Hydraulic Direct Drive Solution
for Cutterhead function

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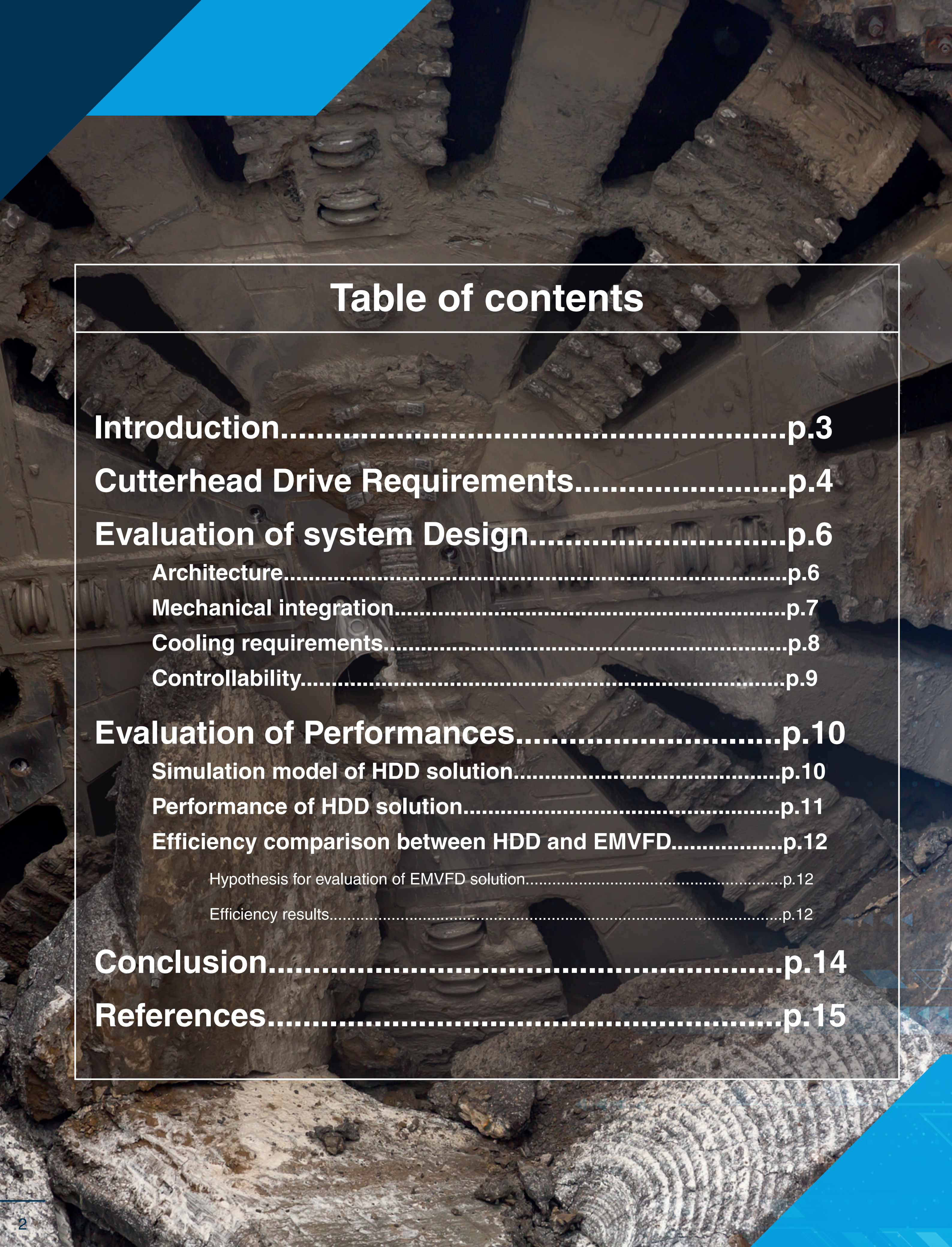

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Introduction

Cutterhead drive systems in TBMs are designed to operate in harsh conditions by maintaining the highest level of performance, reliability, availability, maintainability and safety. Many cutterheads are driven by electric motors with reduction gearboxes [ref. 1, 2, 3]. However, hydraulic drive solutions meet these requirements, while maintaining good efficiency for typical TBM duty cycles.

After a short review of cutterhead function specifications, a design of a hydraulic direct drive (HDD) solution will be described. A simulation model of the HDD solution will be proposed in the last section, and the first results of performance and efficiency will be presented.

