Influence of Fluid Selection on Synchronous Generators Power Output in Compressed Air Energy Storage Systems

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***Abstract*—The use of intermittent sources of energy in modern power grids makes frequency support more challenging. In case of contingent events, fast instantaneous reserve systems should be employed in order to restore the frequency. One of the promising solutions is the use of rapidly accelerated synchronous generators with hydraulic drive-trains. They are driven by energy from compressed gas in pneumo-hydraulic accumulators. To reduce the cost of recharging, nitrogen which is used in these accumulators, can be replaced with air. However, this has the potential to create a dangerous flammable mix of air and mineral oil within the accumulator. This paper investigates the effects of replacing mineral oil with a water-glycol blend in a hydraulic drive-train coupled to a 100 kW, 415 V, 3-phase synchronous generator. We find that water-glycol blends represent a useful approach to reduce the risk of an explosion at facilities where electro-hydraulic drive-trains are employed.**

I. Introduction

Nowadays, the shift from classic fossil fuel generation towards clean energy is more noticeable than ever before, leading towards a smart and sustainable network. Modern power grid is a technologically complex system that comprises a variety of different generation technologies. Meanwhile, the use of distribution generation units creates new challenges for power engineers. Especially in terms of frequency support in power grids, since the presence of intermittent energy sources makes this process more challenging. The project "Small-Scale Compressed Air Energy Storage System" can provide frequency support in power grids with the use of hydraulically driven synchronous generators [1], [2].

Hydraulic units and actuators are becoming more popular solutions than electrical and mechanical drive trains [3]. They have multiple advantages, such as light weight, ease of installation, maintenance and high efficiency (95-98%) [3], [4]. In modern terminology, a hydraulic system usually corresponds to a circuit filled with mineral oil [5]. This fluid imposes a significant risk of ignition, when a system experiences operational leakage or accidental spills. In this case it is imperative to find a feasible solution of replacing an existing hydraulic fluid with a fire-resistant solution (water-based fluids).

The International Standards Organization (ISO) defines four categories of such solutions [6], [7]:

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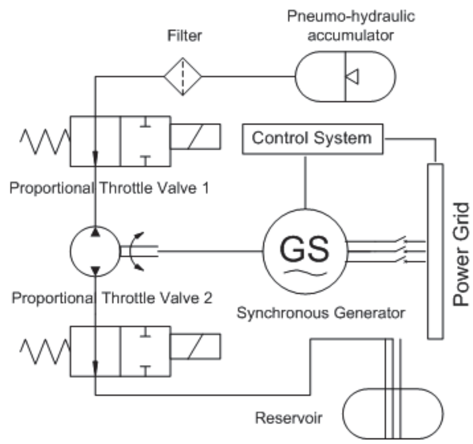


Fig. 1: Block diagram of the CAESS's electro-hydraulic drivetrain [1], [2].

- HFAE - oil-water emulsions with less than 80% water
- HFAS - synthetic aqueous fluids with more than 80% water
- HFB - oil-water emulsions with more than 40% water
- HFC - glycol, water glycol and polyalkylene glycol solutions, usually having more than 35% water

The latter option is the most widely used as it has the best fire-resistant properties, and this solution can be used even in a 600°C environment.

As an example of this system, a hydraulic drive train of the Compressed Air Energy Storage System (CAESS) [1], [2] is depicted in Fig. 1. The speed of the hydraulic motor is controlled by one of the proportional throttle valves, whereas another valve is fully open.

II. Health, Safety and Environment considerations

Water-glycol blends are suited for applications where a hydraulic fluid should be fire-resistant at high temperatures [4]. In order to perform acceptably in these systems, a water-glycol solution should have the following features:

- Good fire resistance

- Acceptable viscosity and viscosity index
- Good resistance to oxidation and deposit formation
- Seal compatibility

A. Fire resistivity of water-glycol solutions

Fire resistivity is one of the most important parameters that determine a choice of certain hydraulic fluids. Depending on the application it can be beneficial to replace an existing hydraulic fluid with a water-glycol mixture. In order to find a proper blend with respect to its fire resistive properties, a flammability chart is used (depicted in Fig. 3) [8].

Some Material Safety Data Sheets (MSDS), report the flash point of the 97%/3% blend is 111°C in a closed cup test (different from the presented value in Fig. 3). This is because of the difference between open and close cup tests, where the latter test shows the lower flash point, due to the absence of outside elements in the laboratory. This test is usually used as the worst case scenario to ensure high HSE standards [9].

The above described HSE conclusions show that it is feasible, just from the safety perspective, to replace hydraulic oil with water-glycol solutions. However, the second question is: will this change cause significant variations in the dynamic characteristics of electro-hydraulic drives, or not? In order to answer this, it is necessary to calculate the density, kinematic and dynamic viscosity of different hydraulic solutions (oil and various water-glycol mixtures).

