HYBRID ASD COMPARISON WITH CONVENTIONAL – SIGNIFICANT EFFICIENCY IMPROVEMENTS ARE STILL AVAILABLE

Paper No. PCIC-2022-XX

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Abstract – High speed pump and compressor applications can frequently gain significant performance improvements when operated via an adjustable speed drive (ASD). By utilizing a fixed speed motor to provide a portion of the rated power (for example, 85%), two small servo motors (combined rating 15%) each connected to an ASD and an epicyclic gearbox, a high performance Hybrid ASD solution can show significant additional benefits beyond the conventional ASD approach. A detailed comparison between this hybrid system and a conventional system utilizing a fully rated ASD and a parallel offset gearbox based on a nominal compressor load of 10.9MW, 10,000rpm is presented in detail. Most notably, these benefits include an efficiency improvement in excess of two percentage points.

Index terms – ASD, VFD, VSI, variable speed drive, adjustable speed drive, hybrid drive, planetary gear, epicyclic gear, efficiency, induction motor, synchronous motor, servomotor.

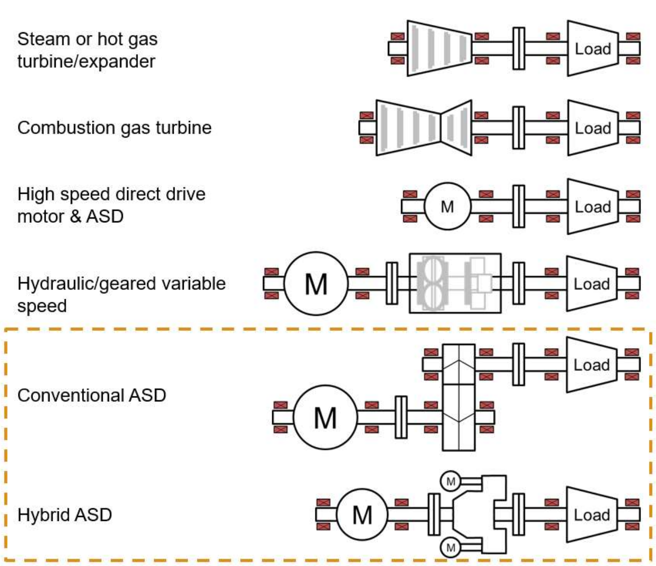


Fig. 1 Drive train options

I. INTRODUCTION

A number of different driver options are available to provide an adjustable speed input for high speed compressor and pump applications. These options are illustrated in Fig. 1. (In this instance, high speed is defined as above 4,000rpm.) This paper provides a comparison of the conventional ASD, motor and parallel offset gearbox with a system superimposing power via an epicyclic (planetary) gearbox, a fixed speed main drive motor and two servomotors (Fig. 2). Tilscher et al, [1] discusses a number of these choices and includes a more detailed description of the theory behind the options utilizing epicyclic gearboxes. For simplicity, the two options being considered here are referred to as a "conventional ASD" and "Hybrid ASD" respectively throughout this paper.

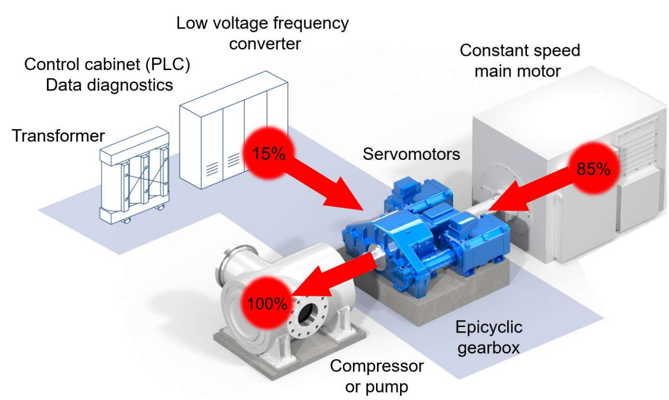


Fig. 2 Hybrid ASD solution

II. CONVENTIONAL ASD

This system utilizes well proven technology with components having a TRL 7 or better per API 691 [2]. (API standards recognize motors and generators are consistent with a technology readiness level [TRL] of 7 – this is an indication of the maturity of the technology utilized.) Electrical ASDs are based on semi-conductors that have evolved through the years. Starting with the LCIs (Load Commutated Inverter) using thyristors in the 1970's driving only synchronous motors followed by the VSI (Voltage Source Inverter) in the 1980's using IGBTs (Insulated Gate Bipolar Transistor) [3].

