TMEIC

We drive industry

TMdrive®-70

Selecting Variable Speed Drives for Flow Control

Reliability, Energy Savings, Lifetime Cost, Availability

metals | cranes | paper | cement | oil & gas | mining | utilities | rubber & plastics

Summary

This paper explains the cost savings obtained when flow is varied by changing the speed of a pump or fan instead of using a control valve or damper. After illustrating several ways to vary pump or fan speed, two very different methods are discussed in detail: hydraulic drives and electric drives. Both systems work well, and each system has good reliability and comparable installed cost. However, the electric drive has higher energy efficiency than the hydraulic drive counterpart.

An electrical variable frequency drive (EVFD) has advantages over a corresponding hydraulic variable speed drive (HVSD) in the following situations:

- The efficiency of the electric drive is superior over the whole speed range. Over the 70 to 100% speed range the electric drive has an efficiency advantage over the typical HVSD of 4-5% on the average. Below 80% speed, the EVFD advantage is quite large.
- Because of the higher efficiency, considerable energy savings can be realized by installing an electric VFD. In the 10,000 hp example studied later, the savings are $230,000.00 per year. With energy and electricity costs rising, these savings will increase year by year.
- With an EVFD, the motor current is always under control. There are no locked-rotor starting currents, excessive temperatures, or mechanical stresses put on the motor. With constant speed motors used with most HVSDs, the driven equipment is subjected to hard starts, and the heat, caused by the starting current, degrades the motor insulation and shortens its life.
- Some large motors cannot be started across the utility line because of large voltage drop in the supply. An EVFD eliminates high utility currents and disruptive voltage drops by controlling motor current at startup while delivering torque required by the load.
- Some applications use two or more pumps in parallel, some running at constant speed, while the others are under variable speed control to produce the desired process flow. For example, three pumps can share one or two EVFDs. An HVSD is dedicated to each motor, so three are required.
- EVFDs can increase the load carrying capability of a system bus with a given switchgear rating. Starting currents are low in magnitude and of relatively high power factor when compared to across-the-line starting of conventional, squirrel-cage induction and synchronous motors. Contributions by motors to bus short circuit currents under faults are greatly reduced by EVFDs when compared to across-the-line connections.
- Electric drives can be configured with a fail-safe characteristic. In the event of an EVFD failure, a bypass contactor can be closed, driving the pump at full speed. Therefore a failure of an EVFD will not take down the plant, where failure of a HVSD probably would.
- If periods of full speed operation are required, the EVFD can be smoothly bypassed with optional synchronized bypass circuitry and put across the line, so there is no power lost in drive efficiency at full speed. An HVSD is dedicated to its machine and cannot be bypassed.

Since the installed costs of the EVFD and HVSD are roughly comparable, and the electrical VFD provides advantages including significant energy savings, the EVFD is usually the best choice.

Four Main Methods of Flow Control

Controlling flow is necessary in many process control and machinery control applications. In industry, some of the more common applications include induced draft fans on boilers and cement kilns, process and pipeline compressors, water circulation pumps, and boiler feed pumps. In most cases, a variable speed pump is a better solution than using a flow control valve to throttle the flow.

There are four main methods of controlling flow, which are summarized in this section and illustrated in Figure 1.

Flow Control Types	Power Supply	Power Control / Conversion	Mechanical Power Conversion	Mechanical Power Coupling	Driven Pump, Fan, or Compressor	Variable Output Flow	Strengths	Limitations
Valve Control	Three-Phase Electric Supply		Electric Motor Fixed speed	1:1	Fixed speed	Bypass control or Valve or Damper Control	Fast acting for good flow control. Valve is inexpensive.	Large energy loss in throttling valve or damper. Mechanical maintenance issues.
Mechanical Transmission Control	Three-Phase Electric Supply		Electric Motor Fixed speed	1: N Hydraulic Var. Speed Control	Variable speed		Can increase speed above motor base RPM. Compact. Efficient at top end of range.	Efficiency good but less than electric VSD. Hard to retrofit due to space required.
Steam or Fuel Control	Steam, Gas, or Kerosene	Fuel or Steam Control	Turbine Variable speed	1:1	Variable speed		Can operate at high speed. Steam or gas may cost less than electric power.	Expensive custom turbine
Electric Frequency Control	Three-Phase Electric Supply	Electric Variable Frequency Drive	Electric Motor Variable speed	1:1	Variable speed		Highest efficiency. Speeds up to 4,000 rpm without gearbox. High reliability. Protects motor & plant power. Application & retrofit flexibility.	More total floor space. Air conditioned area. Power system P.F. & Harmonics

Control — Control component

Figure 1. The Main Methods of Controlling Flow

Valve or Damper Control

Traditionally, flow was commonly controlled using a fixed speed motor and a valve or damper, which closes off the pipe or duct and throttles the flow. Characteristics of valve or damper controlled systems include the following:

- Valves or dampers, especially smaller ones, change flow quickly, which is required for good process control.
- There are large energy losses due to the valve or damper. Mechanical flow control can be compared to driving with the emergency brake engaged.
- Constant speed motors are subjected to hard starts, and the heat and mechanical stress caused by the starting current degrades the motor insulation and shortens its life.
- High velocity through the valve causes deterioration, and regular valve maintenance is required.

Mechanical Hydraulic Transmission

A hydraulic variable speed drive (HVSD), driven by a fixed speed motor, can be used to vary the speed of the pump, fan, or compressor. A constant speed electric motor drives the HVSD, which varies its output speed and the speed of the load. Several characteristics of hydraulic transmission include:

- Valve throttling energy losses are completely avoided.
- Smooth speed control below and above the motor speed can be obtained.
- Good efficiency over the upper part of the speed range.
- Energy losses at the lower flows and speeds are significant, especially at less than 80% speed.

Turbine Speed Control

This method changes flow by changing the speed of the steam or gas turbine driving the pump, fan, or compressor. Key points include:

- Valve throttling energy losses are avoided.
- High speeds can be achieved, which is necessary for boiler feed pumps and axial flow compressors.
- The turbine is expensive, especially if it is custom designed.
- If a gas turbine is used, there can be air pollution concerns.
- Turbine mechanical maintenance can be significant.

Electric Frequency Control

An electric variable frequency drive (EVFD) system can be used to change the voltage and frequency of the three-phase AC supply to a motor and thereby control its speed. Key comparison points include:

- This system avoids valve throttling energy losses and has a higher efficiency than a hydraulic drive over the entire speed range.
- With induction motors, the top design speed is usually limited to 110% of the rated motor. speed; therefore, significantly higher speeds require a gearbox.
- If the load is to run at less than full speed for extended periods, the EVFD can be a better solution than valve control or the hydraulic transmission because of the energy savings.
- With an EVFD, the motor current is always under control. There are no locked rotor starting currents, high temperatures, or mechanical starting stresses put on the motor. Controlled motor current means that motor heating will not limit the quantity or frequency of motor starts.

The remaining sections of this paper will explain these points in more detail.

Energy Losses in Control Valves or Dampers

Most flow control loops use a control valve, damper, or guide vanes to throttle the flow. This common method uses a constant speed motor connected to a fan or pump with a flow control valve. Although the control is good and the response is rapid, the valve causes a pressure drop resulting in significant energy loss. Figure 2 shows a system with mechanical flow control; points B & C refer to the corresponding points on the system curves shown in figure 3.

Figure 3 shows a typical motor operation curve with a pump or fan load. Rated flow and pressure are shown at point A. As the pressure head increases at fixed speed, flow decreases to 50% at point B. If downstream flow at a lower pressure level is required, say point C on the load curve, flow control dampers or a valve can reduce the net flow.

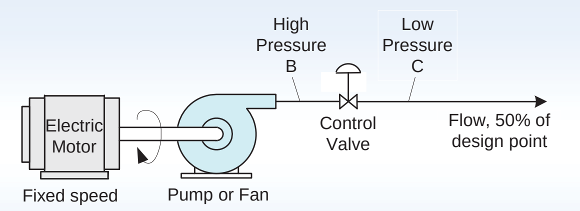

Figure 2. Flow Control Valve

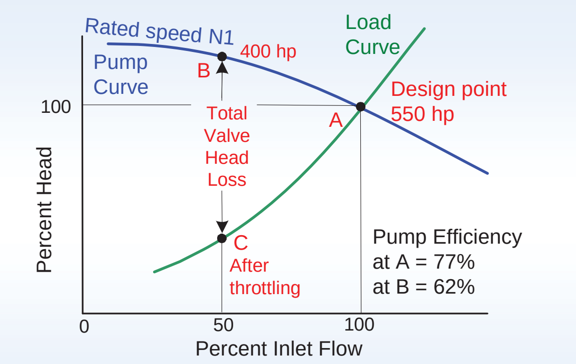

Figure 3. Head Loss Caused by Control Valve Throttling

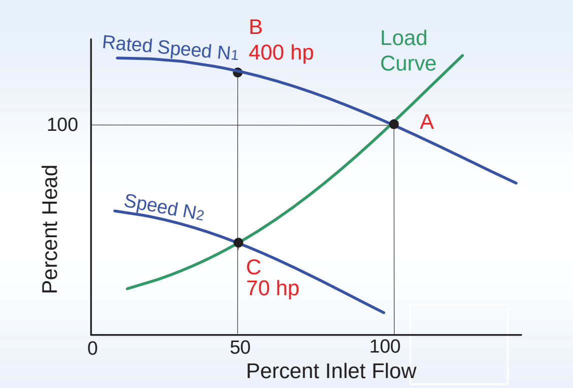

Figure 4. Reduced Motor Speed Eliminates Head Loss

Flow head is composed of pressure and velocity components. Point C is the head and flow downstream of the valve. Head is lost as pressure drops from B to C, and the lost energy is supplied by the motor. This energy lost over extended periods has an economic impact that can be quite large.

