White Paper

Motion Control within Safety Critical Downhole Applications

In Chul Jang
Jeff Blasz

Key Messages

- Reliability: EHA technology will provide increased reliability by eliminating EMA drive train jamming concerns. The reduced well intervention cost will decrease the total cost of ownership.
- Safety Rated: The solution space will include a SIL rated "safety" actuator, decreasing the customers design effort.
- Higher Force: EHA technology will provide a larger force capability for a given diameter compared to EMA technology. The reduced footprint will decrease the total tool cost.
- Modularity / Packaging: EHA technology allows for a modular architecture, providing the flexibility to tailor solutions that require increased functionality and/or diagnostics.

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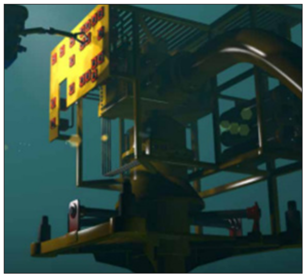
Summary

A Subsurface safety valve (SSSV) is a critical safety element within an offshore production system. The industry has experienced many deficiencies and challenges with the current Electro-Hydraulic (EH) technology associated with safety valve motion control. This technology has environmental and performance pains due to loss or leakage of the hydraulic control fluids over the life of the system.

Industrial markets have benefited from the use of Electro-Hydrostatic Actuation (EHA) systems. These systems combine the benefits of EH and Electro-Mechanical (EM) technology, typically operating at high system efficiencies. Within this paper the readers will see the benefits of EHA associated with SSSV applications. Furthermore, it will provide technology assessments between EHA and EMA. The assessment will provide insight to performance and safety rating for a Safety Integrity Level (SIL) application requirement.

Based on the qualitative and quantitative data developed from the technology development project, we believe the readers will see the value that EHA technology can provide to safety critical control valve applications. Within this report test results will be shared, documenting the performance comparison between EHA and Electro-Mechanical Actuator (EMA). In addition a top down safety risk assessment, and the systematic process used, will be shared. Moog believes the following items will address the pains and challenges associated with the electrification of Subsurface Safety Valve actuators.



1 Introduction

A Subsurface Safety Valve (SSSV), also referred to as a Downhole Safety Valve (DHSV), is a critical element of Safety and Pollution Prevention Equipment (SPEE) system [1],[2]. These systems protect offshore personnel and the environment by stopping the flow of well fluids (crude oil, natural gas, and water) in the event of an emergency. The figure below shows the typical offshore configurations that utilize an SSSV element.

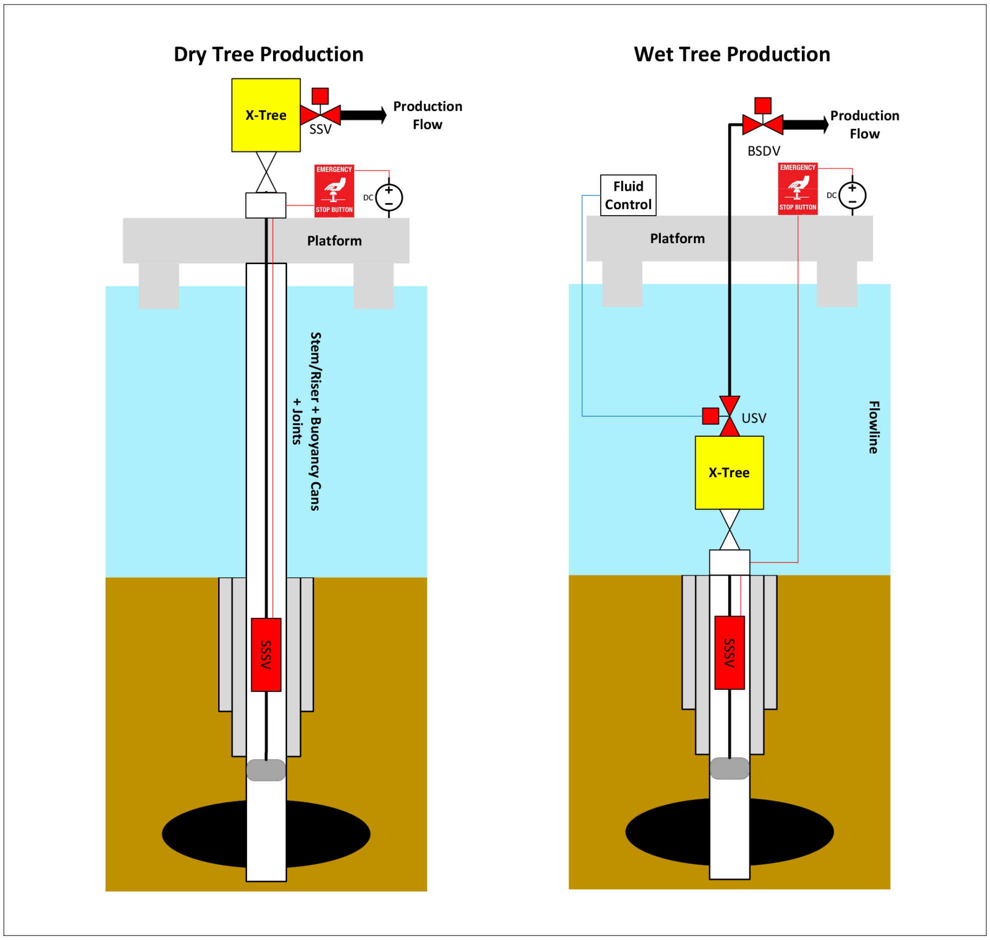


Figure 1 – Offshore Production Configurations [2]

Typically the SSSV is actuated to the open position using hydraulic energy from the surface, these require long hydraulic containment hardware. Due to these long runs of hydraulic power lines and the environmental concerns associated with them, the industry is trending to utilize electric solutions. While there has been focus on Electromechanical Actuation solutions (EMA), Moog believes an Electro Hydrostatic Actuation (EHA) solution is superior. Moog believes the application of SSSV aligns with the typical drivers requiring an EHA solution:

- Combining benefits from electrohydraulic (current state) and electromechanical actuation systems
- Higher efficiency
- Reduction of the machine footprint by eliminating the HPU and/or piping
- Modular setup with multiple customer choices

Main Advantages and Disadvantages

	EM	EH	EHA
Energy Efficiency	✓	✗	✓
Environmental Cleanliness	✓	✗	✓
Low Noise Emission	✓	✗	✓
High Forces	✗	✓	✓
No Backlash	✗	✓	✓

Figure 2 – High Level Technology Drivers

Furthermore, Moog believes the EHA solution to be less complex than the EMA solution by eliminating the jamming risk of a ballscrew or decupling mechanisms at the actuator output and valve interface.