A conventional ASD arrangement is illustrated in Fig. 3. The main components include -

A. Input transformer

Indoor or outdoor MV (Medium Voltage) phase-shifting multi-pulses transformer connecting the ASD to the main grid. Both oil filled and dry type transformers are commonly used.

B. MV ASD

Indoor MV ASD based on VSI or CSI each supplied with either water or air cooling. Multiple topologies are available for the VSI (such as multi-levels, 3 levels NPC [neutral point clamped], NPP [neutral point piloted] and 5 levels) and for the CSI (LCI [6 or 12 pulses] or CSI PWM). The voltage typically ranges between 3.3kV and 13.8kV.

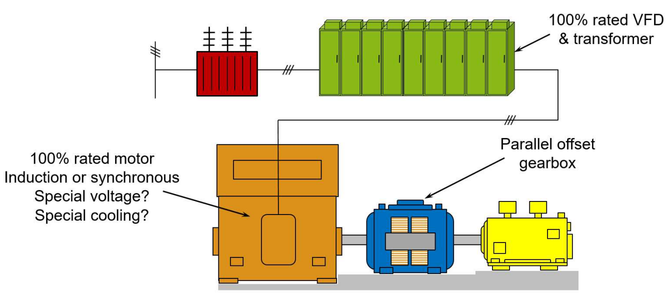


Fig. 3 Typical conventional ASD

C. Main drive motor

The motor (induction or synchronous, air cooled or water cooled) is designed to be suitable for inverter duty and is driven by the ASD to provide the speed variation. Motors are usually 2 pole or 4 pole however 6 pole motors and above can be used for low speed applications.

D. Parallel offset gearbox

Parallel offset gearbox connecting the motor to the main load and allowing the speed increase with a predefined ratio.

E. Auxiliaries

In addition to these main components, a list of auxiliaries are needed such as for the cooling (HVAC system, water chiller, oil cooler, etc.) as well as a lube oil system.

III. HYBRID ASD

Hybrid ASD systems are also packaged with components having TRL 7 or better but supplied to the driven equipment OEM or user as a pre-engineered package. Fig. 4 illustrates a typical arrangement.

Main components include –

A. Epicyclic gearbox

Although not as common as a parallel offset gearbox, hundreds of these units are in operation in oil, gas and petrochemical sites across the world for both fixed speed and variable speed applications. Maragioglio et al, [4] provides additional background on this technology.

B. Main drive motor

A conventional fixed speed induction or synchronous motor commonly available in line with API 541 [5] or API 546 [6] and providing a major portion of the rated power. As the motor is typically rated at 85% of the train needs, an existing motor can readily be utilized on applications where the driven equipment is being upgraded with a higher power requirement. This avoids the need to source a new, larger, motor and allow the use of any existing spares.

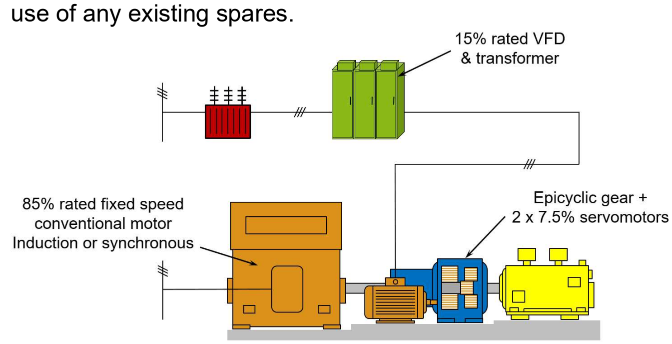


Fig. 4 Typical Hybrid ASD

C. Servomotors

Readily available low voltage cage induction motors each rated to supply 50% of the power difference between the train rated power and the main drive motor. Two motors are utilized to provide some redundancy in the unlikely event of a failure of the power supply to one. TEFC enclosures with blower driven external fans (IC416) or TEWAC (IC71W or IC81W) are commonly offered. These motors can be supplied in line with IEEE 841 [7] or API 547 [8]. Depending upon specific application needs medium voltage motors can be utilized in line with [5].