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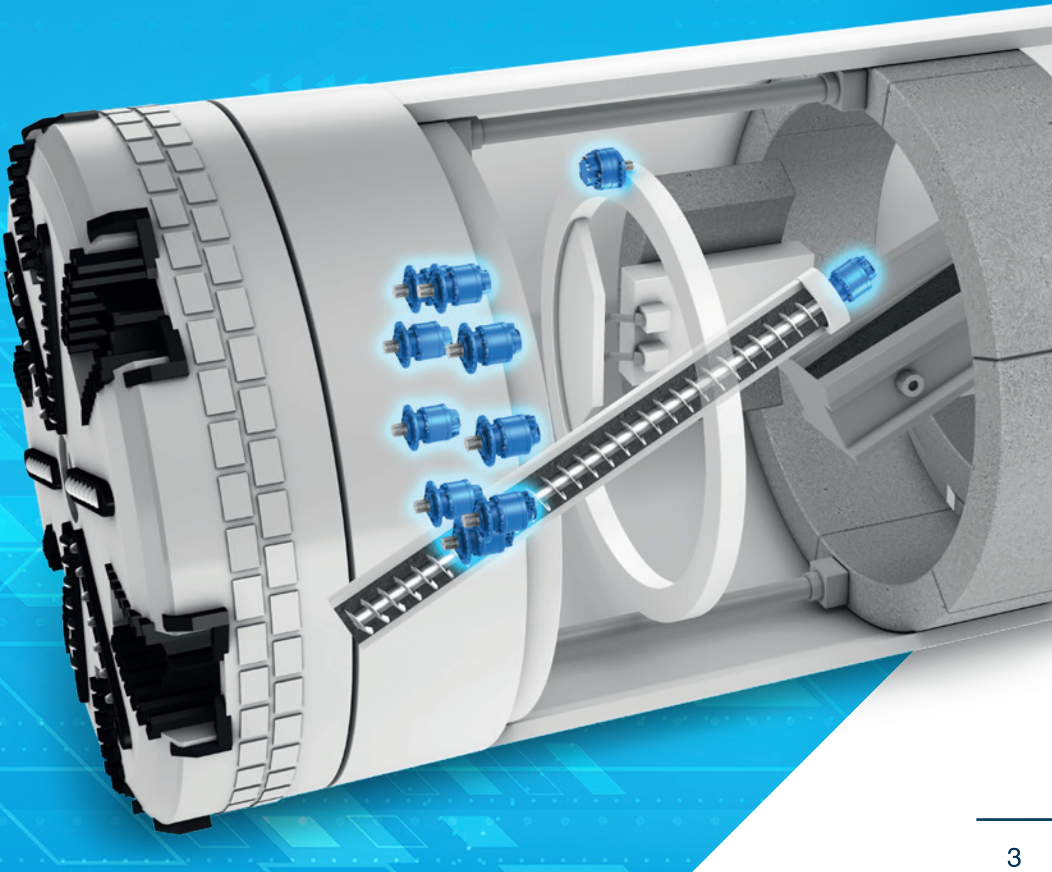


Cutterhead Drive Requirements

For the needs of the study, a typical EPB-TBM with a diameter of 6 meters is taken as an example. Based on [ref. 4], it is possible to determine empirically the torque required to drive the cutterhead according to Equation (1).

$$T = \alpha D^3 \qquad (1)$$

Where T is the cutterhead torque (ton-m), D is the EPB-TBM machine diameter (m), α is an empirical coefficient. For the EPB-TBM, a coefficient α between 1 and 2.5 is proposed. For the purpose of this study, a coefficient of 2.5 is considered. Based on torque requirements and typical rotation speeds, Table 1 summarizes the main specifications for the function. Four operating points between 35% and 150% of maximum torque are specified. Maximum power is also derived from most demanding cases. The breakout torque enables the HDD to handle starting situations with a heavy load.

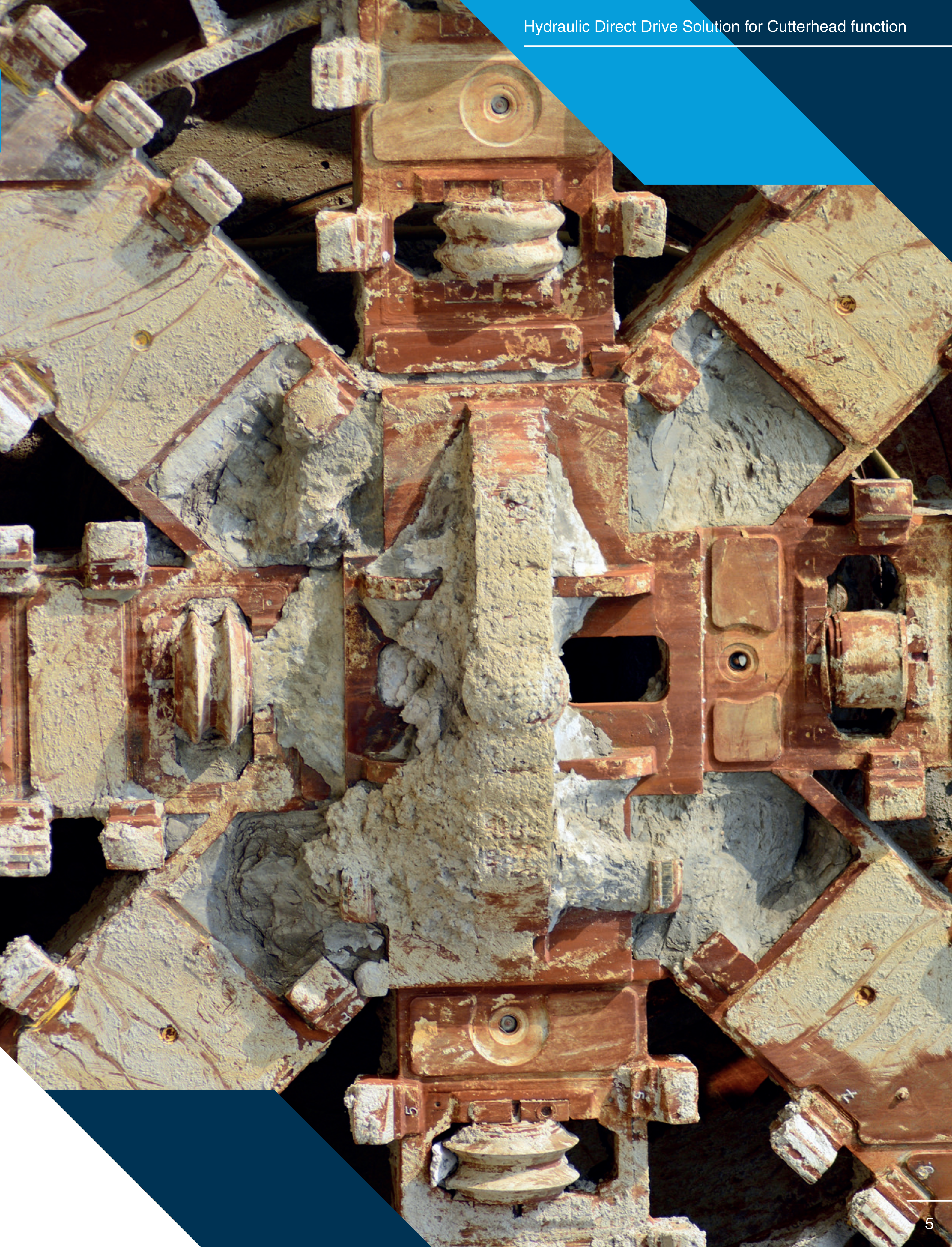
Table 1 – Cutterhead specifications of EPB-TBM