B. Thickness and low viscosity index

Two major issues with the use of a water-glycol mixture are poor film thickness and a low viscosity index (VI). It can be solved by mixing a thickener (usually a polyalkylene glycol-PAG (IV)), that can also change the pour point and fire-resistant properties of the blend.

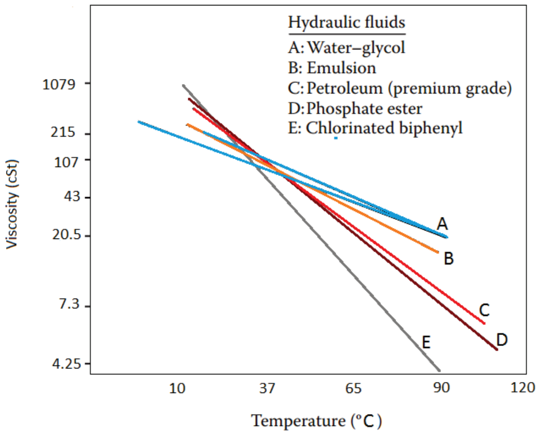
Fluid viscosity is not only an important parameter with respect to hydraulic system operation, but also to lubrication as well. Therefore, the most feasible solution is the fluid that experiences a small change in viscosity with varying temperature, like a water-glycol solution [6], [10] (Fig. 2(a)).

C. Oxidation

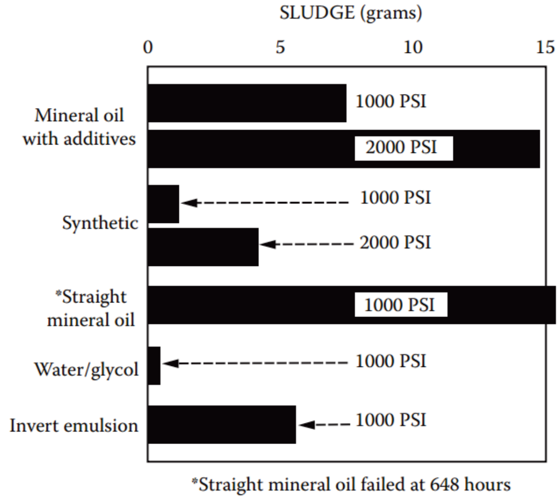
Mineral oil, polyolesters and some other fluids may form sludge that results in poorer lubrication properties. On the other hand, water-glycol solutions do not result in these formations, when a hydraulic system operates below 150°F (65°C) [10]. Conversely, higher temperatures (> 65°C) may result in sludge formation, as it is shown in Fig. 2(b) [10], [11].

D. Toxicity

Water-glycol substances were evaluated in the 7th Luxembourg Report in 1994 [12], where for the testing, animals were exposed to the blend's fumes and monitored for fourteen days. No serious health issues were detected amongst the affected subjects [7], [12]–[14].



(a) Viscosity-temperature relationship



(b) Sludge formation

Fig. 2: Viscosity-temperature correlations with varying temperature and sludge formation for various hydraulic fluids.

E. Elastomer compatibility

Water-glycol solutions, some of the thickeners, and corrosion inhibitors can attack some materials, creating residues. For instance zinc, cadmium, magnesium and non-anodized aluminium [15]. Hence, a compatibility check is always required, when the mixture is introduced into a new hydraulic circuit. In case of the Compressed Air Energy Storage system as an example from [1], [2], a compatibility check with regards to the installed elastomers and o-rings was conducted.

III. Density and Viscosity Calculations

Even though water glycol solutions are widely used in different systems, research with respect to calculation of the density still has some serious gaps. There are studies available that describe the derivation in relation to the mixture's temperature, but not the fluid's pressure [17], [18]. Hence, a comprehensive analysis of the relationship between these parameters should be performed.

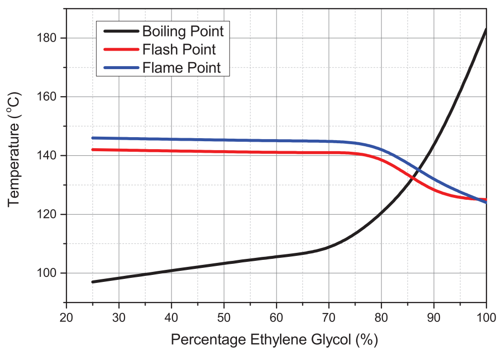


Fig. 3: Flammability of water glycol fluid (open cup test) [16].