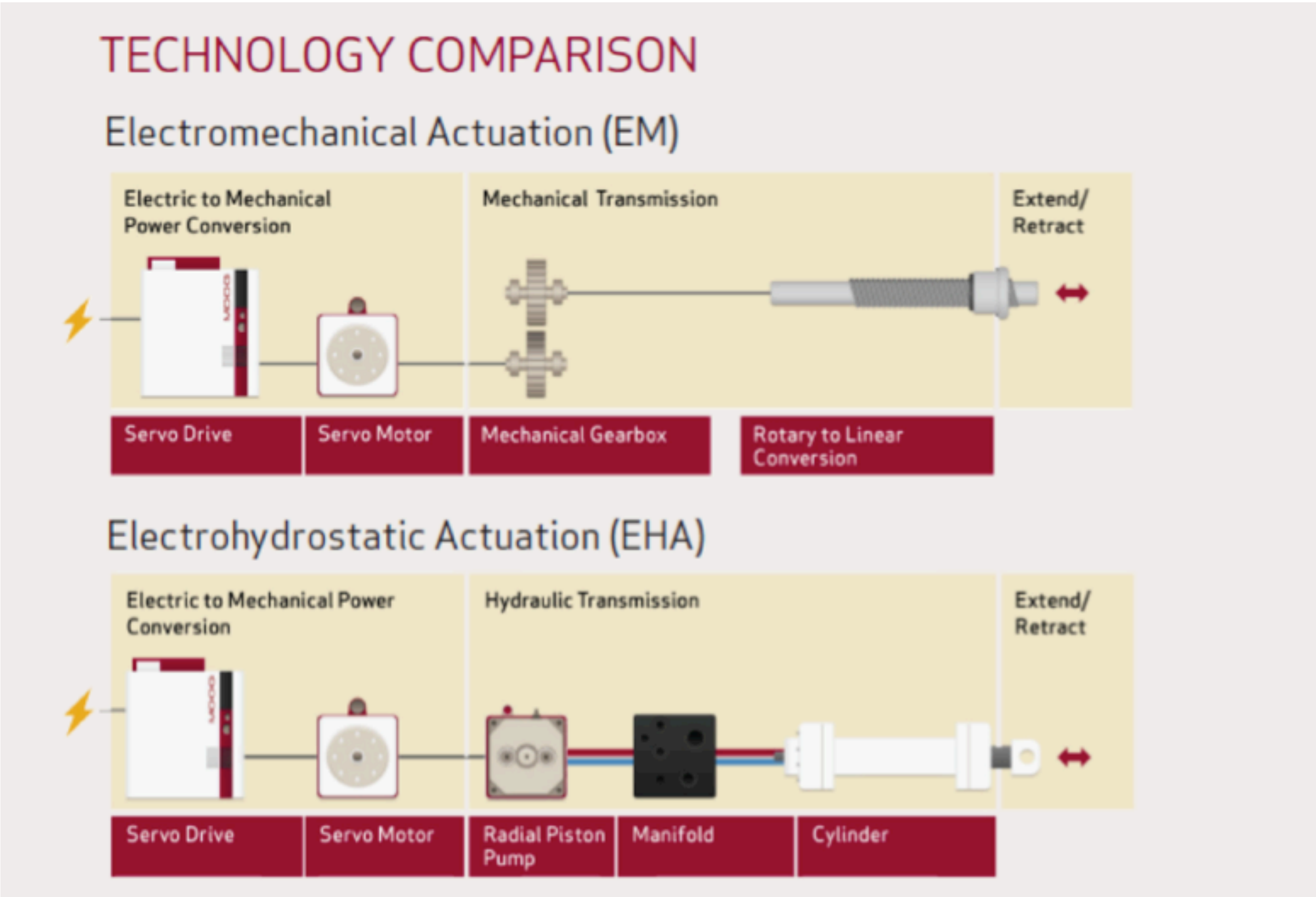


Figure 3 – EHA and EMA Technology Comparison

Looking at the SSSV application and the functionality required for safety and valve operation, Moog has generated and performed verification on the following EHA concept. The concept leverages proven EHA technology used within Aerospace applications demanding safety and reliability. The actuator (Downhole Mechanical / Hydraulics) concept utilizes proven building blocks for a downhole environment and can be tailored as needed to interface with a given Downhole Customer Valve. Shown in Figure 4 is the EHA concept (Downhole Mechanical/Hydraulic Block) and its interfaces for an SSSV application. The downhole electronics provides the interface to the Subsea Control Module (SCM) communicating key attributes of the EHA and sensor data. System diagnostics can automated at the SCM using predefined functions, limiting the computational needs of the Downhole Electronics.