Variable Speed Control

A better system does not use the valve, instead it reduces the motor and system speed from N_1 down to N_2 at C on the pump or fan characteristic, as shown in Figure 4. At C, there is no throttling head loss or energy loss, and the pump is running at a higher efficiency than at B.

Example - Energy savings using a Variable Speed Drive

In this example, the pump was consuming 400 hp at B but at C is only consuming 70 hp, so the energy saved by not throttling is 330 hp. As a quick estimate, assume operation at point C for 60% of the time and at point A for 40% of the time. With 90% motor efficiency and power costs of $0.05 per kWh, annual savings would be just under $60,000. Significant! Of course the larger the motor the larger the savings would be, and they will probably go up with time. If a hydraulic VSD is used instead of an electrical VFD, the savings will be less because of the lower efficiency.

Understanding Hydraulic Variable Speed Drives

Hydraulic Drive Overview

Hydraulic variable speed drives (HVSD) are mechanical transmissions that mount between the motor and the pump or fan. HVSDs usually reduce the speed from motor to the load; however, some types can also increase the input speed. There are two types of hydraulic VSDs:

- **Turbo Couplings** – a simple, single-stage design, which can reduce the input speed but not increase it. Couplings have low power transmission efficiency at the lower speeds.
- **Multi-Stage Variable Speed Drives** – a more complex but more efficient design incorporating planetary gears to smoothly increase and decrease the output speed above or below the motor input speed.

Turbo Couplings-Principle of Operation

Turbo couplings are made by several vendors including Voith Turbo GmbH & Co., and Nelson, Liquid Drive Corporation. The turbo coupling is similar to the torque converter in an automobile automatic transmission. Referring to Figures 5 and 6, the primary wheel A has buckets around the circumference and is driven by the input shaft. The wheel is fed with oil from oil pump B, and centrifugal force throws the oil out to the periphery where the buckets sling the fluid into the secondary wheel.

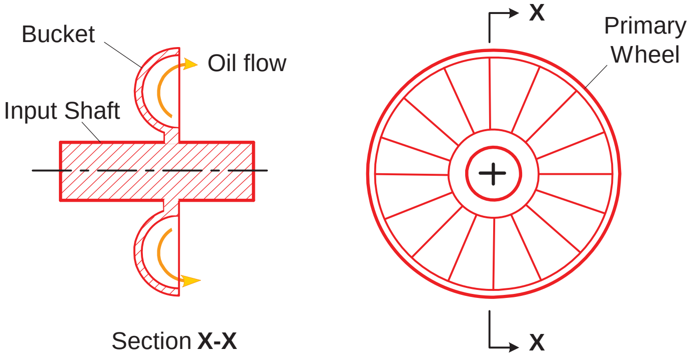

Figure 5. Rotating Primary Wheel Throws Oil Outwards into Secondary Wheel

The momentum of the oil impinging on the secondary buckets reacts with the secondary wheel C and turns the attached output shaft. With the coupling full of oil, the output shaft runs at close to the input shaft speed with small slip and high transmission efficiency.

Reducing Output Speed

Refer to Figure 6. To reduce the output shaft speed, a movable scoop tube D is dipped below the oil surface in the coupling to remove oil. As the oil is removed, the energy transfer between the driving (primary wheel) and driven (secondary wheel) decreases and the output speed drops. By moving the scoop tube, the output speed can be continuously varied down to about 20% of input speed. With a partially full coupling, the transmission efficiency is lower, so running at low speeds wastes energy. An oil cooler removes this waste energy and passes it to continuously supplied cooling water.

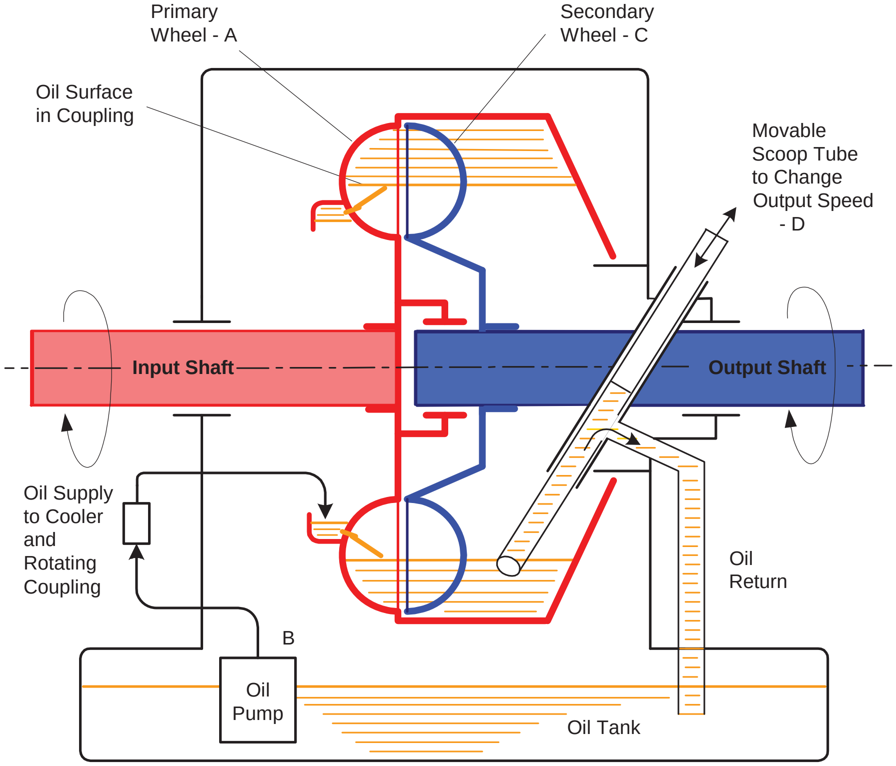

Figure 6. Hydraulic Variable Speed Turbo Coupling

Design Ranges

Various coupling designs offer power ranges of up to 10,000 kW, and speeds up to 5,000 rpm. One of the largest couplings offered runs at 900 rpm and transfers 10,000 kW. The transmission efficiency is 93% at 100% load, and drops down to about 74% efficiency at 50% load.

Summary of Turbo Coupling Features

Advantages:

- Moderate initial cost
- Good reliability
- Compact, often less than half the size of the electric motor
- As a retrofit, may not fit into existing installations with limited space near the motor and driven equipment

Limitations:

- At low speeds the coupling is inefficient and wastes energy. Costs are high for extended running at low speeds (see pg. 20)
- Cannot increase the input speed, only reduce it
- The coupling is located between the motor and the pump or fan, and must be aligned with both of them
- Cooling water must be continually supplied to the oil heat exchanger

Multi-Stage, Variable-Speed Drives - Principle of Operation

Hydraulic multi-stage variable-speed drives are more complicated than turbo couplings, offering a wider speed range and higher efficiency, but at a higher price. One example is the Vorecon® sold by Voith Turbo GmbH. The Vorecon type RWE has a planetary gear to drive the output shaft and a torque converter to take off power to drive the planetary gear carrier.

Planetary gear operation is illustrated in Figure 7. In the final stage of the Vorecon transmission, all the gears rotate, and the output speed can be increased or decreased by any amount determined by the number of teeth on the three gears and the speed of the two input gears. Table 1 describes how operation is affected by various combinations of fixed and movable gears in the assembly. Note that in the final stage of the Vorecon transmission all three groups of gears move; the inputs are to the ring and planet gear, and the sun gear is the output shaft.

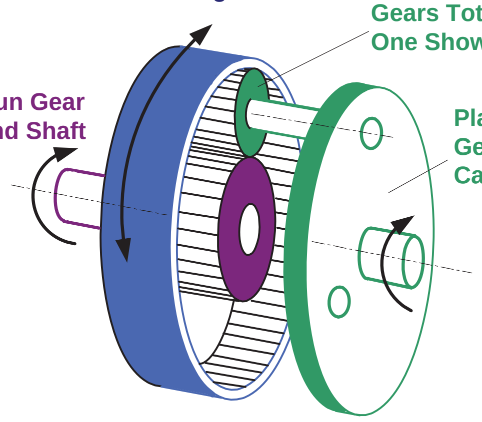

Figure 7. Diagram of Planetary Gear

Table 1. Various Combinations of Fixed and Movable Gears Available in Planetary Gear

	Gear Condition	Resulting Operation	Output Speed
1	**Fixed Outer Ring Gear**	Fixed speed ratio between Sun and Planet Carrier.	Increase or decrease input speed.
2	**Fixed Planet Carrier (with 3 planet gears)**	Fixed speed ratio between Sun and Ring gear.	Increase or decrease input speed.
3	**Fixed Sun Gear**	Fixed speed ratio between Planet Carrier and Ring gear.	Increase or decrease input speed.
4	**All Gears rotating - as with Vorecon output gears**	Infinitely variable speed ratio. Add or subtract two input speeds multiplied by the individual gear ratios.	Increase or decrease input speed, varied by Planet Carrier speed.

Figure 8 shows a torque converter with its rotating input wheel and output turbine. The torque converter uses centrifugal force to throw oil out of the buckets on the wheel and impinge it on turbine blades around the periphery of the wheel. These blades drive the power take off, which goes through a fixed gear and then to the planetary gear of the HVSD.