Key technical parameters	Input data
EPB-TBM diameter	6m
Cutterhead rotation speed range	From 0 to 3 RPM
Maximum torque @ 1.3 RPM	5400 kN.m (100%)
Nominal torque @ 2 RPM	3510 kN.m (65%)
Minimum torque @ 3 RPM	1890 kN.m (35%)
Breakout torque @ 0.1 RPM	8100 kN.m (150%)
Maximum needed power at the cutterhead	735 kW @ maximum torque @ 1.3 RPM
Gear ratio between crown/pinion	7
Main bearing diameter	3m
Rotation direction	Clockwise (CW) and Counter clockwise (CCW)
Cutting head crown inertia	1 400 000 kg.m²

In order to enable evaluation of average power consumption presented at the end of this document, a weight of the four operating points of Table 1 is proposed in Figure 1.

Figure 1 – Duty cycle for Cutterhead

Load case	Applied torque at crown		Rotation speed of crown	Time
	N.m	%	rpm	%
Max Speed Min Torque	1 890 000	35	3	30
Nominal orque	3 510 000	65	2	64
Max Torque	5 400 000	100	1.3	5
Breakout Torque	8 100 000	150	0.1	1



Evaluation of system Design

Architecture

Figure 2 gives an overview of the main constituents of different cutterhead drive architectures, from electro-mechanical variable frequency drive (EMVFD) to HDD solution. One can note that the different solutions offer different positioning of the components from the control room to the head.

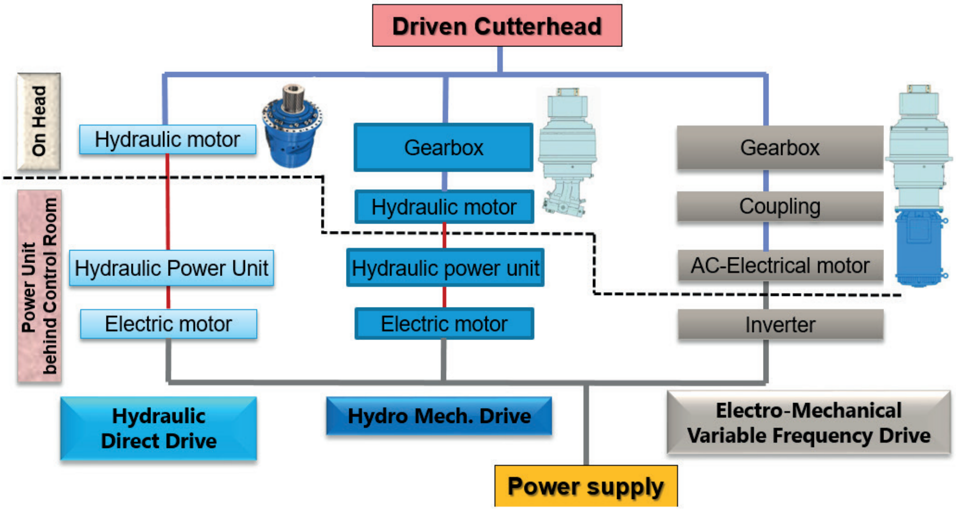


Figure 2 – Cutterhead drive types

A typical sizing of both HDD and EMVFD solutions for the specific requirements of a 6m-TBM is given in Table 2.

Table 2 – Proposed drive solutions

Cutterhead Drive design	Hydraulic Direct Drive	Electro-Mechanical Variable Frequency Drive
Cutterhead drive motor	9 hydraulic high torque low speed motors MI250 (HTLSM radial design) in direct mounting (displacement of 9*30L)	8 electric motors (110 kW each –1000 rpm) coupled to 8 planetary gearboxes GB 31003 [ref. 5] (reduction ratio: 66.94)
Transmission type	Closed-loop hydrostatic transmission	Electro-mechanical transmission
Variable speed generator	Hydraulic power unit (HPU) with 7 heavy duty variable displacement pumps coupled to 7*E-motors (160kW each) at 1480 rpm	Variable Frequency Drive (VFD) unit
Cooling unit	Oil cooling unit in HPU	Liquid cooling for gearboxes, E-motors & VFD
Total weight on Cutterhead	~10 tons (9 valves x 130kg+ 9 motors x 920kg)	~27 tons (8 E-motors*1120kg + 8 GB*2220kg)
Maximum drive length	694 mm	2 270 mm
Additional moment of inertia on cutterhead	162 kg.m^2 (9 motors x 18 kg.m^2)	175 656 kg.m^2 (8 motors/GB x 21957 kg.m^2)

Mechanical integration

As can be seen in Figure 2, one of the advantages of hydraulic transmission solutions is the simplicity in the arrangement of the different constituents. The position of the Hydraulic Power Unit (HPU) remains very flexible and can be adapted to each TBM design. This also offers the possibility to adapt the installed power without heavy modification of the arrangement of components on the head side.
Table 2 shows us that the HDD comes with a much smaller length (-70%) and less weight (-63%), thus facilitating the installation when space is limited, and no special need to reinforce the cutting head structure. It is interesting to notice that high torque low speed motors (HTLSM) technology provides integrated bearing support.