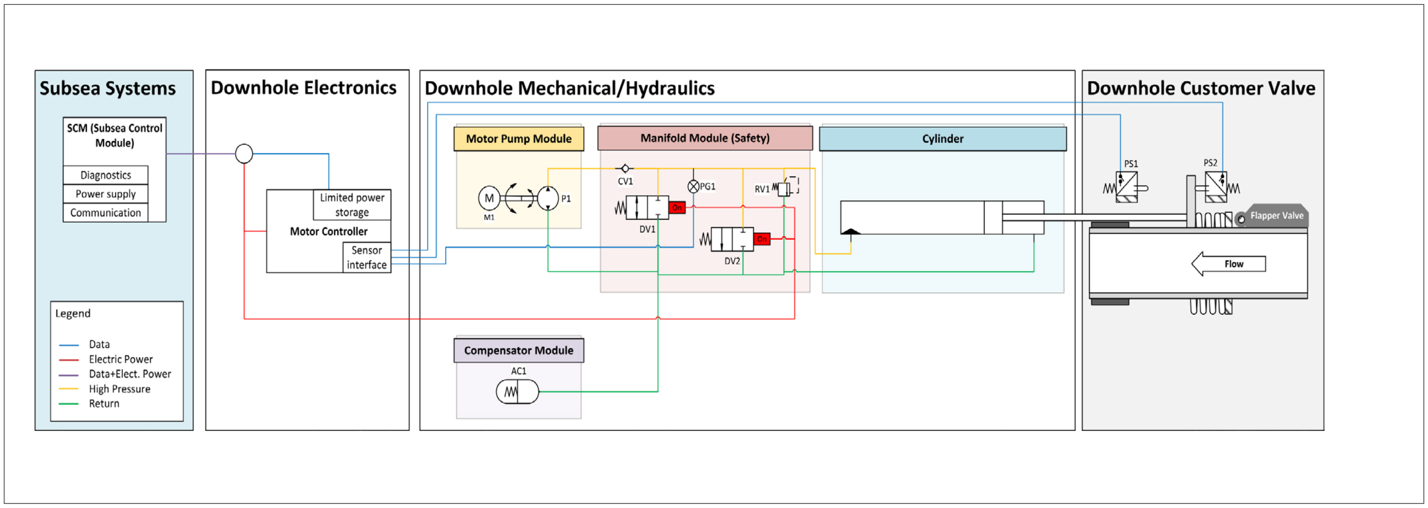


Figure 4 – Moog SSSV EHA Concept Diagram

Likewise, the representation in Figure 5 shows the core elements located within the wellbore of an SSSV application. From the Figure 5 one can further understand the Modularity benefit associated with EHA technology. Moog believes EHA technology allows the customer to tailor the packaging of the key modules (Motor Pump Module, Manifold / Safety Module, Compensator Module, Cylinder, and Electronics) within the well tubing much easier than EMA technology. EMA technology typically utilizes highly customized and integrated solutions, resulting in a long single-axis physical architecture.

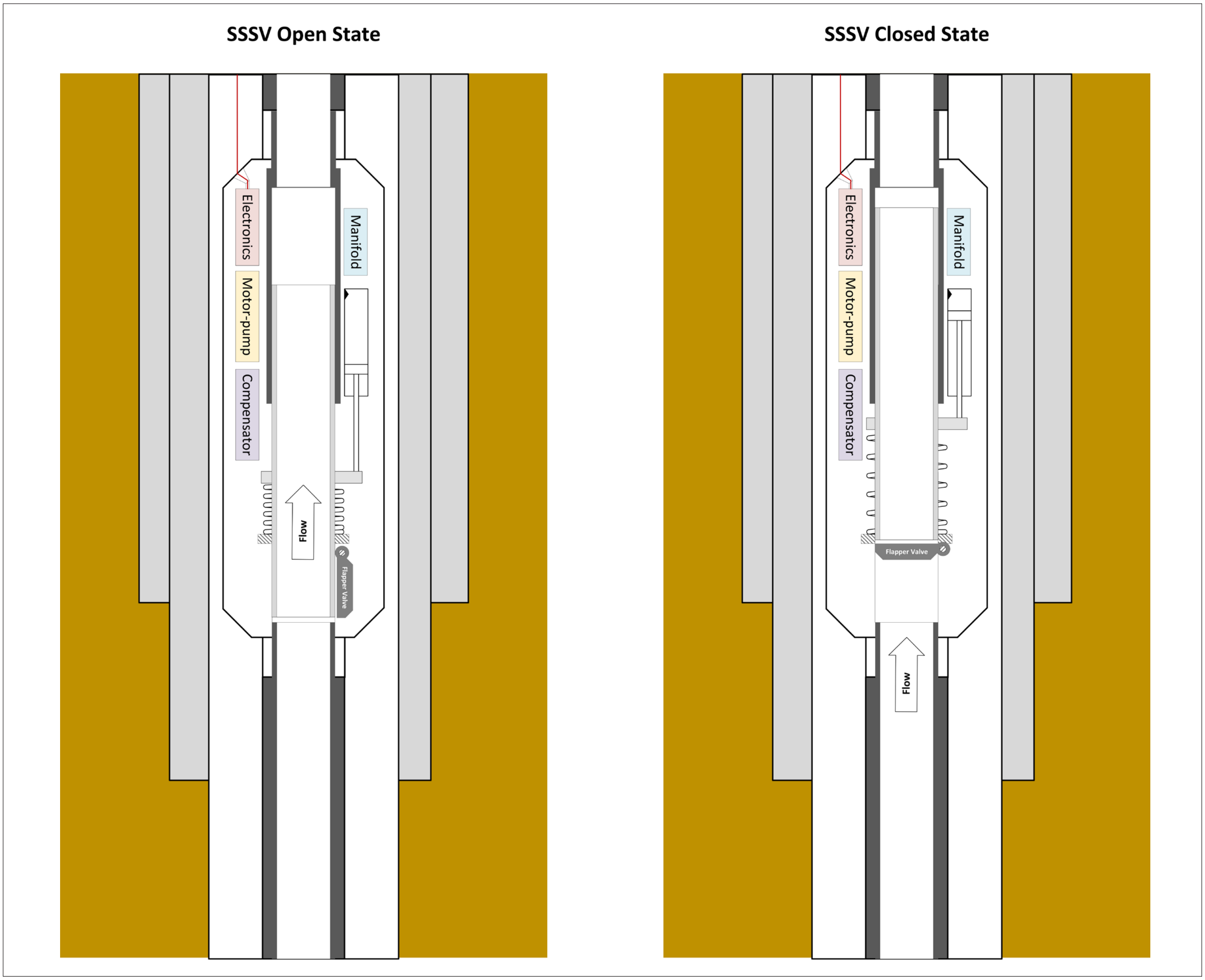


Figure 5 – SSSV EHA Physical Architecture Concept

2 Functional Safety

The SSSV is part of a system dedicated to executing a SIF (Safety Instrumented Function); isolation of production/injection bore. According to the Norwegian Oil and Gas Association [1], a SIL 3 is needed to achieve the safety function. This statement assumes a low demand mode where regular activations (i.e., diagnostics test and/or actual demands) are required to confirm the ability of the device to function. As defined by IEC 61508 [2], a low demand system is a system that operates only upon a demand and where the frequency of demands is no greater than one per year and applies the PFD (Probability of dangerous Failures on Demand) as the measure for loss of safety (see Table 1). Common examples of such systems include HIPPS (High Integrity Pressure Protection System) and an ESD (Emergency Shut Down).