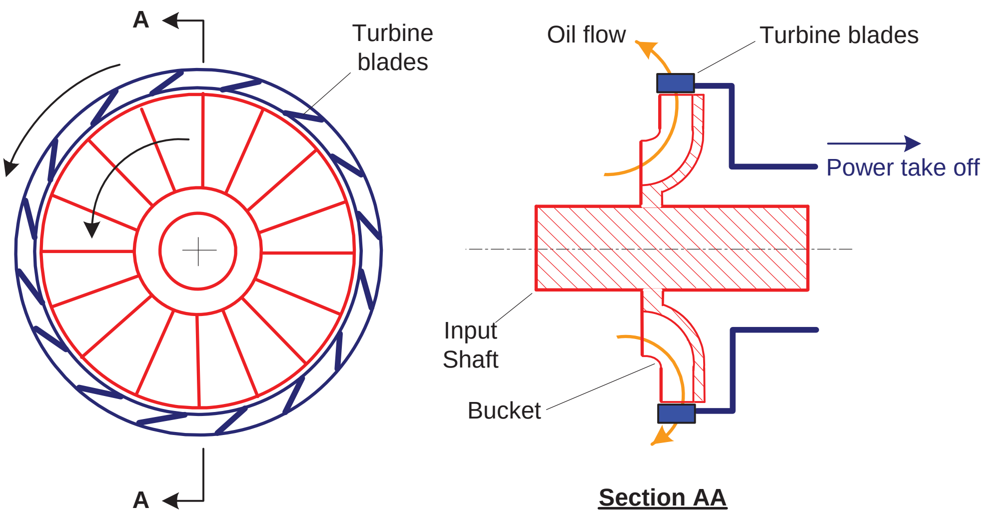

Figure 8. Power Take Off Through Turbine Blades for Speed Control

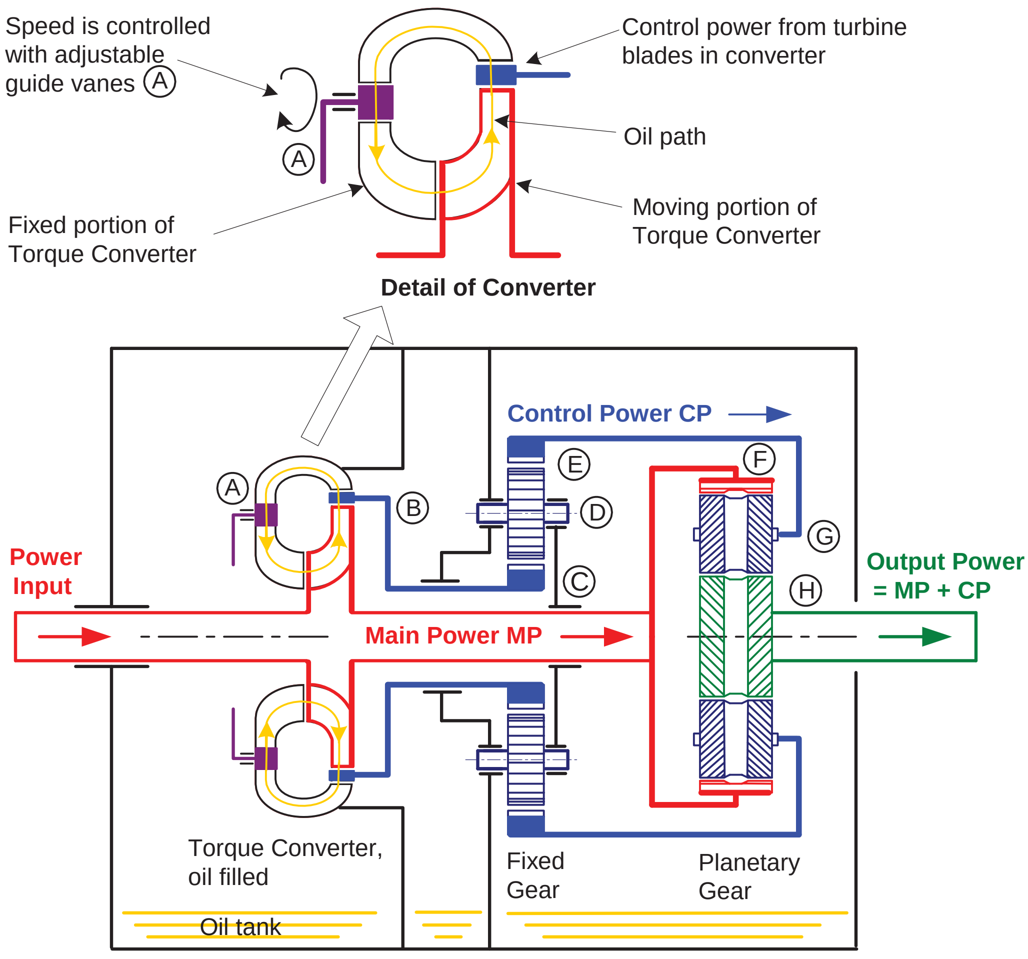

Figure 9. Hydraulic VSD Similar to Vorecon® Type RWE

Figure 9 shows the entire assembly of a torque converter and gearing of a multistage HVSD. By adjusting the guide vanes Ⓐ in the torque converter, the power take off speed at Ⓑ is varied. The power take off turns the control sun gear Ⓒ, which turns the ring gear Ⓔ through fixed planet gears Ⓓ (configuration 2 of Table 1). The main power MP and control power CP add in the final planetary gear acting through ring gear Ⓕ, planet gears Ⓖ, and sun gear Ⓗ (configuration 4 of Table 1). The sun gear output speed is the sum of the two input speeds multiplied by the individual gear ratios involved.

As noted in Table 1, one feature of the planetary gear is the ability to increase the speed above the input speed, something the turbo coupling of Figure 6 cannot do. Output speeds of several times the input are possible. By means of the guide vanes, the planetary carrier speed is adjusted to alter the output shaft speed. The practical adjustable speed range is approximately 60% to 100% of the maximum output speed.

Another key feature of the planetary gear is that the major part of the power is transmitted purely mechanically with little loss to the outer ring gear, (the red shaft), thus producing high efficiency for the entire unit. The efficiency is over 94% for output power levels between 75% and 100%. This translates to a speed range of approximately 90% to 100% for a fan or pump.

Wider Speed Range VSD

The Vorecon® type RWS has additional features that allow it to extend the low speed range and load below that of the type RWE. Such an HVSD is shown in Figure 10. Since the efficiency of the torque converter drops off below about 75% of design speed, the RWS adds a hydraulic adjustable brake to slow the power take off speed and thereby reduce the output speed, as shown in Figure 10. At the lower speeds when the brake is operating, the torque converter is drained so it does not supply power to the planetary carrier. Movable guide vanes in the brake vary the output speed.

Above about 75% speed, an automatic change-over takes place, which drains oil from the brake and fills the torque converter. For the higher speeds, the unit operates in a more efficient mode similar to the type RWE.

The RWS can regulate speed over a speed range from approximately 45% to 100% of the maximum output speed.

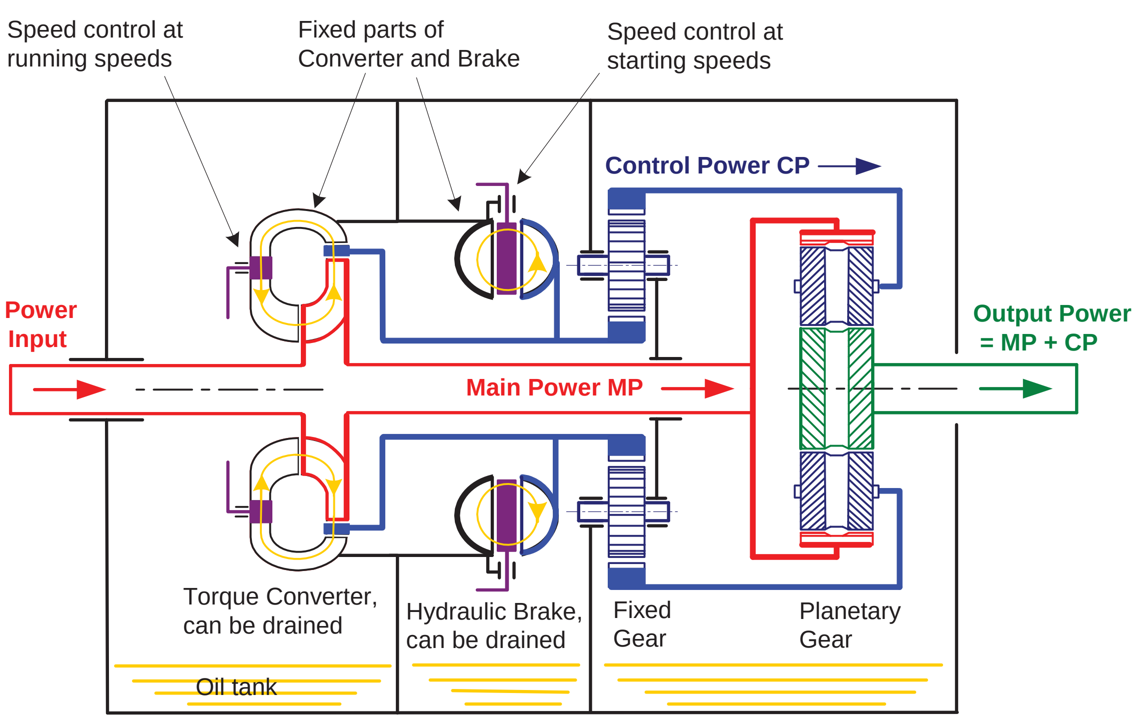

Figure 10. Hydraulic VSD with Wider Speed Range, Similar to Vorecon® Type RWS

Relieved Start-up VSD

The Vorecon® type RW looks like a type RWS but has an additional variable speed coupling on the input shaft at the front end, as shown in Figure 11. The coupling scoop tube allows operation at low speeds down to 10% of maximum speed. Since the coupling introduces a large speed slip, it reduces torque demand during motor start up. In spite of this, there is still a large current inrush to the motor. When the output speed is up to about 80%, the coupling is bypassed by operating a clutch, and speed is controlled by the torque converter as with the RWS. This allows output speeds to be varied from 80% to 100% of maximum speed with reasonable efficiency.