D. AFE servomotor ASD

Low voltage AFE (active front end) drive with two inverters. Options for additional redundancy can be provided with two converters. Depending upon the specific application, medium voltage drives can be utilized as an alternative.

E. Auxiliaries

Same as for the conventional ASD, the main auxiliaries required for the Hybrid ASD are for cooling the ASDs (air cooled for the required power range) as well as the oil system.

IV. MAIN DRIVE MOTOR COMPARISON

A number of characteristics need to be assessed to provide a comparison between the main drive motors including a look at the following points -

A. Voltage & harmonics

With a conventional ASD system, motor voltages are limited to the ASD output voltage. Utilizing a standard high voltage motor that matches the grid voltage simplifies the installation resulting in savings on the cables used as well as avoiding the use of an input transformer. Eliminating the input transformer reduces the system footprint, mass, CAPEX and system losses. Motor efficiency is also improved with the Hybrid ASD system since the main motor is a fixed speed machine optimized for operation with a sinusoidal supply. This has a further benefit as it also eliminates any concerns associated with harmonic content, dV/dt, common mode voltages and shaft currents that could adversely impact the motor and/or the utility supply. In addition, the main motor power rating with Hybrid ASD is not required to provide the full power compared to the conventional ASD system. In the Hybrid ASD solution, the total power is the sum of the servomotors power and the main motor.

B. Cooling

For the conventional ASD main drive motor the cooling circuit is usually augmented with internal blower motors to ensure sufficient cooling air is circulated at lower speeds. These blower motors are typically supplied with built-in redundancy (e.g., 2 x 66%, 3 x 50% or 4 x 50% capacity). Although these arrangements are commonly available, they add complexity to the motor design and need to be accounted for in the overall efficiency comparisons. Fig. 5 and Fig. 6 show these options and help illustrate the difference in size associated with 100% capacity vs. 85% from the Hybrid ASD.

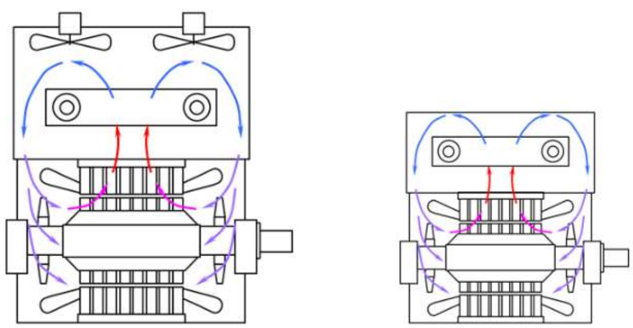


Fig. 5 TEWAC Enclosures (IC86W and IC81W)

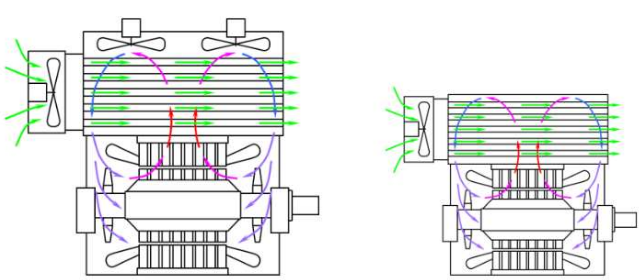


Fig. 6 TEAAC Enclosures (IC666 and IC616)

C. Starting

The conventional ASD has minimal impact on the electrical system when starting with an inrush current below the rated full load current (FLC). The Hybrid ASD utilizes a conventional fixed speed motor along with its associated locked rotor current (LRC). The voltage dip associated with this LRC can be addressed in the normal ways [9]. However, the motor designer has an additional degree of freedom here during the design phase since the load curve is significantly reduced due to the servomotors "assist" during starting. This "assist" means the motor only sees a maximum load during starting that equates to the torque the driven equipment has at 70% of the rated speed. Fig. 7 shows the full impact of this. (In the example shown, less than 40% torque as opposed to 90% if it were started without the "assist".) This reduced load allows a lower LRC design to be utilized. A further option can be considered where the servomotors act in the same way as a pony-motor start. (This option adds some additional components and cost.) Under these conditions the servomotors accelerate the main drive motor to synchronous speed and the load to 50% of rated speed (point "S" in Fig. 7). Once up to speed, the main drive motor is connected to the power supply and the servomotors are then able to take control and accelerate the load to the required speed. Utilizing an induction main drive motor limits the inrush current solely to the magnetizing current and only for a very short duration. If a synchronous main drive motor is utilized, the current seen during starting would be below the rated full load current. Regardless of the starting method selected, a power system study may be required to optimize the system and ensure an acceptable voltage dip.