Safety Integrity Level (SIL)	Average probability of a dangerous failure on demand of the safety function (PFD_{avg})
4	→ 10^{-5} to < 10^{-4}
3	→ 10^{-4} to < 10^{-3}
2	→ 10^{-3} to < 10^{-2}
1	→ 10^{-2} to < 10^{-1}

Table 1 – Target failure measures for a safety function operating in low demand mode of operation

Unlike EH actuation systems with a central HPU and hydraulic capable umbilicals used in traditional SSSV installations, EHA and EMA SSSV systems rely solely on electric power (or lack thereof) to both actuate and trigger the safety function demand (via ESD). Figure 6 illustrates the overall bore isolation system using an ESD.

Based on the bore isolation system on Figure 6, a block diagram representing the functional safety elements was illustrated on Figure 7 below. PWV/CIV (Production Wing Valve/Chemical Injection Valve) and PMV (Production Master Valve) are actual elements carrying their independent PFD, while CCF (Common Cause Failures) are additional PFD factors based on historic reliability data.

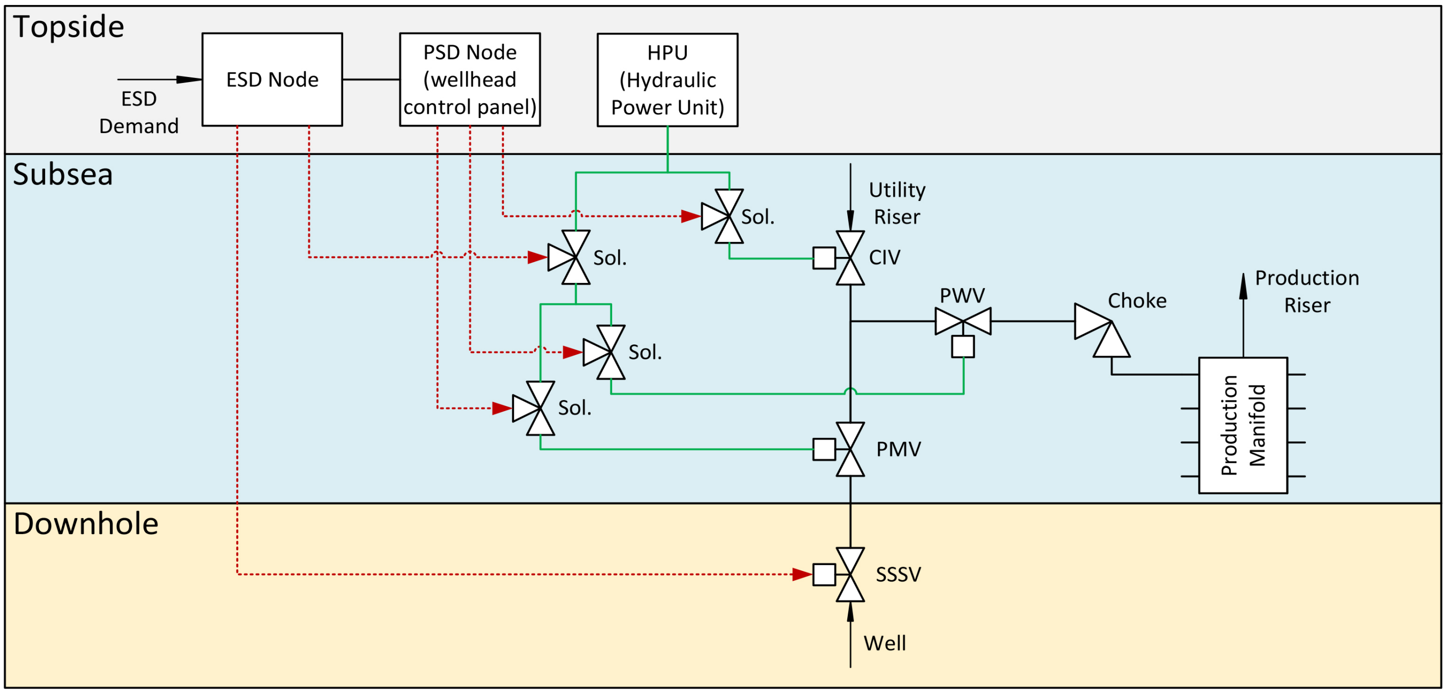


Figure 6 - Isolation of production/injection bore using ESD function definition with electric SSSV