Another important feature of HDD solution is the limited moment of inertia added to the head. In EMVFD, the reduction ratio of the gearbox highly amplifies the inertia of the electric motor (e.g. Figure 3) and the gearbox also participates in the total inertia.

Figure 3 – Mass moment of inertia of gearbox (left) versus HTLS hydraulic motor (right)

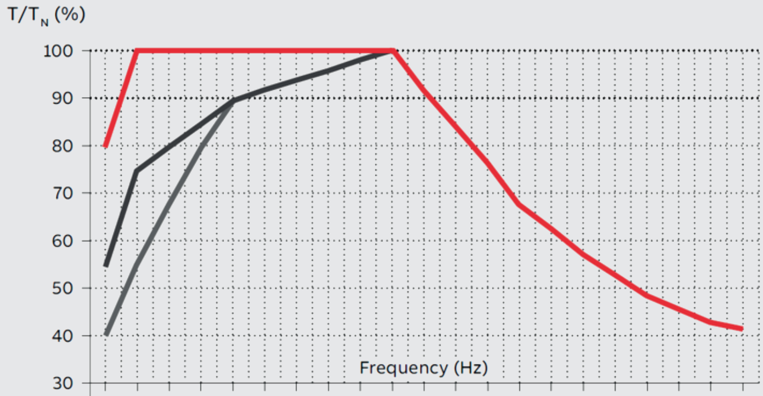
Based on our evaluation of the crown inertia given in Table 1, it is possible to estimate that the final drive can represent at least 10% of the total inertia for electro-mechanical solutions while it is negligible in the case of HDD transmission. This facilitates good management of transients either coming from the load or the control.
This characteristic also participates in the self-protection of the system: low moment of inertia will limit risk of overload or backlash on the mechanical shaft of the final drive during fast transients (blocking head for instance). As an addition, the torque of the HTLSM will be limited hydraulically using pressure limiters, standard valves that offer a simple solution with good reactivity when positioned close to the motor. In the end, due to these specificities, the HDD solution does not require safety coupling to act as a fuse on mechanical shaft, thus increasing availability of the TBM and reduced maintenance.

The capacity of the HTLSM and heavy duty pumps to go up to very high pressure (450 bar as a standard value) enables full transmission downsizing, which will limit the flow, the tank volume, the power demand and the piping sizing.
Finally, the choice of a closed-loop circuit for the HDD solution can drastically reduce the volume of the oil tank compared to an open-loop solution. The majority of the total flow recirculates in the closed loop. Thus, the flow going in and out of the tank through the charge pump is low, and only used to keep pressure level and cool the closed-loop circuit (e.g. Figure 6). This limits the need for deaeration, which is one of the criteria for sizing the tank.

Cooling requirements

One of the advantages of hydrostatic technology is the ability to carry load without power consumption. HTLSM can operate at maximum pressure/torque without any time restriction, and cumulate start/stop sequences. Moreover, due to an infinitely variable transmission ratio thanks to a variable displacement pump, the torque and speed of the electric motor driving the pump are dissociated from the torque and speed on the cutterhead. It is thus possible to run the electric motor at a nominal speed of 1500 rpm for instance, enabling ideal natural cooling, work at breakout torque, and very low speed on the head without risk of overheating the electric motor.

On the opposite hand, working in breakout conditions for an EMVFD solution needs to be undertaken with care. First, the high current level involved in low speed (i.e. low frequency) and high torque conditions generates heat due to electric losses. Secondly, a cooling solution based on a shaft-mounted fan may turn too slowly to dissipate heat [ref. 6, 7].
According to data available in an electric motor catalog [ref. 6], forced cooling is highly recommended in order to enable operating below rated speed or below 50 Hz (e.g. Figure 4). Ratio of real torque T on nominal torque TN (i.e. T/TN) remains at 100% at low frequency with separate forced cooling.



	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
▬ IC411[1]	40	55	68	80	90	92	94	96	98	100	92	84	76	68	63	57	53	49	46	43	42
▬ IC411[2]	55	75	80	85	90	92	94	96	98	100	92	84	76	68	63	57	53	49	46	43	42
▬ IC416[3]	80	100	100	100	100	100	100	100	100	100	92	84	76	68	63	57	53	49	46	43	42

[1] Self ventilated, IEC frame size 71 - 132
[2] Self ventilated, IEC frame size 160 - 400
[3] Separate motor cooling (force ventilated), IEC frame size 160 - 400

Figure 4 – Characteristics of a standard E-motor VS type of cooling

Generally speaking, to limit volume in the TBM head, and enable cooling of both the motor and the gearbox, liquid cooling may be preferred. This will lead to a specific liquid circuit going from the operation room to the cutterhead. Additionally, no matter the cooling solution chosen for electric motors, going to breakout torque will only be possible for intermittent situations, and a protection of the system must be proposed.
In a hydrostatic transmission, due to the capacity of hydraulic oil to carry heat, the hydraulic fluid used to transfer power is also able to cool down the circuit and the components via two main methods: flushing of the components and, for closed-loop configuration, exchanging of hot oil with fresh oil in the high pressure loop. The flow required to do so is generated by the HPU, thanks to specific low-pressure pumps that are generally integrated in the main high-pressure pump or in tandem configuration with it. The power analysis done at the end of this document already integrates this capacity.
Figure 5 summarizes the operating limits of both HDD and EMVFD from proposed definition and sizing. The first one offers continuous operations on almost all of the required range while the second one is restricted in time for higher loads and lower speeds, despite appropriate cooling devices.