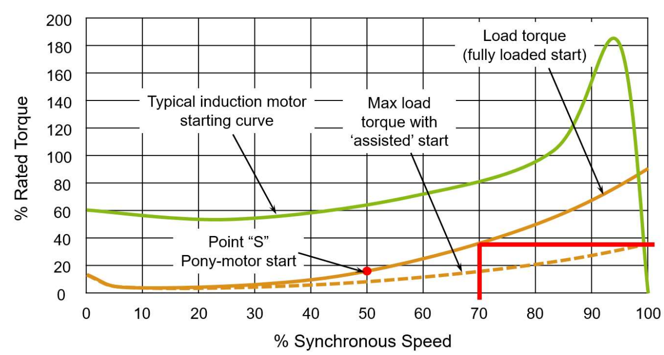


Fig. 7 Servomotor Start Options

V. GEARBOX AND LUBE SYSTEM

A motor driven pump or compressor drive train usually utilizes a step-up gearbox if the motor speed cannot be matched with the requirements of the driven equipment. Single stage gearboxes can provide a ratio up to 10:1. There are two types of gearboxes available for this purpose. The choice is largely determined by the gear arrangement, the parallel shaft gear and the epicyclic gear.

The power path within a parallel shaft is introduced via the low-speed shaft driven by the motor and then going through the bull gear and transmitted via the gear mesh to the pinion shaft which is then connected to the driven equipment. Parallel shaft gears have a shaft offset, typically a horizontal one or, in some cases, a vertical one. (Fig. 8)

With an epicyclic gear, the gear arrangement consists of three components; the annulus (or ring) gear, the planet gears and the sun gear. The incoming power path splits from the low-speed shaft that is connected to either the planet or ring gear and transmitting the power via two gear meshes to the sun gear, which is connected to the driven equipment. This gear arrangement is co-axial and provides a more compact design. Fig. 9 illustrates these arrangements.

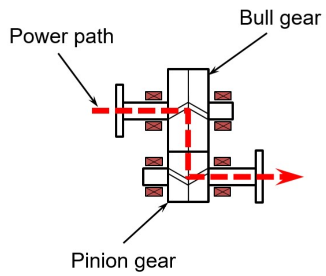


Fig. 8 Parallel Offset Gear

Both epicyclic gear designs have two rotating and one fixed element providing a fixed speed ratio. When all three elements are rotating, this allows the adjustment of the ratio and, thereby, providing variable speed operation. This design type allows a change in the output speed using a fixed speed motor either by using a hydrodynamic or electrical superimposition of the planetary gears.

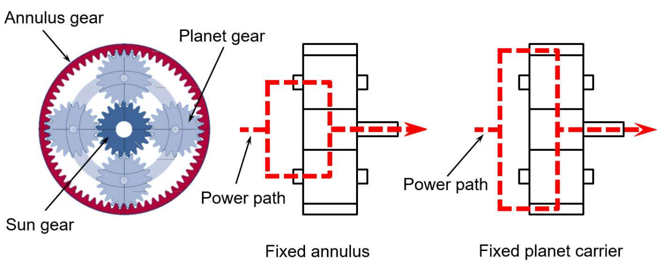


Fig. 9 Epicyclic gear arrangement and power flow

Beside the shaft arrangement, the epicyclic gear shows smaller gear design parameters, like the pitch line velocity of the gearing, as well the journal speeds and loads on the bearings. Fig. 10 illustrates an example of this for a 12MW 1,500 to 10,000rpm design.

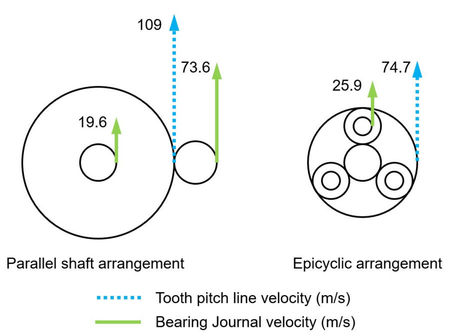


Fig. 10 Gear characteristics

Although the epicyclic gear contains more components than the equivalent parallel shaft gear box, the resulting lube oil consumption and efficiency is dependent upon the pitch line velocity and journal bearing velocities. The lower velocities of the epicyclic gear result in a better efficiency compared to the parallel shaft gear (Fig. 11).