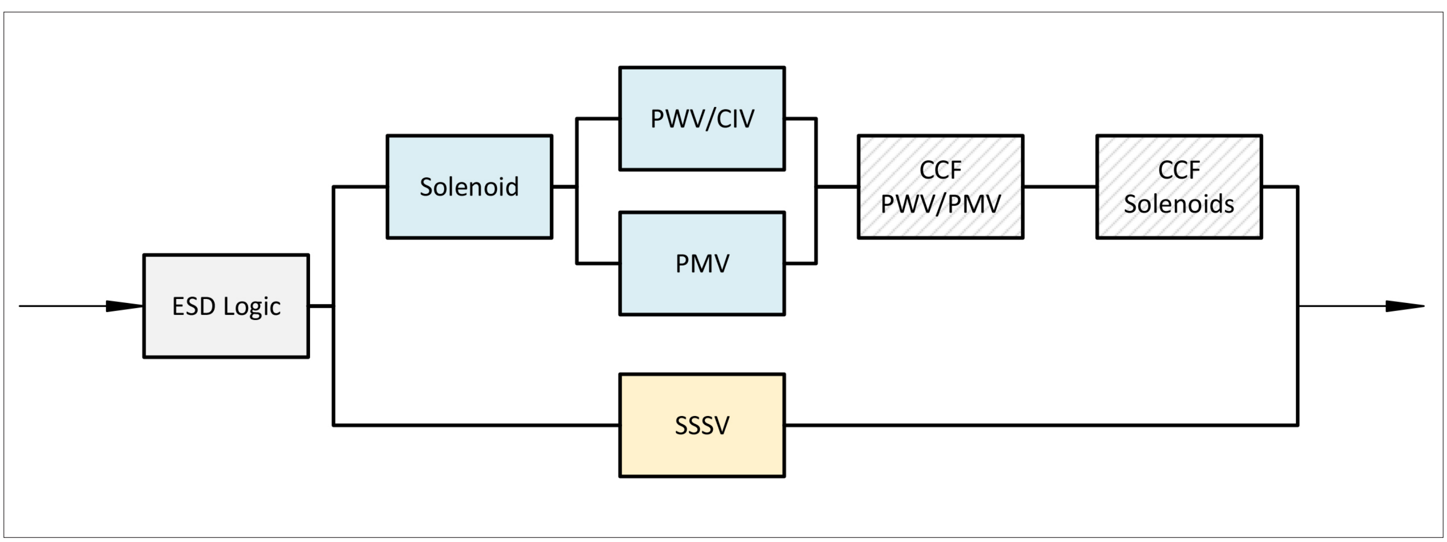


Figure 7 - Safety function block diagram for isolation of production/injection bore with electric SSSV

In order to achieve a SIL 3 for the isolation of production/injection bore SIF, it can be estimated that a maximum PFD of 9.6 x 10-3 could be budgeted for an SSSV hardware given the assumptions listed on Table 2 below. Therefore, a conservative PFD budget of 30% (2.9 x 10-3) could be allocated to the actuator within the SSSV considering that mechanical valve component technology is very much mature within this application space. Alternatively, a system composed of only SIL 3 capable elements (e.g. SSSV actuator), can ease the safety integration process to reach a system SIL 3. This is achieved by ensuring that all elements within the systems are SIL 3 capable given the right architecture.

Component	Proof Test Interval (τ) [Months]*	Demand Mode	Failure Rate (PFH_D/λDU) [$1/10^6$ hrs]**	PFDavg
SSSV System	6	Low	4	9.6×10^{-3}
SSSV Valve Asm.	6	Low	3	6.7×10^{-3}
Actuator	6	Low	1	2.9×10^{-3}

****Intervals can be as low as 1/month right after installation, reducing PFDavg***

*****Assumes automated diagnostics implemented***

Table 2 – SSSV assumed minimum requirements for production/injection bore isolation for ESD function

By leveraging a Category 3 architecture, based on the ISO 13849-1 [4] framework and SISTEMA software [3], an EHA SSSV actuator concept capable of achieving SIL 3 (equivalent to Performance Level e, per ISO 13849-1) was created using commonly used downhole rated component technologies. Figure 8 and Figure 9 provides a schematic representation of the physical and safety function architectures respectively. The design features 2 solenoid operated normally open micro-hydraulic valves working independently in parallel to add redundancy ensuring valve closure when a safety function is demanded.

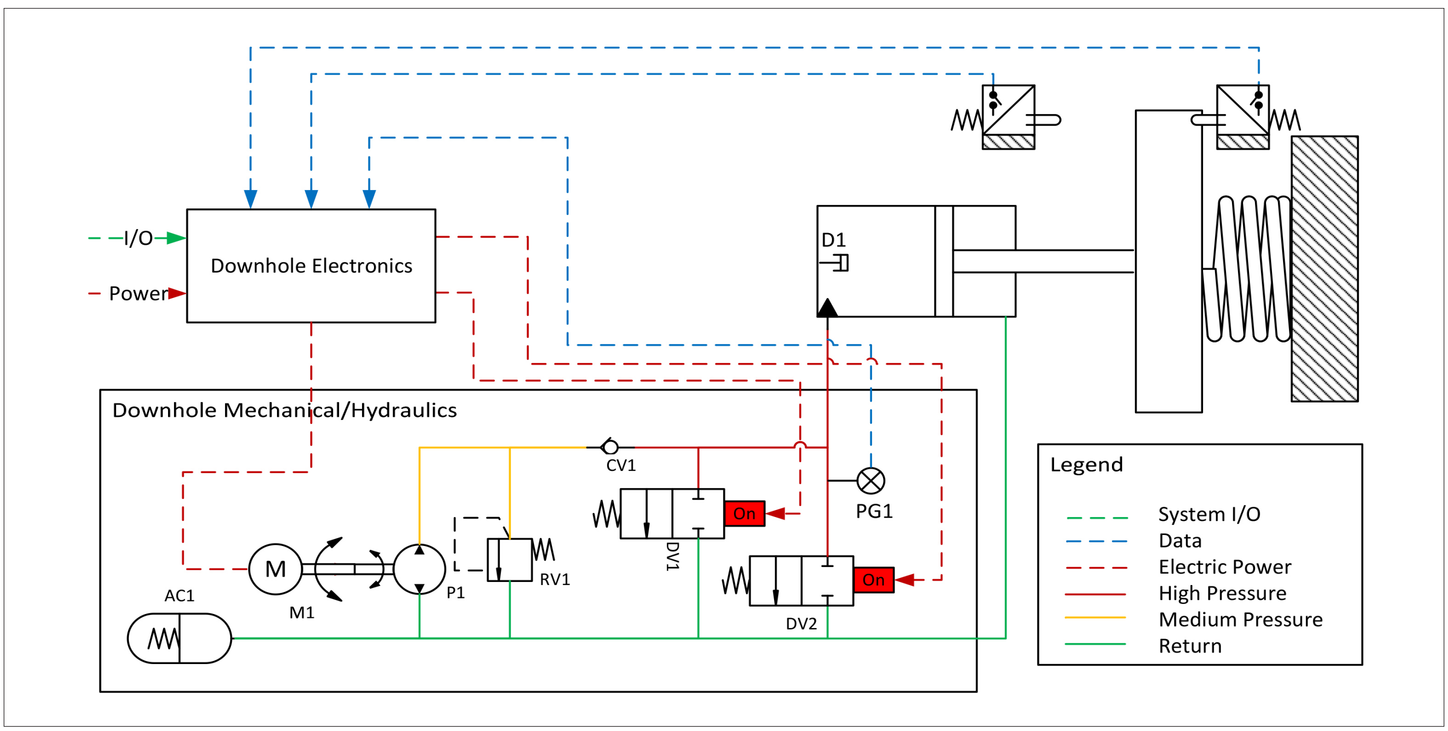


Figure 8 - SSSV EHA actuation SIL 3 capable concept (at energized extend state)