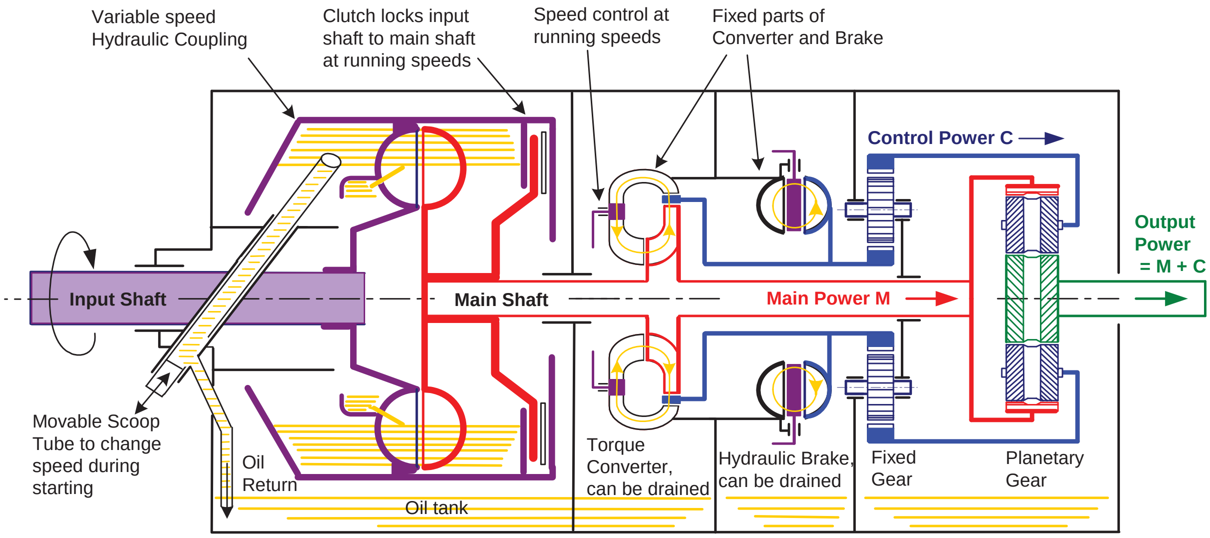

Figure 11. Hydraulic VSD with Wider Speed Range & Relieved Start-up, Similar to Vorecon Type RW

Electronic Controls

A typical HVSD has extensive electronic controls, so it is not just a mechanical transmission. For example, the type RW requires electronic and electrical equipment including most of the following:

- Electro hydraulic servo to position the coupling scoop tube, with servo amplifier and position feedback
- Electro hydraulic servo to position the torque converter guide vanes, with servo amplifier and position feedback
- Clutch control, based on speed feedback
- Vibration pickups (7) and one keyphasor
- Total of 12 RTD temperature sensors
- AC motor driven auxiliary lubricating pump
- Level transmitter
- Pressure transmitter
- Oil heaters
- Differential pressure switch for filter monitoring

Main Features of the Vorecon HVSDs:

The main features of the family of Vorecon drives are as follows:

Speed range:	Output speeds from 100 to 20,000 rpm
Power:	Transmitted powers from 1,000 kW to 50,000 kW (67,000 hp)
Efficiency:	About 94% from 100 to 90% speed (100 to 80% load), falling off at lower speeds (see pg. 19)
Space:	Photos of typical installations show the HVSD takes less space than the electric motor and about the same space as the compressor or pump being driven. A typical Vorecon had dimensions of H=123 in, L=128 in, and W=71 in.
Cooling:	Cooling water supply and return are piped to the HVSD cooler

Mounting:	The HVSD, motor, and compressor or pump are bolted to a common base plate.
Temperature:	No operating data available in publications.
Service:	Maintenance interval is claimed to be 8 years. Service requires specially trained personnel. The literature mentions a Mean Forced Outage time of 84 hours for the Vorecon.
Reliability:	The Mean Time Between Failure is claimed to be between 107,500 and 154,000 hours.

Understanding Electric Variable Frequency Drives

Electric variable frequency drives (EVFD) convert a fixed frequency three-phase power input to a variable frequency three-phase output to a motor. The output frequency can be greater or less than the input frequency, but generally the output frequency is less than or equal to the supply because of motor constraints. There are two main types of EVFDs:

- **Current Source** – the source converter produces a current, which supplies the load converter, such as a Load Commutated Inverter (LCI). The LCI is designed for synchronous motors.
- **Voltage Source** – the source converter produces a voltage, which supplies the Pulse Width Modulated (PWM) inverter, such as the TMdrive-70 and DB5i MV drives from TMEIC. The voltage source PWM drive is suitable for induction or synchronous motors.

Load Commutated Inverter LCI

The LCI current source type drive uses SCR (thyristor) power rectifier devices. The general circuit arrangement is shown in Figure 12.

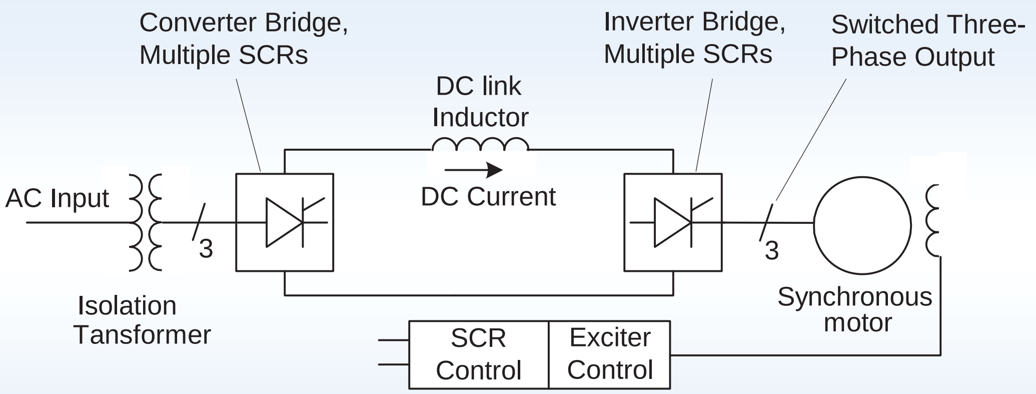

Figure 12. Simplified Current Source Load Commutated Inverter

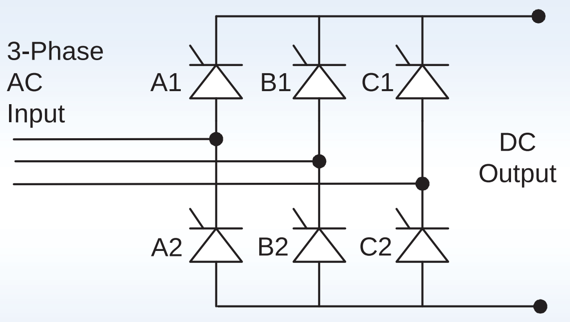

Figure 13. Simplified Converter Bridge

An incoming rectifier converter bridge, shown in simplified form in Figure 13, creates a regulated current in the dc link inductor. The level of current is regulated to match the motor current required to generate the torque needed by load. The output inverter bridge also uses SCRs to switch the current from phase-to-phase in the connected motor. The input section and inverter are fully regenerative, meaning they can pass power to or from the load.

The voltage output levels typical of LCI drives and motors are between 2300 and 4160 volts. Several SCR devices are used in series at positions A1 through C2 to achieve the needed voltage ratings.

Figure 14 shows a typical modern LCI power bridge assembly, with 6 SCRs in series, one of which is redundant. The SCRs in the converter bridge are water-cooled.

The leading power factor within the synchronous motor is used to provide energy to commutate (turn off) the SCR inverter switches; hence, the name LCI. LCI drives were the first Medium Voltage drive topology to be introduced, and they are still in current production.

.

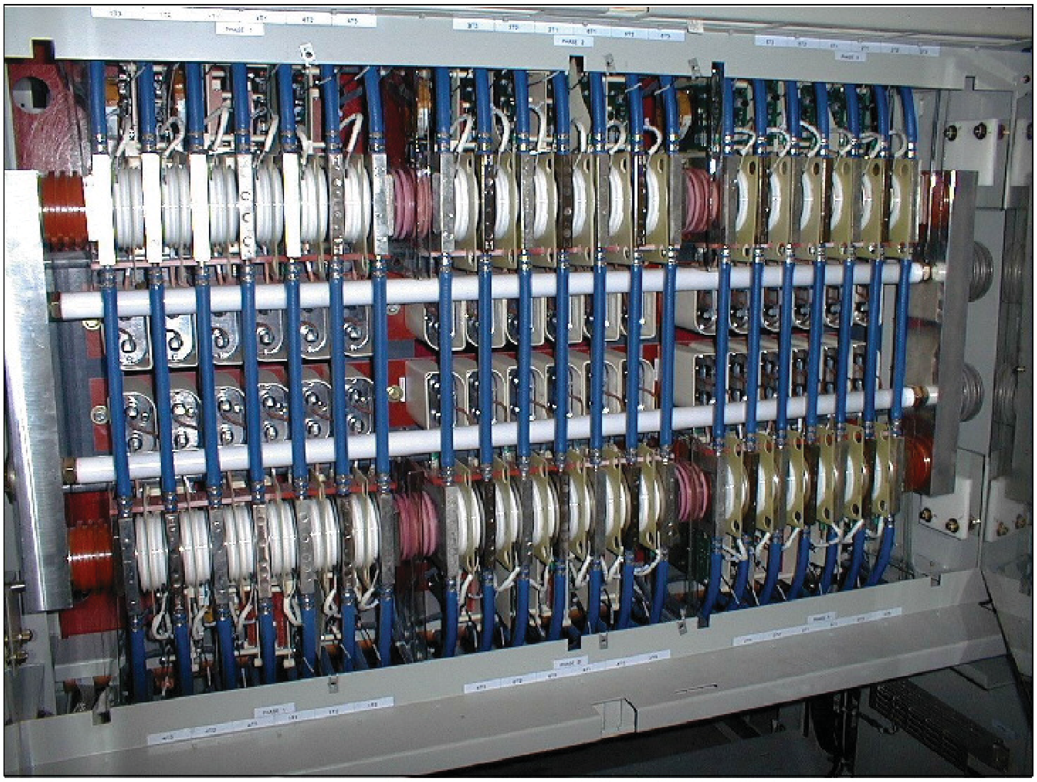

Figure 14. Water Cooled LCI Converter Bridge Showing SCRs (white discs)

Power Device Redundancy

The LCI architecture offers several opportunities for component and channel redundancy with substantial increase in reliability. An additional SCR device, beyond what is needed for conservative design, is inserted into each series device string in the converter and inverter sections of the LCI. The logic of this design is as follows:

- The switching devices used are SCR thyristors connected in series as needed to achieve the required voltage rating.
- The normal failure mode of SCR devices is to short out, that is to remain permanently ON in both directions. Since the device failure rate is very low anyway (about 80 per billion hours), adding an additional spare device does not significantly decrease the overall normal system reliability.
- By adding a spare device, operation can continue until maintenance repair can be made. If an SCR fails, the drive just keeps running. No control action is needed. The LCI controls detect the failed device, so it can be replaced.