API 613 [10] is a well-recognized standard that covers parallel shaft gearboxes. It can also be applied to epicyclic gearboxes as an alternative gear design, however, it does leave numerous points for discussion/clarification. API 677 [11] is a more appropriate standard to use for epicyclic gearboxes.

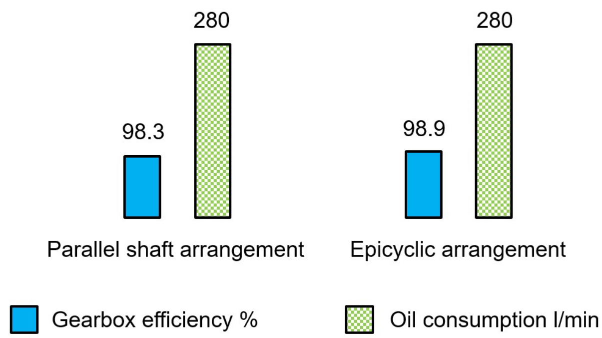


Fig. 11 Gear efficiency and oil consumption

VI. ASD & TRANSFORMER COMPARISON

By using the power split principle, the Hybrid ASD system allows to have the speed variation while providing only 15% of the total power through the ASDs and 85% through the fixed speed motor. The primary benefit is that the ASD and transformer power rating is only 15% of the required power as compared to a conventional ASD arrangement with 100% of the power requirement being provided by the drive. This difference allows the use of LV ASDs instead of MV ASDs in some cases. By reducing the power of the ASD, air cooling becomes a practical alternative to liquid cooling. Air cooled is often smaller, less expensive and more reliable than liquid cooled ASD's. Footprint and mass are significantly reduced as well. The harmonic impact on the grid is also drastically reduced as only 15% of the power is using a nonlinear load (ASD). In addition, the Hybrid ASD uses the AFE topology which by its nature has a lower harmonic content. The transformer, power, size and mass are reduced allowing a move from an ONAN (oil natural air natural) outdoor to an integrated indoor air-cooled transformer if needed. The use of AFE for the Hybrid ASD allows the use of a two winding transformer instead of a multiphase shifting transformer (12 pulse and above).

VII. EXAMPLE PROJECT

The project being evaluated required an absorbed power of 10.9MW at 10,000rpm. Power supply is available at 11kV, 50Hz. Cooling water (sea water) is available at 36°C; ambient outdoor cooling air is available at 55°C. For the two options being evaluated, this had the following impact –

A. Conventional ASD

The motor was rated 12MW, 1,500rpm, TEWAC, IC81W, 6.9kV driven by a water cooled VSI ASD 6.9kV 5-level topology with a 36 pulse input ONAN outdoor transformer (15MVA) fed from the 11kV grid. Two cooling options were considered for the ASD: water-to-water heat exchanger using sea water or a water-to-air chiller with an ambient air temperature of 55°C.

B. Hybrid ASD

Customer preference and electrical power supply limitations required that the pony-motor start approach be utilized. Based on this and the compressor load characteristics, it was determined that the servomotors must be 'oversized' above the typical 15% to 22% of the total power. The final design included a main drive induction motor rated 10MW, 1,500rpm, 11kV, TEWAC (IC81W). As cable length between ASDs and servomotors was 600m, medium voltage ASDs and servomotors were preferred over low voltage. The servomotors were each rated 1,400kW 6p, 3kV, TEFC (IC416). For redundancy purposes, two AFE ASDs have been considered, each rated for 1,400kW, 3kV, 3-levels NPC topology with integrated dry type air cooled 2 windings transformers (1,700 kVA).

VIII. EFFICIENCY COMPARISON

The use of the power split principle is the primary reason that there is an efficiency gain with a Hybrid ASD system. The efficiency of each component considered for the project is shown in Table I.

TABLE I
EFFICIENCY COMPARISON MAIN COMPONENTS

Component	Conventional	Hybrid
Transformer	99%	99%
ASD	98.2%	97%
Main drive motor	97.5%	97.7%
Gearbox	98.3%	98.0%
Servomotors	--	96.8%
System @ rated point	93.17%	95.04%

The component arrangements of the two systems are different and the losses per components are proportional to the efficiency of each component and the power going through as illustrated in Fig. 12.