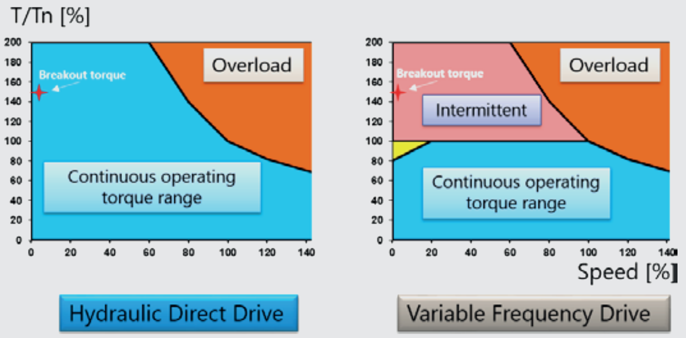


Figure 5 – Operating limits of HDD and EMVFD

Controllability

The HDD transmission solution can work on four quadrants (driving or braking mode in forward or reverse direction), when in a closed-loop circuit configuration.
Contrary to an open-loop circuit, there is no need to use directional control valves to reverse the direction (e.g. Figure 6).

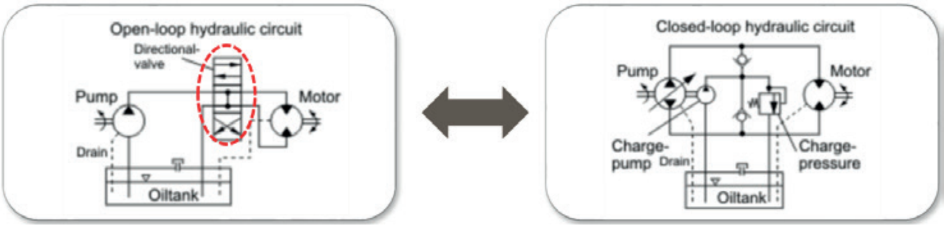


Figure 6 – Open-loop versus Closed-loop hydraulic circuit

An over-center variable displacement pump, used on closed-loop circuits, allows flow distribution in both directions. The flow, and thus the motor speed, can be controlled from null to maximum value. Classic pump control with mechanical feedback provides easy control of the flow enabling native speed control of the cutterhead. In this case, the pressure in the circuit will be a result of the load on the head. With a specific hydraulic control device or pressure sensors and electronic close-loop control, it is also possible to control both torque and/or speed, to adapt to required functioning modes and operating conditions. Finally, safety stop can be managed softly, electronically or hydraulically.

Working in four quadrants, and especially providing braking torque on the head, may be limited by the capacity of the electric motor driving the pump to work in generator mode. If needed, specific arrangements of hydrostatic circuits may have the capacity to dissipate braking power without wearing parts.
An important feature of hydrostatic transmission is the possibility to connect all components in parallel following the simplified schematic of Figure 7. This can be seen as a common rail with identical pressure, leading to perfect load synchronization of each pump and motor.

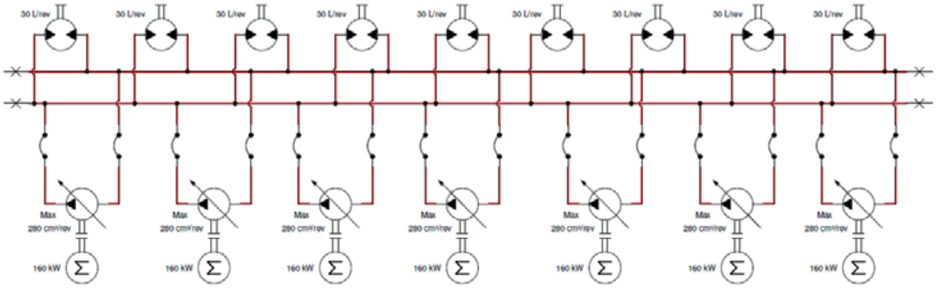


Figure 7 – Simplified cutterhead hydraulic direct drive system

Finally, the HTLSM can be individually deactivated with reduced drag torque. This feature is useful to limit installed flow and/or increase speed capacity (e.g. Figure 8), and needed to cover the requirements of Table 2.

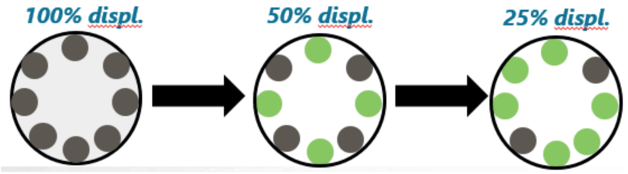


Figure 8 - HTLSM deactivation to reduce installed displacement and increase speed availability

Evaluation of Performances

Simulation model of HDD solution

In order to perform a simulation of the HDD solution for the purpose of performance and efficiency evaluation, commercial software Simcenter AMESim is used. The model (e.g. Figure 9) will integrate sizing of the HDD solution according to Table 2.

