years yet. Combining PTOs, hydraulics, and electrical systems together will lead to novel implement configurations and increased design flexibility.

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