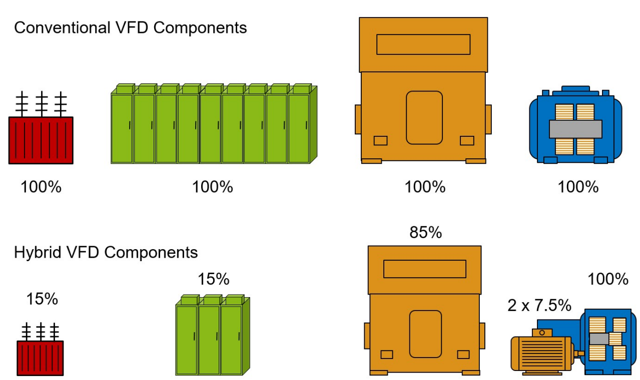


Fig. 12 System comparison

For instance, at the rated operating point, the Hybrid ASD uses 15% of total power for providing variable speed this means the ASD and transformer losses are proportional to 15% of total power while in conventional ASD system, the equivalent transformer and ASD losses are proportional to the 100% power flow.

Motor losses are proportional to 85% for Hybrid ASD compared to 100% for conventional ASD system. The gearbox losses in both cases have to bear 100% of the power and therefore the losses are proportional to the full power.

At the rated operating point, we can use the following equations to determine the system efficiency for both cases:

Conventional ASD –

$$\eta_{Syst} = \eta_{Tr} \times \eta_{ASD} \times \eta_{MM} \times \eta_{PSG} \times 100\%$$

Hybrid ASD –

$$\eta_{Syst} = (0.15 \times \eta_{Tr} \times \eta_{ASD} \times \eta_{SM} + 0.85 \times \eta_{MM}) \times \eta_{PG} \times 100\%$$

Where

η_{Syst}	System efficiency
η_{Tr}	ASD transformer efficiency
η_{ASD}	ASD efficiency
η_{MM}	Main drive motor efficiency
η_{PSG}	Parallel shaft gear efficiency
η_{SM}	Servomotor efficiency
η_{PG}	Epicyclic gear efficiency

The auxiliaries required for such systems have an important impact on power consumption and therefore on the overall system efficiency. The type of cooling considered has a major impact on the power consumption of the auxiliaries. Cooling of the ASDs is crucial and will be air cooled (limited power range) or water cooled. Air cooled ASDs have an adverse impact on the electrical room air conditioning while water cooled ASDs require a more complex setup. The water cooled ASDs are cooled via an external water-to-water plate heat exchanger, with de-ionized water in the primary circuit and raw water in the secondary circuit. The primary circuit is a closed circuit. The raw water for the secondary circuit is either available on site (sea water, cooling towers, etc.) or within a closed circuit cooled by a dedicated chilling system. The chilling system is composed of a chiller unit and a raw water pumping skid [12].

The auxiliaries relative efficiency is calculated according to the below formula:

Auxiliaries efficiency –

$$\eta_{Aux} = (P_{Load} / (P_{Load} + P_{Aux})) \times 100\%$$

Where

η_{Aux}	Auxiliaries relative efficiency
P_{Load}	Driven machine power
P_{Aux}	Main auxiliaries power consumption

The categories included are listed in Table II.

TABLE II
MAIN AUXILIARIES PER SYSTEM

Auxiliaries	Conventional	Hybrid
HVAC for e-room	☑	☑
ASD water cooling system*	☑	☒
Lube Oil Pump	☑	☑
Oil Cooler	☑	☑

*ASD water cooling was not considered for the Hybrid ASD since the required power range allowed the use of air cooled ASDs. ASD air cooling requirement is included in the HVAC e-room power consumptions.

The total system efficiency considering the main components and the main auxiliaries are summarized in Tables III and IV.