The SCR redundancy methodology was pioneered and introduced by GE into the LCI and is known as *(N+1) redundancy*, where *N* is the quantity of SCRs needed, and the one more redundant device makes the count N+1. In practice, most LCI drives are shipped with N+1 redundancy since the price premium for N+1 in SCR LCI drives is quite small.

Channel Redundancy

The LCI can be built with redundant channels, for example a 30,000 hp drive consists of three channels, each of 15,000 hp. In the case of a drive problem, two channels can continue to power the motor, resulting in very high reliability. Hydraulic VSDs can't offer this level of redundancy.

Starting Redundancy

The electric VFD also offers the option to bypass the drive in case of a problem and start the motor directly off the line. This provides a good solution in the situation where shutting down the compressor or pump can create serious problems in the plant or pipeline. For this option, the drive motor needs to be designed to allow direct starting. Hydraulic VSDs are dedicated, so they can't offer this redundancy feature.

LCI Comparison Points

The following list defines the key features, strengths, and limitations of the LCI drive system.

LCI Strengths

- Low parts count
- Inherent full regeneration
- Rugged & proven reliable
- High energy efficiency, over 97% at high horsepower
- SCRs N+1 redundancy and channel redundancy can be supplied

LCI Limitations

- A controlled front end is required
- High motor current THD at low speeds
- Slow transient response
- Reduced starting torque
- Synchronous motors only
- Low line power factor at low motor speeds
- Significant ac power line harmonics unless multiple channels are used – may require harmonic filters
- Potential torsional effects; possible induced resonances in load at low speeds

System Ratings, Other

- Power output levels most practical above 6 megawatts
- Input voltage levels transformer isolated
- Transformer isolation – inherent
- Output voltages – actual inverter channels are usually either 2.3 or 4.16 kV. However, any practical motor voltage can be accommodated through output transformers
- Ease of startup, setup, troubleshooting; cannot run or test without a motor connected

Packaging & Mechanical Features

- Most LCIs in production today use liquid cooling, a sealed system with redundant pumps and remote heat exchangers
- Sizes – separate enclosures or assemblies for inverter, reactors, transformers, switchgear, and heat exchangers

Cost of Ownership

- LCI efficiency is over 97% and also benefits from synchronous motor high efficiency
- Life cycle – this technology is mature yet modern. Designs have been updated and all components are current.

TMdrive-70 Pulse Width Modulated Voltage Source Drive

The latest voltage source drives use high-power transistors such as the Injection Enhanced Gate Transistor (IEGT). A good example is the TMdrive-70, which uses the high switching speed and low losses of the IEGT to produce high power levels.

Three DC bus levels are used for motor voltages up to 3,300 volts. Figure 15 shows a PWM inverter output voltage waveform, illustrating the three power supply levels used to create the output sine wave.

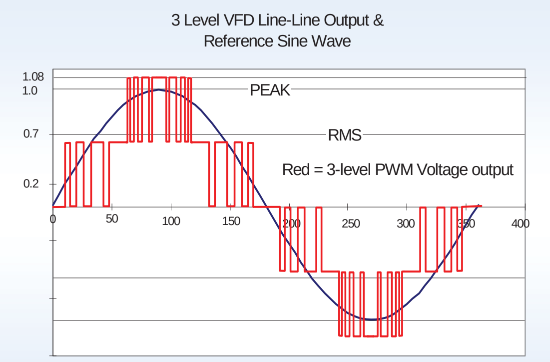

Figure 15. Simulated 3-level Inverter Voltage Waveform

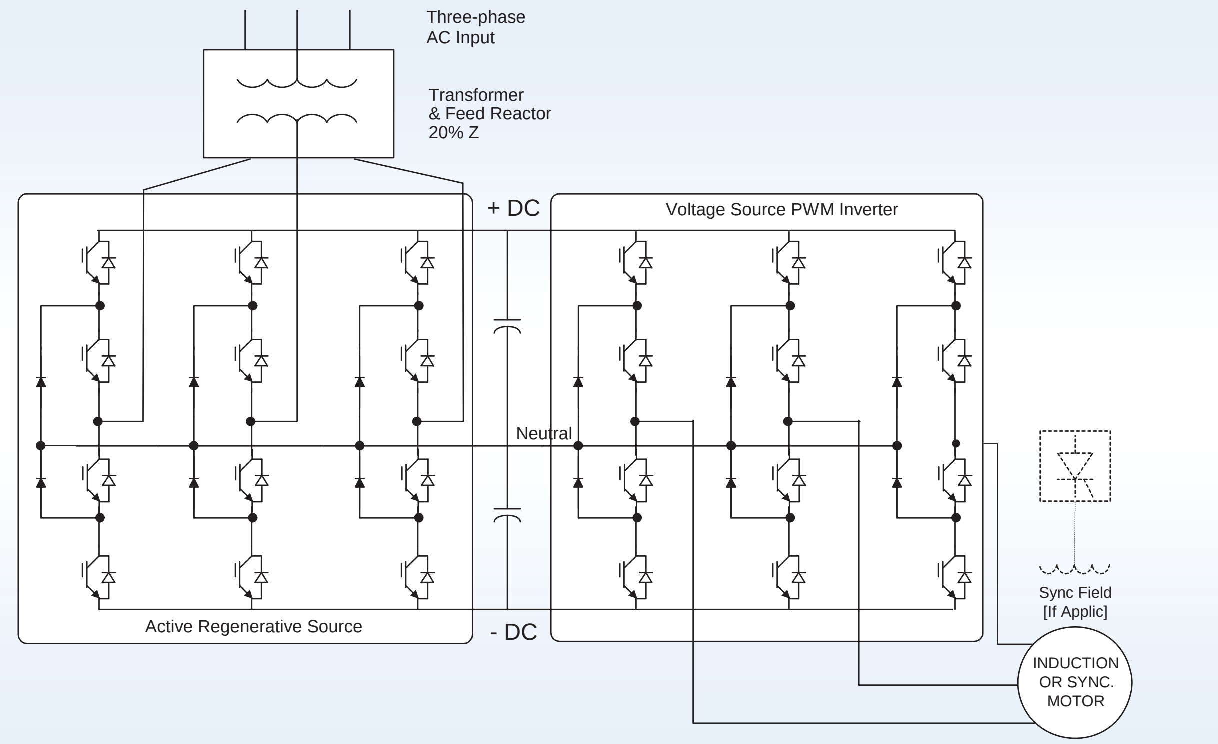

Figure 16. TMdrive-70 IEGT 3300 Volt Voltage Source Inverter and Active Regenerative Source

Figure 16 shows a power one-line of a voltage source inverter with an active regenerative source for motor voltages up to 3300 volts. The two capacitors store energy on the dc bus.

The compact, regenerative eight (8) MW inverter shown in Figure 17 includes all devices shown in Figure 16.

Control Cabinet   Source Cabinet   Inverter Cabinet

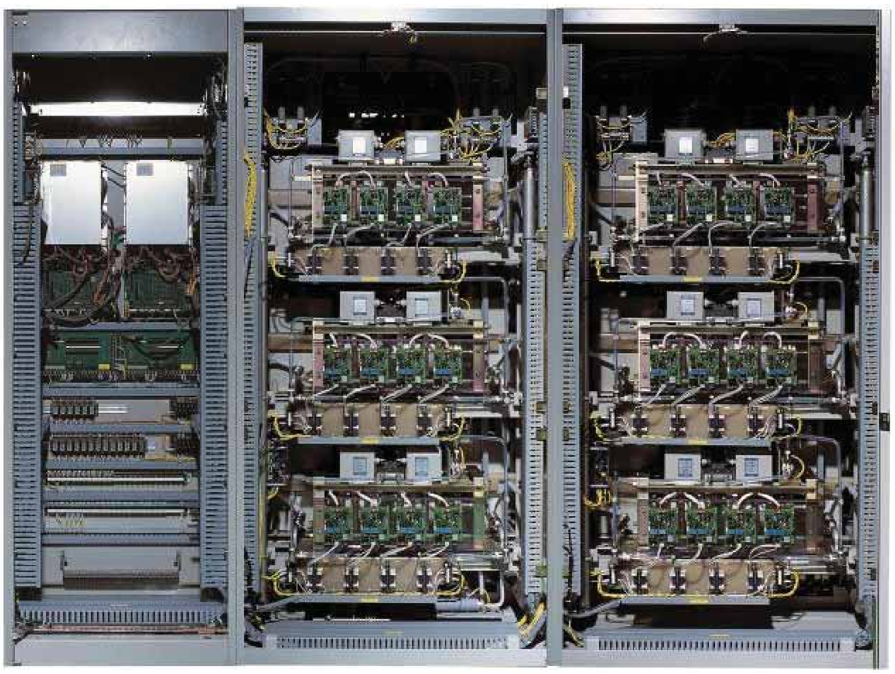

Figure 17. TMdrive-70 IEGT, 3300 Volt, 8 MW, Regenerative Inverter from TMEIC

TMdrive-70 Strengths

- Low power device count – only 24 for complete 8 MW regenerative inverter-converter systems
- Very high system MTBF
- Mean time to repair 60 minutes
- DC link energy is stored in liquid filled power capacitors with 20+ year life
- Low power systems harmonics
- Unity or leading power factor
- 3-level output and less than 5% motor current total harmonic distortion
- Simple, very reliable voltage-controlled gate circuit
- Rugged and proven reliability
- Fast response
- Wide range of speed and torque control
- High starting torque
- Synchronous or induction motor compatible
- Can run in test mode with motor disconnected
- High overload capability