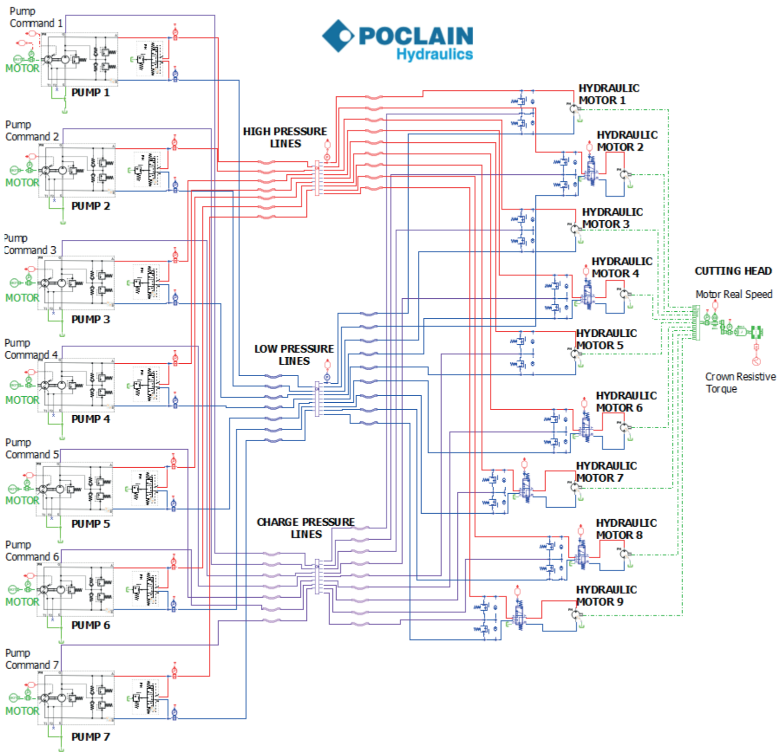


Figure 9 – HDD AMESim model

For performance and efficiency calculation, the following hypotheses are given:

- Hydraulic motors and pumps: table based losses – internal and external leakages, torque losses
- Valves (high-pressure relief valve, motor engagement/disengagement + exchange valves): main functional characteristics, pressure drop level in high pressure lines
- Charge pump consumption: 7 * 44cc low pressure pumps (mechanical efficiency 0.7)
- Hydraulic lines : regular pressure drop according to length and diameter, stiffness of the pipes can be adjusted (rigid or flexible) for accurate dynamic behavior
- Oil temperature: 50°C with HV46 oil (viscosity ~31 cSt)
- Gear efficiency at crown/pinion: 0.95

In order to follow a dynamic duty cycle, crown inertia is considered, and extra load can be added to simulate the soil resistance. In order to control the operating speed, a speed regulation loop is used.
To catch the maximum tractive effort of the transmission, a specific implementation of the model is chosen, imposing the speed of the cutterhead and regulating the load of the transmission considering maximum pressure and speed. It is then possible to adjust level of power and/or level of pressure to get the maximum performance envelope.

Performance of HDD solution

In order to study the efficiency of the hydraulic drive on duty cycle described in Figure 1, the model is used with imposed output load and speed regulation loop active. A typical result is presented in Figure 10.

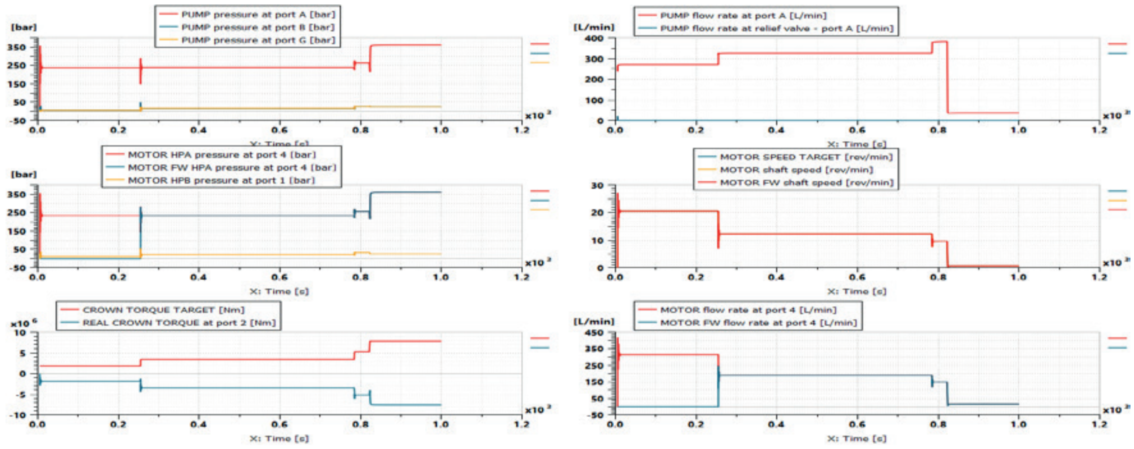


Figure 10 – Evolution of main parameters of the system following the cutting head duty cycle

The average high pressure for the load cases “Max Speed”, “Nominal Torque” is around 235 bars. For “Max Torque” load case, the average HP is around 260 bars. For “Breakout Torque” load case the average HP is around 360 bars. The speed target is appropriately achieved for each case.

In order to have complete overview of the performance of the system, the maximum envelope is calculated based on the model, for 160kW input power per pump, and a maximum differential pressure of 350 bars between the high and low loops, for different number of motor engaged, from three to nine motors engaged (e.g. Figure 11).

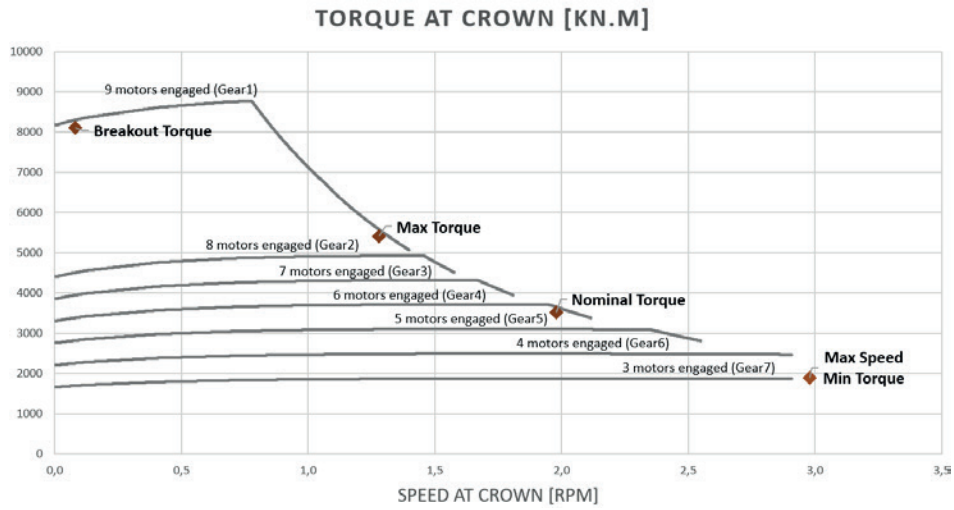


Figure 11 – HDD performance envelope

Efficiency comparison between HDD and EMVFD

Hypothesis for evaluation of EMVFD solution

Typical sizing of the EMVFD solution is taken in Table 2.