Overall, the design concept produced an SSSV EHA capable of achieving a PFDave of 1.8 x 10-4 (assuming a 6 month proof test interval). Ultimately, such EHA would allow the system integrator to easily achieve the desired SIL 3 safety function by either meeting SIL 3 component level readiness or exceeding PFDave requirements for the isolation of production/injection bore SIF.

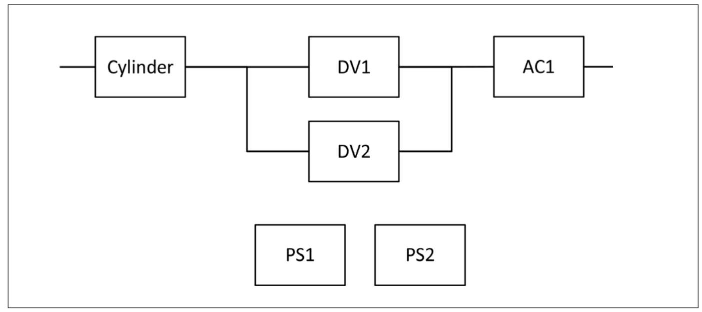


Figure 9 – Safety function block diagram SSSV EHA

3 Technology Comparison

When comparing an EHA and EMA technologies in the context of an SSSV application, the following characteristics can be highlighted:

Maturity → Historically Moog has been successful in the downhole permanent completions market with EMA solutions. Moog EMA technology has been continuously improved over the years by challenging our technology to smaller diameter and relatively higher force capacities. Recently, Moog has produced and tested a 1 inch diameter EMA design prototype for SSSV applications. Similarly, a 1 inch diameter EHA design prototype was also produced and tested (see Figure 10 through Figure 13).

Force/diameter → Maximizing force output at a small diameter is always challenging for linear actuators. SSSV applications require small diameter (e.g. 1 inch) actuators, as these are installed in an annular cavity within the valve body. While an EMA is more suitable for mid-range force loads with high peaks of short durations, EHA systems are ideal for constant high force outputs. In general, an EHA tends to provide a higher continuous force relative to an EMA. However, this performance gap has been hard to distinguish for applications requiring small diameters, low life/total cycle/speed requirements.

Like ball bearings, EMA ballscrew designs are generally limited by the contact stresses between the ball and ball track. Moog ballscrew fundamental design approach follows ISO 3408-5 [7], limiting the basic axial static load to that which produces a permanent deformation of 0.0001 times the ball diameter at the ball and ball track at the most heavily stressed point of contact. This limit, based on application specific needs, can be pushed to an extent at the expense of expected life. On the other hand, EHA designs are limited by the effective piston area and the pressure the system is rated to.

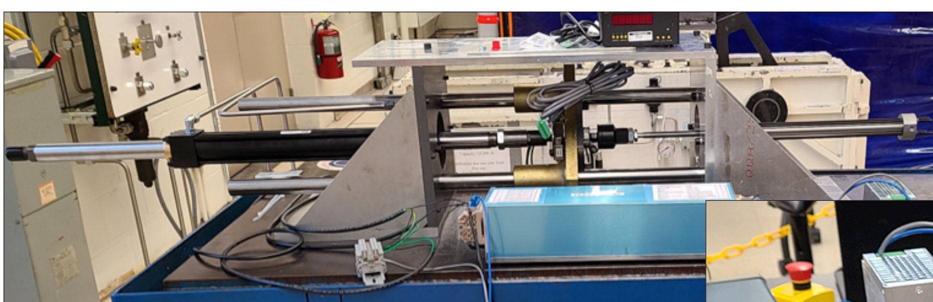


Figure 10 – SSSV EHA test setup

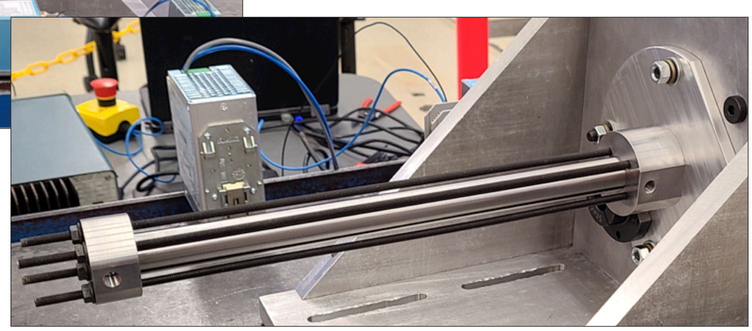
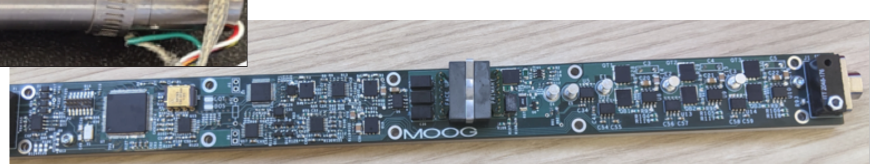


Figure 11 – SSSV EHA 1 inch diameter cylinder

Figure 12 – SSSV EHA 1 inch diameter motor pump module

Figure 13 – 1" Wide Downhole Electronics



One primary advantage of the EHA is its capability to sustain a dynamic axial load equal to its static load due to the lack of high contact stresses that are generally produced by rolling elements. At the same time, one of its main drawbacks is the lower force capacity under tension (relative to compression) given that cylinders are generally un-equal area types within this application space.