TMdrive-70 Limitations

- Power device redundancy not practical
- IEGT switching speed can produce motor waveform transient voltages, and some installations may require a dv/dt filter on the drive output

TMdrive-70 System Ratings, Other

- Very high power levels – up to 10 MW per single bridge, 40 MW with parallel bridges
- Input voltage levels – transformer isolated
- Transformer isolation – inherent
- Output voltage: 3.3 kV
- Packaging and mechanical features – liquid cooling, with closed loop redundant system, operating temperature 0 to 40 ºC

TMdrive-70 Cost of Ownership

- System efficiency of over 96.5%, including transformers
- Life cycle – this technology is solid and growing
- Very small footprint using water cooling

Comparison of Hydraulic VSDs with Electric VFDs

The features of the Vorecon RW hydraulic VSD and two types of large electrical VFDs, LCI and TMEIC's TMdrive-70, are compared in Table 2. Important considerations such as energy efficiency, reliability, space and installation requirements, motor protection, and electrical systems are covered.

Table 2. Comparison of Representative Hydraulic VSD with Electric VFDs

Feature	Hydraulic VSD	Electric VFD	
	Voith Vorecon	**LCI**	**TMEIC TMdrive-70**
Output speed range	0 to 20,000 rpm	0 to 1800 rpm (higher with gear box)	0 to 3600 rpm (higher with gear box)
Output Voltage	Not applicable	2300 or 4160 V, 3-phase, 50 or 60 Hz.	3300 V, 3-phase, 50 or 60 Hz
Output power range	Up to 67,000 hp (50,000 kW)	Over 70,000 hp (52,220 kW).	Up to 53,619 hp (40,000 kW)
Efficiency: **100% speed** **85% speed** **70% speed**	 93.7% 92.5% 86.8%	 97.4% 97.3% 97.0%	 96.5% 96.4% 96.1%
Motor requirements	Any prime mover	Synchronous motor	Induction motor, or synchronous motor
Motor start requirements	Special motor starter may be required to reduce high inrush current starting across the line.	No motor inrush current during starting	No motor inrush current during starting
Space requirements	Type RW14 Vorecon is approximately: 128.3 in (3260 mm) W 70.9 in (1800 mm) D 122.8 in (3120 mm) H A large base frame supports the Vorecon and motor.	Cabinet lineup for 7,000 hp drive: 158 in (4000 mm) W 55 in (1400 mm) D 100 in (2500 mm) H Cabinet can be remote from motor; transformer and link reactor outside cabinet.	Cabinet lineup for 8,000 hp drive: 165 in (4191 mm) W 65 in (1650 mm) D 94 in (2375 mm) H Cabinet can be remote from motor; transformer outside cabinet.
Weight	Not available	Cabinet weight 7500 lbs (3400 kg)	Cabinet weight 8600 lbs (3900 kg)
Equipment requirements	Drive, Motor, Base Plate, and Motor starting switchgear	Drive, synchronous motor, transformer, reactors, feeder switchgear, & heat exchanger (plus sometimes gearbox and power equipment room).	Drive, induction or synchronous motor, transformer, feeder switchgear, & heat exchanger (plus sometimes gearbox and power equipment room).
Application flexibility	One HVSD per driven machine	One EVFD can be shared between multiple motors. A motor can be connected to and from the EVFD and the utility system bumplessly.	One EVFD can be shared between multiple motors. A motor can be connected to and from the EVFD and the utility system bumplessly.

Feature	Hydraulic VSD	Electric VFD	
	Voith Vorecon	LCI	TMEIC TMdrive-70
Installation requirements	HVSD is installed between the motor and driven machine, aligned to both shafts. Cooling water is piped to the heat exchanger.	Install cabinet in any convenient air-conditioned location; can be remote from motor. Redundant pump systems recirculate de-ionized water for cooling.	Install cabinet in any convenient air-conditioned location, can be remote from the motor. Redundant pump systems recirculate de-ionized water for cooling.
Retrofit requirements	Retrofit of constant speed motor requires the motor be moved to make room for the VSD. Space may be a problem, pipes must be re-routed, and foundations re-built.	For constant speed motor with flow control valve, very little change; the pump-motor train can be left where it sits. For a variable speed turbine, replace with a synchronous motor.	For constant speed motor with flow control valve, very little change; the pump-motor train can be left where it sits. For a variable speed turbine, replace with an induction or synchronous motor.
Operating Temperature	Not available	0°C to + 50°C	0°C to + 32°C
Cooling requirements	Cooling water supply and return lines for oil cooler	Air-conditioned space. Clean water supply with 50°C maximum temperature, or external air-to-air exchanger.	Air-conditioned space. Clean water supply with 50°C maximum temperature, or external air-to-air exchanger.
Protection of motor	Usually drive does not protect the motor against starting inrush current.	Low motor starting current and extended motor life. Motor is buffered against bus voltage variation.	Low motor starting current and extended motor life. Motor is buffered against bus voltage variation.
Electrical system	Drive does not protect the electrical system against motor transients during fault conditions. Power factor is equal to motor power factor.	Low starting currents reduce the impact on the bus. There is no fault contribution to the utility from a fault on the motor; the drive absorbs it. Utility power factor varies with motor operating point.	Low starting currents reduce the impact on the bus. There is no fault contribution to the utility from a fault on the motor; the drive absorbs it. The utility power factor improves to about 0.95 with diode source converter or 1.0 with PWM source converter.
Reliability MTBF	Published Mean Time Between Failures is quoted as 107,500 and 154,000 hours.	Mean Time Between Failures is 30,000 hours for standard LCI, up to 175,000 with redundancy as discussed	Mean Time Between Failures is estimated to be greater than 10 years.
Availability	0.9994 (published data gives mean forced outage time 84 hours)	0.9999 with redundancy (the mean time to repair is 1.1 hours)	The mean time to repair is 1.0 hours
Expected equipment Life	30 years	30 years	30 years
Price	The equipment costs for these three systems are roughly comparable when the cost of the drive and additional items such as transformer, gearbox, and air-conditioned power equipment room are included. See Table 5.		

Electric Drives Can Be Shared Between Multiple Machines

Some situations arise where there are two or more pumps or compressors in parallel, some running at constant speed while the others are under variable speed control to produce the desired process flow. For example, three pumps may require only two EVFDs, saving on initial equipment and installation cost, as shown in Figure 18.

A single electric VFD can be used to start and run the motors individually and then be used to run one of the motors at variable speed. The EVFD can be connected to either motor while it is running or stopped, and either motor can be connected to the line. This redundancy provides high reliability. Some drives which have this advanced feature include the LCI, TMdrive-70, and DuraBilt5i MV drives.

An HVSD is dedicated to one motor, with no redundancy, so any failure brings the machine down.

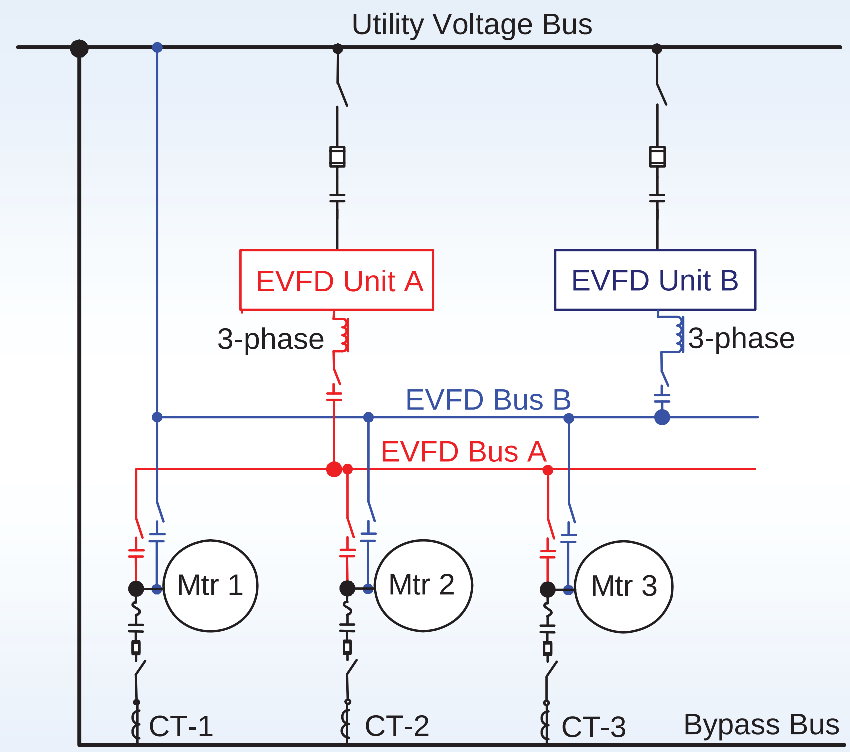

Figure 18. Sharing Drives with Multiple Motors

Energy Efficiency

Both electric drives provide a higher efficiency than the hydraulic drive across the entire load and speed range, especially at the lower speeds where the HVSD has very low efficiency. Figure 19 compares four different drives at various loads, and Figure 20 compares them at various speeds. This data was obtained from GE, Voith users, and the Voith web site; some intermediate points are interpolated.