For efficiency calculation, the following hypotheses are given:

- Gearboxes (3 stages – ratio 66.94) - efficiency
  - at rated power: 0.93 (0.975 per stage => 0.975^3)
  - at 50% rated power: 0.89
- Asynchronous motors (110kW – 6 poles – 1000RPM – IE3) - minimum efficiency values defined in IEC/EN 60034-30-1: 2014 at 50 Hz for IE3: 0.951
- Variable Frequency Drive [ref. 8] - efficiency
  - at continuous operating conditions: 0.93
  - at maximum operating conditions: 0.91
  - at breakout conditions: 0.2
- Gear efficiency at crown/pinion : 0.95

Moreover, electric motor rotation is evaluated for each load case:

- Min torque at 35% x Tmax. & at 1406 rpm
- Nominal torque at 65%*Tmax. & at 937 rpm
- Max torque at 100% x Tmax. at 609 rpm
- Breakout torque at 150% x Tmax. at 47 rpm

Efficiency results

Based on these hypotheses, a mechanical gearbox delivers better efficiency in comparison to a hydrostatic transmission. However, when taking into account all components for HDD & EMVFD solutions, results are slightly different (e.g. Table 3). In terms of overall power efficiency, the HDD solution has 11 to 15 efficiency points lower than EMVFD solution for the three load cases up to 100% maximum torque. However, at breakout load case (150% breakout torque), HDD efficiency is 14 points higher when compared to electric drive architecture.

Table 3 – Global power efficiency comparison between HDD (hydrostatic transmission + electric motors) & EMVFD solution (gearboxes + electric motors + VFD)

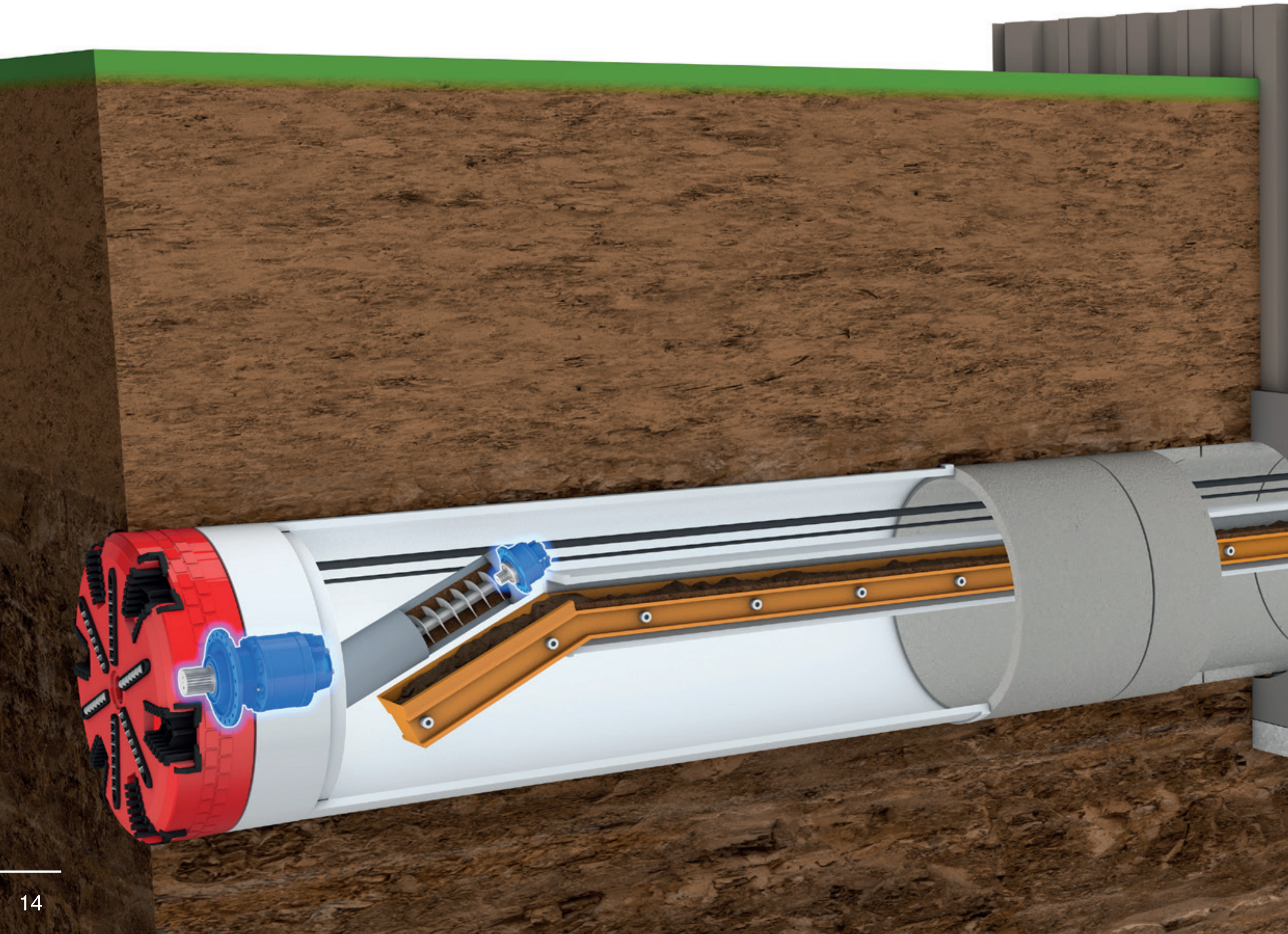
Time	Load Case	HDD solution	EMVFD solution
30%	Minimum torque at 3 rpm	75%	86%
64%	Nominal torque at 2 rpm	72%	86%
5%	Maximum torque at 1.3 rpm	69%	84%
1%	Breakout torque at 0.1 rpm	32%	18%
-	Average power efficiency for the global duty cycle	72%	85%