Figure 14 and Figure 15 below illustrate capabilities (empirical) of the 1 inch diameter EHA and Figure 16 illustrates the capabilities of the 1 inch diameter EMA. A key differentiation of EHA is its maximum force handling capacity which is nearly 2 times that of the EMA. Table 3 summarizes the comparative performance capabilities.

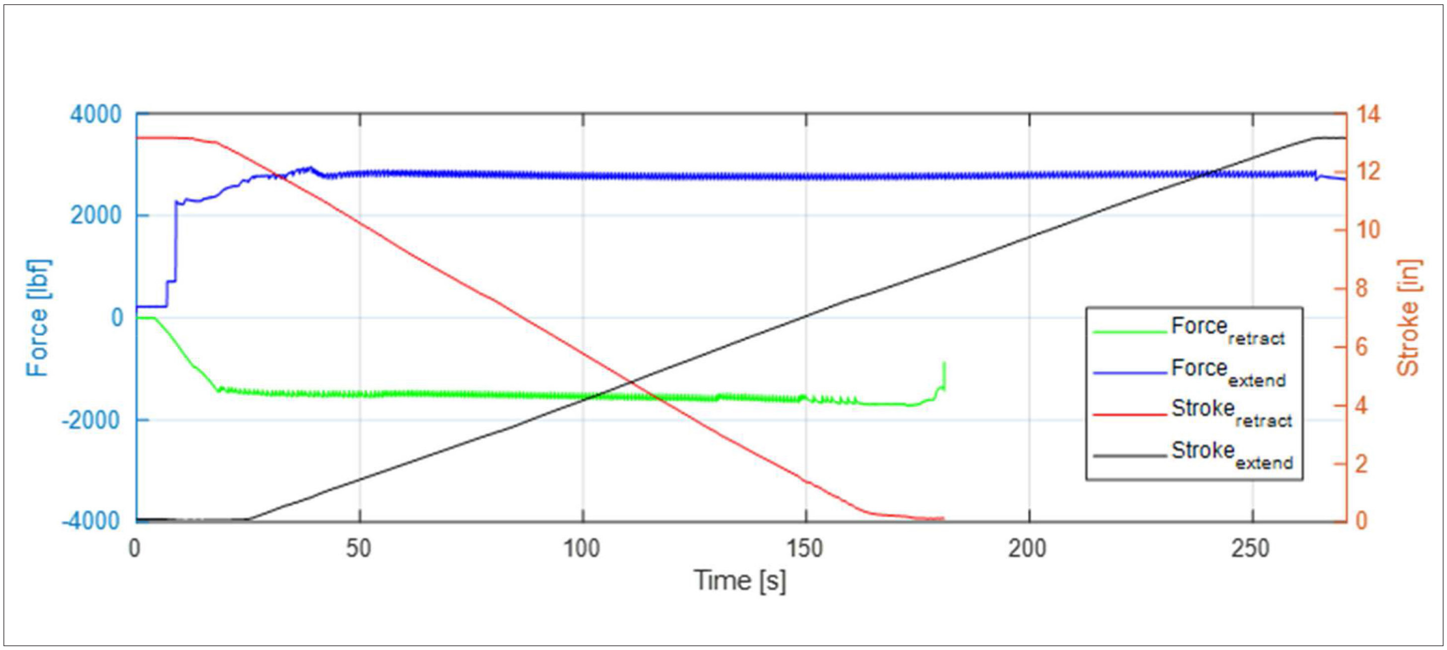


Figure 14 – SSSV EHA full stroke (extend and retract) at maximum loads

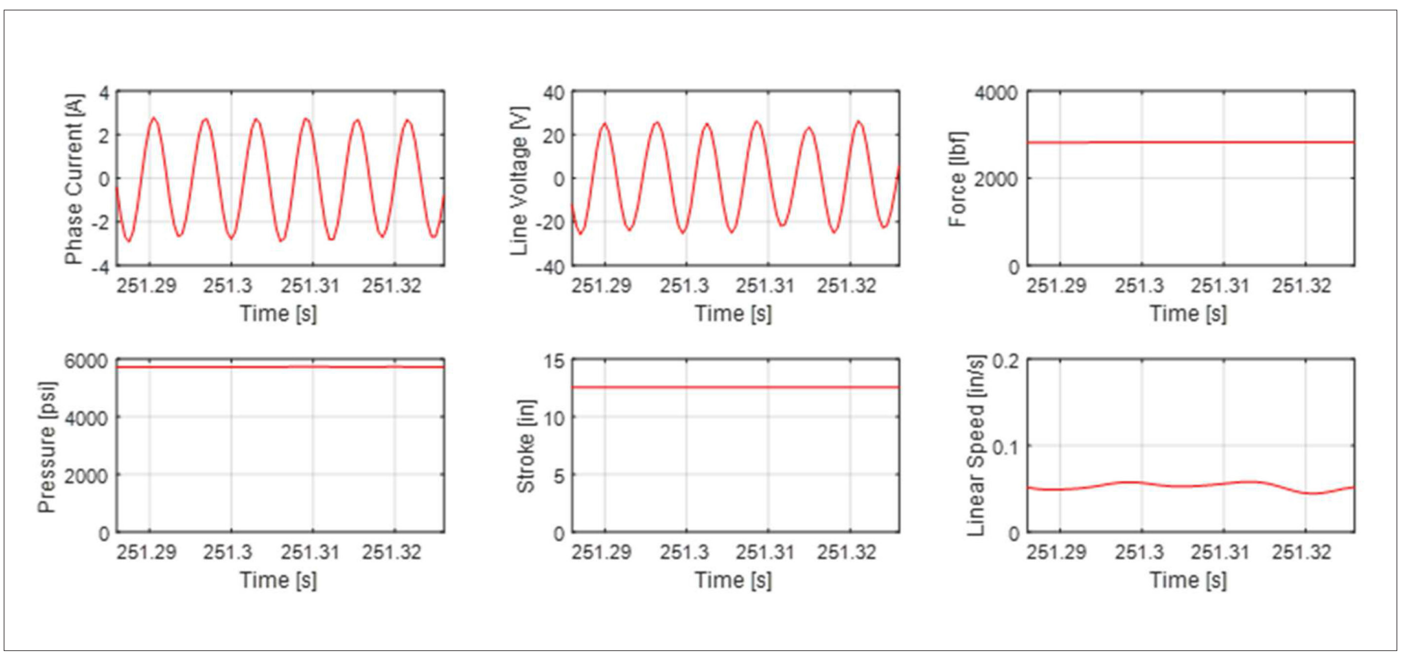


Figure 15 – SSSV EHA full stroke (extend and retract) at maximum loads

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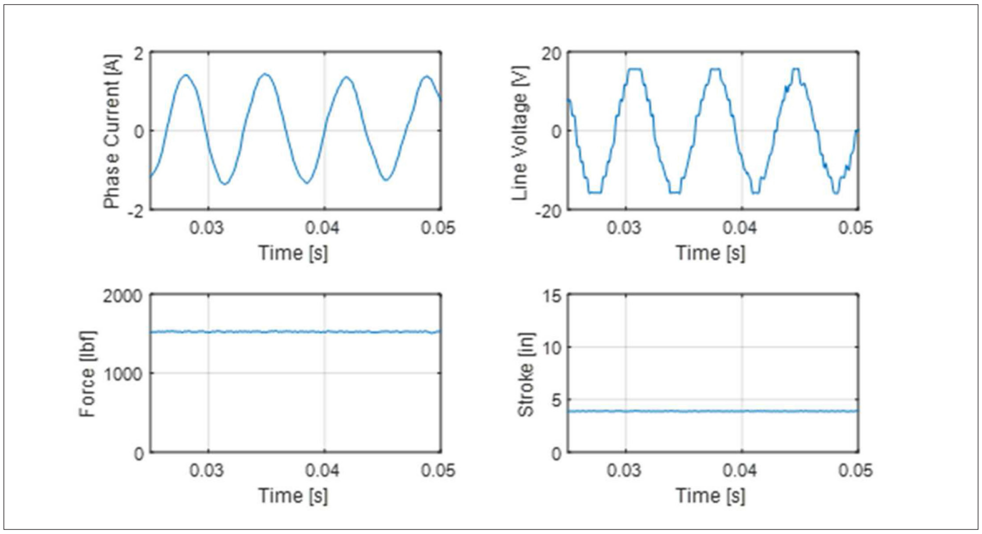

Figure 16 – SSSV EMA during extend at full load (0.034 in/sec)

System	Force [lbf]	Phase Current [A_{rms0}]	Power Out [W]	Efficiency [1%]	Kf [lbf/A_{rms}]
EHA	2831	1.9	15.6	24	1442
EMA	1520	0.9	6.5	38	1588

Table 3 – 1 inch SSSV EMA vs EHA performance capability comparison at extend (SSSV opening operation)

Impact resistance → EMA designs are limited by drivetrain inertia induced stresses which drastically reduce its impact resistance capabilities unless additional mechanisms (e.g. clutch) are introduced. In contrast, EHA designs allow for high impact resistance capabilities as existing internal pressure relief valves can safely manage the added impact induced pressure. This feature drastically enhances life and reduces actuation control complexities, which is critical given power and computational cost limitations on downhole electronics.

Efficiency → Unlike traditional EH systems for SSSV applications, EHA systems can achieve similar efficiencies to that of an EMA system given the right operating conditions and low leakage micro-hydraulic components. This is primarily achieved by eliminating centralized long hydraulic power transmission and localizing hydraulics at the actuator strictly for power transduction..

Reliability and robustness → The inherent metal-to-metal rolling/sliding contact interfaces within the EMA, introduces a catastrophic risk of seizing the actuator resulting in the SSSV's inability to close. This drives the need for additional drivetrain decoupling mechanisms and/or redundant actuators to remedy this risk at the expense of overall system efficiency and footprint. In contrast, the highest risk carried by an EHA system is internal leakage (across both sides of the cylinder). Such risk can impact performance (e.g. time to open SSSV and system efficiency), however it does not affect the key safety function of the SSSV (valve closure).