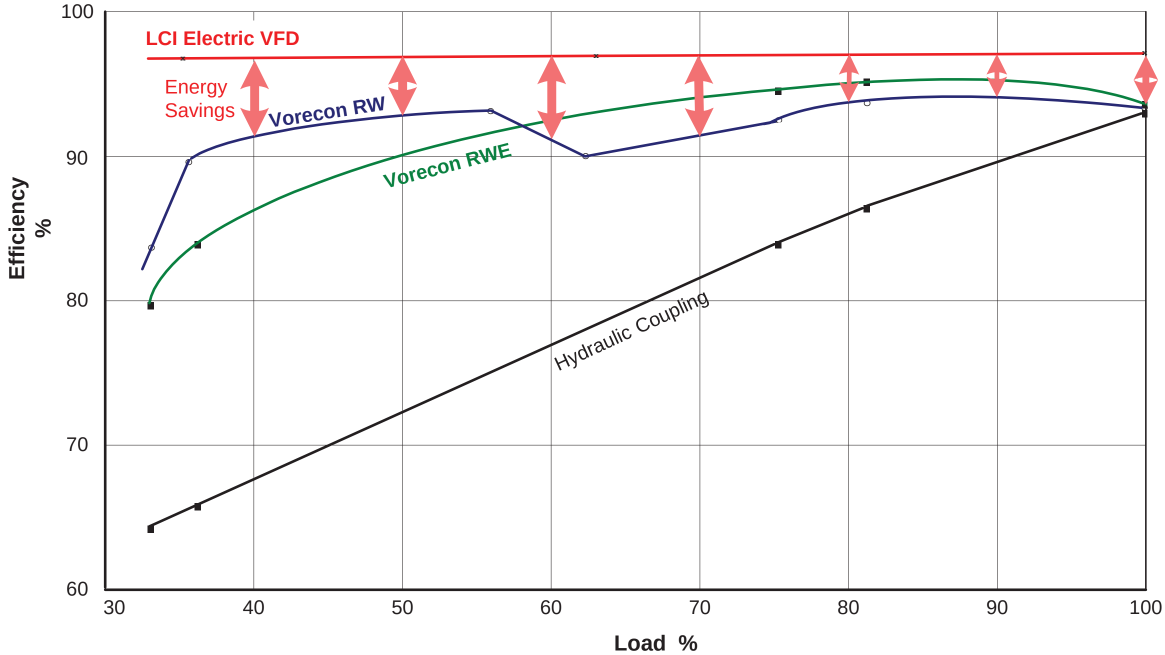

Figure 19. Comparison of EVFD & HVSD Drive Efficiencies vs. Transmitted Load

The electric drive maintains high efficiency over the entire load range, but the hydraulic drive efficiency falls off at loads below about 50%. The hydraulic coupling efficiency is very low except at close to full load.

Figure 20 illustrates the superior efficiency of the electric drive over a wide speed range. Below 80% output speed, the mechanical drive efficiency falls off very quickly. Over the 70 to 100% speed range, the electric drive has an efficiency advantage over the type RW of 4 to 5% on average. Below 80% speed, the LCI advantage is quite large.

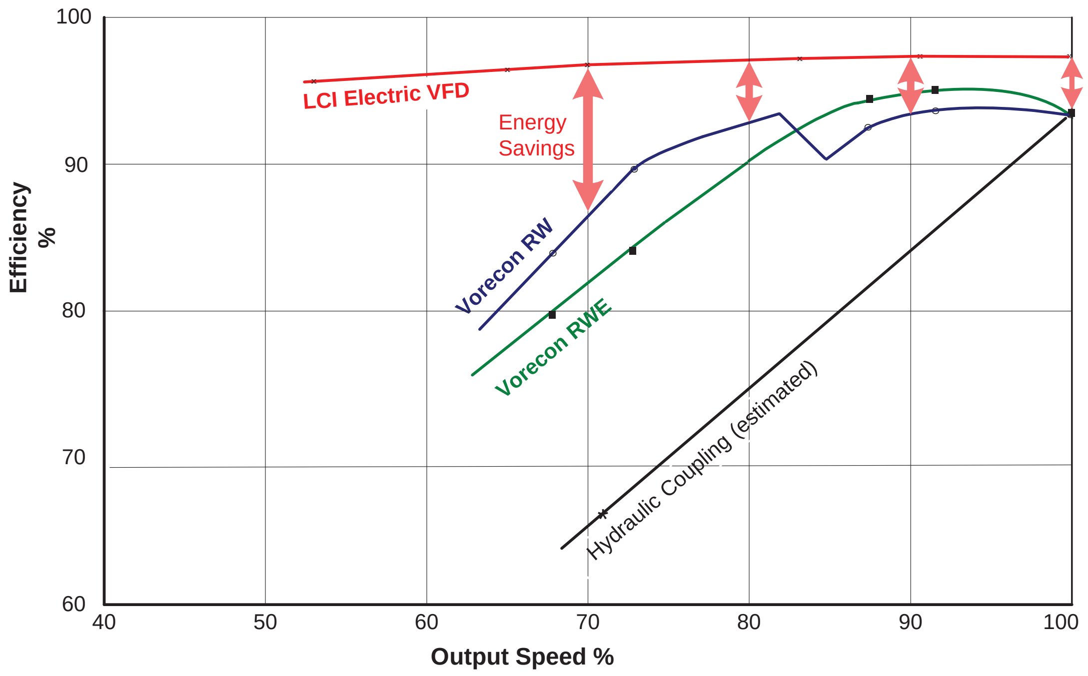

Figure 20. Comparison of EVSD & HVSD Drive Efficiencies vs. Output Speed

Energy Consumption Calculations

For the high power transmission applications discussed in this brochure, the electric VFD starts saving money on day one. For example, Table 3 refers to an application driving a 10,000 hp load, with the motor speed varying over the 70 to 100% speed range.

For the duty cycle of Table 3, the efficiency of the electric VFD is 97.32%, – higher than the HVSD by 4.66%.

Many compressors and pumps run faster than 1800 rpm, and in these cases the EVFD system requires a gearbox to increase the speed. The gearbox has a fixed ratio and mounts between the electric motor and the compressor.

Figure 21 shows the mechanical and electrical equipment usually required by three alternative drive types. Note that the TMdrive-70 can drive an induction motor or synchronous motor, and the HVSD can be driven by any kind of motor.

Table 3. Example Duty Cycle & Speed Variation Effect on Drive Efficiency

	70% Speed	80% Speed	90% Speed	100% Speed	Mean Value
Duty Cycle, % of time at Speed	10	20	30	40	-
Estimated Load Horse-Power (pump)	3,480	5,570	7,930	10,000	-
Hydraulic VSD - type RW Efficiency %	86.8	92.7	93.2	93.7	92.66%
Electrical VFD - LCI Efficiency %	97.0	97.2	97.4	97.4	97.32%
Efficiency Difference EVFD -HVSD	10.2	4.5	4.2	3.7	4.66

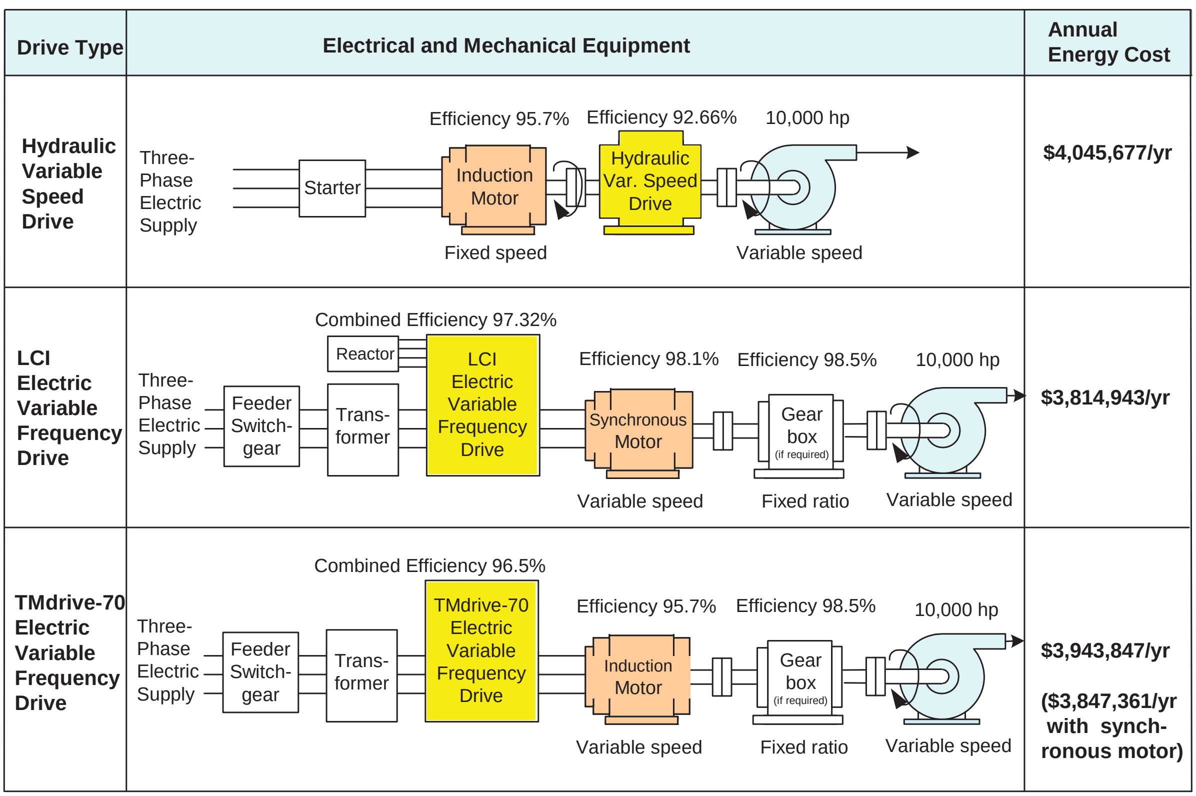

Figure 21. Comparison of Energy Savings (Energy cost at $0.07/kWh)

Over this speed range and duty cycle, the mechanical drive has an average efficiency of 92.66%, and the LCI electric drive an efficiency of 97.32%. The induction motor has an average efficiency of 95.7%, and the synchronous motor an efficiency of 98.1%. Using an average cost of $0.07/kWh for electric power, and assuming continuous operation, Figure 21 shows the annual energy costs can be calculated:

- The hydraulic drive system uses $4,045,677 of electrical power per year
- The electrical drive system uses $3,814,943 of electrical power per year.