Conclusion

Two cutterhead drive systems have been analysed for an Ø6m-diameter EPB-TBM, comparing hydraulic direct drive and electro-mechanical variable frequency drive. HDD solution takes the advantage in terms of integration (compactness, reduced weight & length of hydraulic motors, integrated cooling system in closed loop hydrostatic solutions), load synchronization, and self-protection. Where the EMVFD solution has the advantage in terms of efficiency for nominal working conditions, the HDD solution brings higher performance levels and better efficiency at breakout conditions.

A hydraulic direct drive solution offers a relevant sustainable alternative to cover cutterhead function requirements, with a high level of robustness in harsh conditions and easy maintenance.

The proposed simulation model is ready to be used for the evaluation of system thermal stability, transient sequences, development of control strategies and study of interfaces with other TBM functions. Some of the advantages being already recognized by the OEMs we are in contact with, next steps are to test the proposed HDD solution on a TBM at prototype phase.



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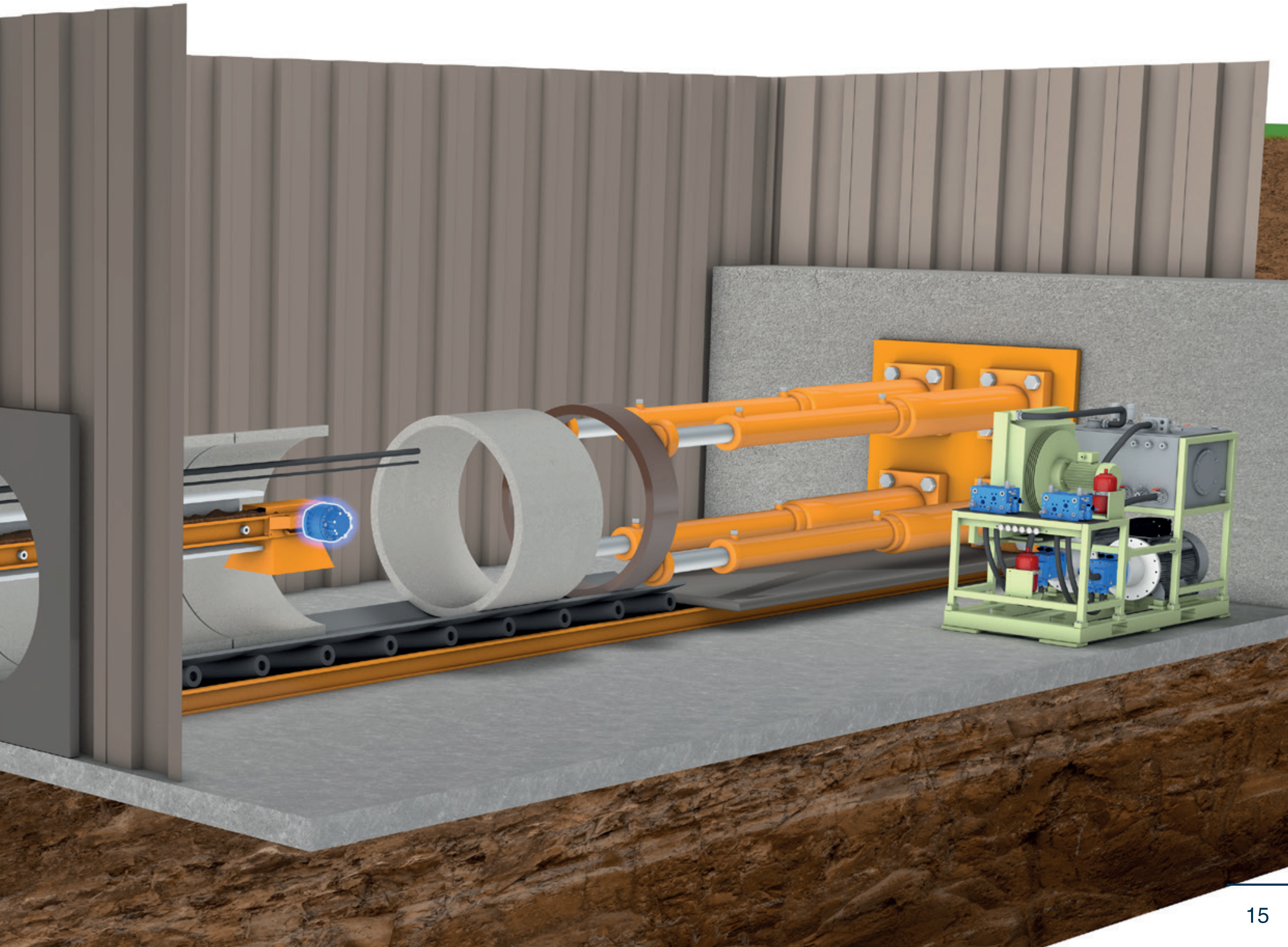

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