TABLE III
TOTAL EFFICIENCY COMPARISON WITH COOLED RAW WATER AVAILABLE ON SITE

Component	Conventional	Hybrid
Auxiliaries relative efficiency with cooled water available on site	98.9%	99.2%
Main component system efficiency @ rated point	93.17%	95.04%
Total System efficiency @ rated point	92.14%	94.28%

TABLE IV
TOTAL EFFICIENCY COMPARISON WITH DEDICATED CHILLING FOR RAW WATER

Component	Conventional	Hybrid
Auxiliaries relative efficiency with dedicated chilling for raw water	96.5%	99.2%
Main component System efficiency @ rated point	93.17%	95.04%
Total System efficiency @ rated point	89.91%	94.28%

Across the full speed range, an improvement in efficiency can be achieved. Fig. 13 shows a comparison between the two technologies. Fig. 14 and Fig. 15 show the efficiency improvement including the main auxiliaries based on the two cooling scenarios.

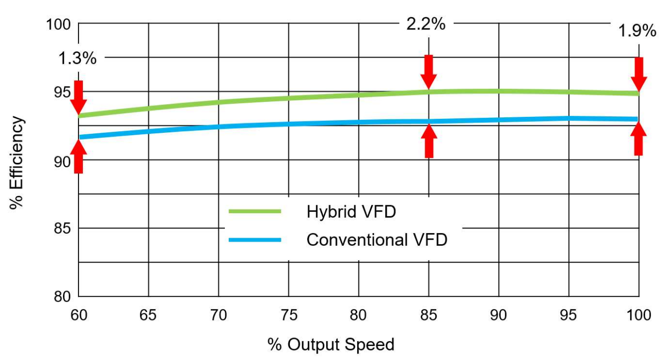


Fig. 13 Main Components Efficiency over full operating range (Table I)

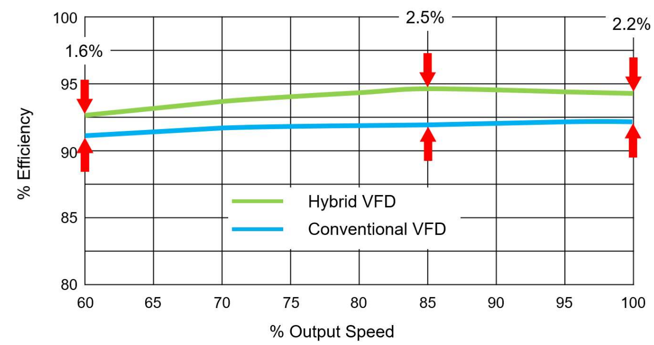


Fig. 14 Total system efficiency with cooled raw water over full operating range (Table III)

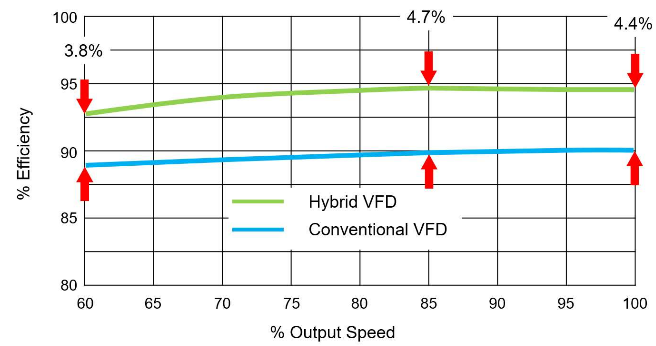


Fig. 15 Total system efficiency with dedicated chilling for raw water over full operating range (Table IV)

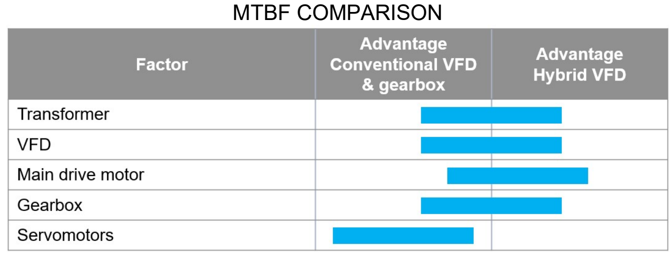
IX. RELIABILITY AND AVAILABILITY COMPARISON

Efficiency improvement is an important aspect and a major advantage, however, system reliability and availability are crucial as well to get the best system.

The conventional ASD system is an established design utilizing a well-known topology and proven components. The Hybrid ASD system also utilizes standard and well proven components with the same TRL level.

The definition of MTBF (mean time between failure) is clear, but the procedure as to how the values are calculated and interpreted can differ from component to component and from manufacturer to manufacturer. Therefore, we will consider a comparison of the MTBF of each equivalent component rather than a numerical comparison. Table V shows the comparison between each system.