Modularity → While an EMA requires its drivetrain components to be ideally in-line to the actuator axis in a single package, an EHA can be very flexible in terms of installation. There are two main packages within the EHA: motor-pump module and actuator cylinder. These two sub-assemblies are always linked by two hydraulic lines and can be installed in flexible arrangements in near proximity.

Part complexity → Both EMA and EHA do share common components such as motor and resolver. However, the rest of the transmission components are quite distinct between the two systems in terms of manufacturing complexity. An EHA requires common hydraulic components (such as pump, cylinder and manifold) and uses a lower overall number of parts. On the other hand an EMA requires more complex parts such high ratio precision gearboxes as well as a small diameter precision ballscrew.

4 Conclusion

As the industry looks to electrify within the O&G market, Moog is capable of providing EMA and EHA solutions. However, the EHA concept presented is an attractive solution for safety rated applications, while providing the benefits associated with electrification. An EHA solution is less complex and more reliable than a ballscrew driven EMA. An EHA can easily and more readily facilitate a SIL 3 rating for an SSSV system. Furthermore, an EHA itself could be SIL 3 rated reducing the safety integration effort for a required application. This SIL 3 rating assumes an example Low demand application. If the application requires a continuous demand it will require further diagnostic sensing elements. The EHA solution would leverage Moog's proven products, Downhole Motors and Downhole electronics, allowing for tailored solutions. Given the same footprint, the EHA concept can provide a greater output force (>1.5 times) when compared to an EMA solution.

The EHA has appealing tradeoffs compared to EMA technology for downhole motion control. Likewise, Moog believes an EHA is better suited for a SIF system and shall decrease the total cost of ownership over systems life cycle.

5 References

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AMERICAS
USA +1 716 652 2000
Brazil +55 11 3572 0400

EUROPE
France +33 1 45 60 70 00
Germany +49 7031 6220
United Kingdom +44 168 429 6600
Russia +7 (83171) 3-18-11

ASIA PACIFIC
Australia +61 3 9561 6044
China +86 21 2893 1600
India +91 80 4057 6666
Japan +81 463 55 3615
Korea +82 031 764 6711
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