Therefore, choosing the **electrical drive system saves $230,734 per year**.

If electric power costs increase at 5% per year over the next 10 years, and the savings are discounted at 6%, the net present value of the savings will be $2,085,826. Several financial scenarios are shown on Table 4. If power costs continue increasing over the 30-year life of the drive equipment, the value of the cumulative savings will be large.

Table 4. Ten-Year Energy Savings

Electrical Energy Inflation Rate	**Annual Savings in First Year**	**10 Year Net Present Value, using Discount Rate 4%**	**10 Year Net Present Value, using Discount Rate 6%**
0%	$230,733	$1,871,245	$1,698,195
5%	$230,733	$2,316,559	$2,085,826

Equipment Cost Comparison – Single Motor and Load

If there is air-conditioned space inside the building for the electric drive, then the cabinets can be located there. However, if there is no space, an inside or outside air-conditioned power equipment room is required for the EVFD cabinets. Table 5 includes air conditioning in the equipment items involved for the two types of drive.

The EVFD often requires a gearbox, so for a single motor and load, the total equipment could cost more than for an HVSD. Installation of the EVFD may cost more than the HVSD because there are more separate pieces of equipment involved. The EVSD total installed cost, which is the sum of the equipment and installation, may be slightly higher than the HVSD, but this depends on current monetary exchange rates (most HVSDs are built in Europe) and whether an equipment room and gearbox are required.

Table 5. Installed Cost Comparison Mechanical vs. Electrical Drive

Mechanical Drive System Components		**Electrical Drive System Components**	
Hydraulic variable speed drive, 10,000 hp, with auxiliary lubricating pump, RTDs, vibration pickups, speed sensor, and gauges Price range:	$950,000 to $1,300,000	LCI electrical variable frequency drive, 10,000 hp, with transformer and 2 link reactors	$650,000
Motor starter	$40,000	Feeder switchgear	$30,000
10,000 hp induction motor	$300,000	10,000 hp synchronous motor	$450,000
		Fixed ratio gearbox (if required), with RTDs, vibration pickups, and inspection points	$105,000
		Air conditioned power equipment room (if required)	$85,000
Total Equipment Cost	$1,290,000 to $1,640,000	**Total Equipment Cost** (all of above)	$1,320,000
Estimated installation cost including motor and starter	$50,000	Estimated installation cost including motor, room, and gearbox	$100,000
Total Installed Cost approx.	**$1,340,000 to $1,690,000**	**Total Installed Cost approx.**	**$1,420,000**

When to Use an Electric VFD

Assuming you will be using a variable speed drive, here is a summary of situations where an electrical VFD has advantages over a corresponding hydraulic VSD.

To Save Energy

Considerable energy savings can be realized by installing an electric VFD instead of an HVSD, regardless of the speed and range of speed fluctuation. In the 10,000 hp example on page 21, the savings were $230,000.00 per year, and would be proportionally larger for larger machines. With energy and electricity costs rising, the savings will increase year by year.

To Smooth Motor Starting and Extend Motor Life

With an EVFD, the motor current is always under control. There are no locked rotor starting currents, excessive temperatures, or mechanical stresses put on the motor. With constant speed motors used with HVSDs, the driven equipment can be subjected to hard starts; and the heat, caused by the starting current, degrades the motor insulation and shortens its life. Controlled motor current also means that motor heating will not limit the quantity or frequency of motor starts.

With an HVSD, the motor experiences large inrush current, which produces heat and reduces the life with each start. However, the more complex type RW Vorecon can offer reduced torque at starting through the use of its special front-end hydraulic coupling (refer to page 10), but this does not reduce the motor current inrush, only its duration.

To Share Drives between Multiple Machines

Some applications use two or more motors in parallel, some running at constant speed while the others are under variable speed control to produce the desired process flow. For example, three pumps can share one or two EVFDs. On the other hand, an HVSD is dedicated to one motor, so three are required. Using the electrical system provides considerable savings on the initial equipment and installation.

To Reduce Bus Impact

EVFDs possess characteristics that can increase the load-carrying capability of a system bus with a given switchgear rating. The characteristics contributing to this are:

- Starting currents are low in magnitude and of relatively high power factor when compared to across-the-line starting of conventional, squirrel-cage induction and synchronous motors. This characteristic eliminates significant voltage dips during the starting of large adjustable speed drives.
- Normally there is no EVFD contribution to short circuit current. This characteristic permits a reduction in the auxiliary transformer's impedance, resulting in improved system voltages at a given load condition or permitting greater load carrying capability.

The reduced starting current and lack of short circuit contribution also allows an increase of the total motor load that can be applied to a piece of switchgear. For an existing system, there is a reduced voltage dip during motor starting and lower short circuit duty.

To Obtain Fail-Safe Operation

Electric drives can be configured with a fail-safe characteristic. In the event of an EVFD failure, a bypass contactor can be closed, driving the load at full speed. During this time, the drive can be repaired, and, with a meantime to repair of 1.1 hour, the drive can be quickly back on line. Therefore, a failure of an EVFD will not take down the plant, where failure of a HVSD probably would.

To Handle Full-Speed Operation

If periods of full-speed operation are required, the EVFD can be bypassed with optional synchronized bypass circuitry and put across the line, so there is no power lost in drive efficiency at full speed. The transfer can be done without any line surges whatsoever. An HVSD is dedicated to its machine and cannot be bypassed.

Conclusion

This paper has demonstrated the energy savings obtained when the speed of a flow-producing machine is varied instead of using a control valve or dampers. It illustrates two different methods of speed control: hydraulic drives and electric drives. Both systems work well, and each system has good energy efficiency, reliability, and roughly comparable installed cost. A summary of selection factors was shown in Table 2.

The final decision on which way to go requires a careful review of the application requirements, desired availability, and the future cost of the electrical energy that will be purchased. For a large machine, a small increase in energy efficiency can produce impressive cost savings, and since electrical energy costs are expected to continue to increase, these savings should be taken into consideration.

TMEIC Drive Equipment • Motors • Control Components • Engineering Services • Construction Services

Total Plant Solutions

Process Knowledge and Control
- Real-time Closed Loop Control
- State Variable Control
- Statistical Quality Control
- HMI & Supervisory Control
- Modeling & Adaptation Optimization
- Data Acquisition, Process Diagnostics, & Simulation

Services
- Process Audits & Surveys
- Construction Engineering
- Installation and Commissioning
- Remote Monitoring & Diagnostics
- Parts Management

System Engineering and Integration
- Control System Design & Implementation
- Power System Planning & Analysis
- Process Computer Integration
- Gauging & Instrumentation
- Network Design
- Integration of IT Solutions into Process Automation

Quality Systems
- ISO Certification
- Production Testing
- System Test
- Simulation Testing
- FMEA Studies
- Six Sigma Processes

Core Products
- Drive Systems
- Controllers & Instrumentation
- Power Delivery Equipment
- Motors
- Induction Heating Equipment

Project Management
- Contract Administration
- Resource Planning & Scheduling
- Site Management
- Risk Abatement Strategies

Marketing Voice of the Customer
- Product Development
- Market Research & Analysis
- Sales Force Deployment & Effectiveness

Automation and Control Systems • Commissioning • Post Sale Service

Global Office Locations:

TMEIC Corporation
Roanoke, Virginia, USA
Tel: +1-540-283-2000
Email: OilGas@tmeic.com
Web: www.tmeic.com

TMEIC Corporation
Houston Branch Office
Tel: +1-713-784-2163
Email: OilGas@tmeic.com
Web: www.tmeic.com

TOSHIBA MITSUBISHI-ELECTRIC INDUSTRIAL SYSTEMS CORPORATION (TMEIC)
Tokyo, Japan
Tel: +81-3-5444-3828
Web: www.tmeic.co.jp

TMEIC Europe Limited
West Drayton, Middlesex, United Kingdom
Email: info@tmeic.eu
Web: www.tmeic.eu

TMEIC Industrial Systems India Private Limited
Andhra Pradesh, India
Email: inquiry_india@tmeic.com
Web: www.tmeic.in

TOSHIBA MITSUBISHI-ELECTRIC INDUSTRIAL SYSTEMS (Beijing) CORPORATION
Email: sales@tmeic-cn.com
Web: www.tmeic-cn.com

TOSHIBA MITSUBISHI-ELECTRIC INDUSTRIAL SYSTEMS (Shanghai) CORPORATION
Email: sales@tmeic-cn.com
Web: www.tmeic-cn.com

A-1140