TABLE V
MTBF COMPARISON



Another important aspect is the MTTR (mean time to repair). For the MTTR, the definition is also clear, but the interpretation still differs from manufacturer to manufacturer. What should be considered as MTTR is not just the repair time but the total downtime caused to the system. This starts from the diagnosis to the availability of personnel and spares required, followed by the fault correction until the restart of the system. A redundancy on critical elements, allowing a continuous normal or de-rated operation in case of single failure of these critical elements, increases the MTBF of the component and the overall system. The same logic will allow a reduction in the MTTR as the system remains operational while fault diagnosis and mobilization of personnel and spares are going on.

For ASDs used in both conventional or hybrid systems, n+1 redundancy on power electronics, 2x100% redundancy on cooling fans or pumps, 2x100% on chilling system, etc., can be implemented to increase MTBF and reduce MTTR. For the hybrid system an additional redundancy is available due to the use the two ASDs and two servomotors. In case of a failure of one ASD or servomotor, the Hybrid ASD can operate with a reduced power (~80% of rated power) and speed range allowing for a fully optimized and planned intervention.

From a reliability perspective, the two systems can be compared by looking at the availability of each system as they are not identically structured. The same failure might have a different impact on the system operation (a failure on the ASD of the conventional solution will stop all the operation while a failure on the ASD of the hybrid solution will allow operation in a de-rated mode). The availability is defined as the ability of a device to be in a state to perform the required function under given conditions at a given instant in time or over a given time interval assuming that the required external resources are provided [13]. Availability illustrates the relationship between system total uptime (MTBF) and unplanned downtime (MTTR).

$$Availability = \frac{MTBF}{MTBF+MTTR}$$

Regarding maintenance and service requirements, since both solutions use existing and well proven components, they both benefit from a well-designed overall service concept. This allows optimized overall service and maintenance to minimize downtime.

The Hybrid ASD system provides an increased system availability when compared to the conventional ASD approach. This is achieved by using similar components with equivalent reliability data but with the added ability to run in a derated mode in the event a loss of power to or from one of the servomotors.

X. CONCLUSIONS

By utilizing standard, well proven, components (each with a TRL of 7 or better) a high-efficiency Hybrid ASD system has been shown to have significant advantages over a conventional ASD. Advantages include –

a) An efficiency advantage of close to (or in excess of) two percentage points across a typical 70 – 100% speed range. Efficiency figures will vary from project to project and OEM to OEM. In addition, the efficiency basis (estimated vs nominal vs guaranteed with or without tolerances) and standards (IEC vs IEEE or other) should be equivalent and an allowance should be made for any auxiliary blower motors as these are typically not included in motor efficiency figures.

b) A smaller main drive motor with a voltage rating matching the site utility and a less complex cooling circuit (eliminating the need for blower motors).

c) Optional main drive motor starting methods with an “assisted” start or pony-motor type start reducing voltage dips during starting.

d) A packaged system with clearly defined ownership of the motors, ASDs, gearbox, lube oil system, couplings as well as lateral and torsional analysis of the complete train.

In addition to these factors, Table VI illustrates others including areas where the conventional ASD still retains some advantages.

TABLE VI
ADVANTAGES OF EACH SYSTEM

Factor	Advantage Conventional VFD	Advantage Hybrid VFD
Main motor LxWxH/kg		■
Main motor losses		■
Driver lube oil kW & l/min	■	■
Driver inertia	■	■
Driver & skid LxWxH/kg	■	■
Starting torque	■	
Starting current	■	■
Max foundation load	■	
Gearbox maintenance	■	■
ASD LxWxH/kg		■
ASD shipping & installation costs		■
Commissioning time & skills		■
Overall CAPEX	■	■
Overall OPEX		■
Carbon footprint (from losses)		■

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XII. VITAE

Mark Chisholm is a graduate of Loughborough University of Technology with a Bachelor of Technology (Hons) in Mechanical Engineering. After graduation he worked for GEC in Rugby, England. He has worked for GE as a Director of Application Engineering and as Principal Business Development Manager for Siemens Industry, Inc. Today he manages the ELIN Motoren GmbH business in North America. He has over 40 years of experience in the field of medium and large motors and generators. He is a senior member of IEEE, author and coauthor of a number of IEEE PCIC papers and is a voting member in API 541, 546 and 547 task force meetings.

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