Cheng [17] proposed a new approach for the viscosities calculations [18]–[20], where the dynamic viscosity of water (μ_w) and glycol (μ_g) can be obtained as

$$\mu_w = 1.790exp\left(\frac{(-1230-T)T}{36100+360T}\right) \quad (1)$$

$$\mu_g = 12100exp\left(\frac{(-1233+T)T}{9900+70T}\right) \quad (2)$$

where μ is in cP or 0.001 Ns/m^2, and T is within the range of 0-100 °C [21], whilst the constants are taken from [22].

Meanwhile, the density of water and glycol can be computed as

$$\rho_w = 1000\left(1-\left|\frac{T-4}{622}\right|^{1.7}\right) \quad (3)$$

$$\rho_g = 1277 - 0.654T \quad (4)$$

where ρ_w is the water density and ρ_g is the glycol density, both in kg/m^3 and T in °C.

Taking into account that all these equations calculate the density and viscosity at athmospheric pressure (0.1 MPa or 1 atm), it is necessary to compute these values for the pressure range of 0-500 bar (0.01-50 MPa). It can be done by using the three-dimensional Hooke's law

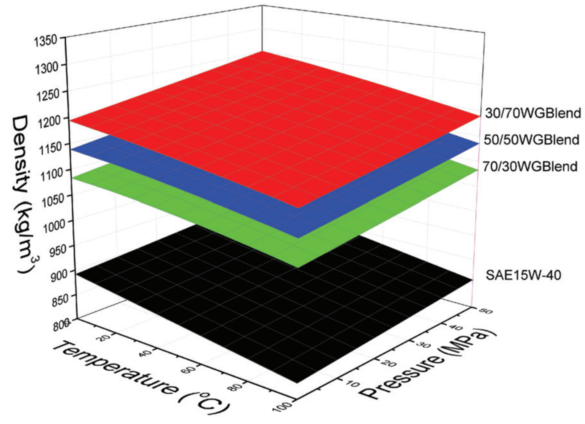
$$E = -dp/(dV/V_0) = -(p_1-p_0)/((V_1-V_0)/V_0) \quad (5)$$

where E is a bulk modulus that describes liquid elasticity (N/m^2), p_0 - atmospheric pressure, p_1 is the specified pressure, V_0 and V_1 - volumes at the atmospheric and specified pressure respectively. The minus sign in the equation describes a decrease in volume with a rise of pressure, hence

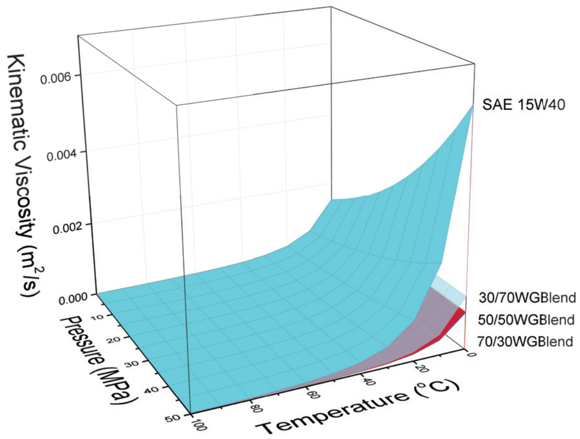
$$V_1 = V_0(1-(p_1-p_0)/E) \quad (6)$$

$$\rho_1 = \rho_0/(1-(p_1-p_0)/E) \quad (7)$$

By employing these relationships, the densities for different hydraulic solutions can be obtained. By applying data from Schmelzer [23] we can derive the densities and viscosities of water-glycol mixtures at different pressures and combine them in Fig.4.



(a) Density plot



(b) Kinematic Viscosity plot

Fig. 4: Density and viscosity of different hydraulic fluids with respect to temperature and pressure.

A. *Hydraulic oil calculations*

Calculations for hydraulic oils are widely presented in literature, especially for the ISO grades 32-100 [3], [5], [24]–[26]. As an example for the following calculations, oil SAE 15W-40 is used in order to obtain the density and viscosities. In order to derive the density of the chosen fluid, the corresponding equations were taken from [27]:

$$\rho_{tP} = \rho_{15}K_tK_P \quad (8)$$

where ρ_{tP} is the oil density at the specified temperature and pressure (kg/m^3), ρ_{15} is the oil density at 15 $°C$ and specified pressure P (kg/m^3). K_t is the temperature coefficient that can be obtained as follows

$$K_t = e^{-\alpha_{15}(t-15)(1+0.8\alpha_{15}(t-15))} \quad (9)$$

t is the oil temperature in $°C$. K_p is the overpressure correction coefficient

$$K_P = \frac{1}{1-\gamma_t P\cdot 10^{-3}} \quad (10)$$

P is the pressure in MPa. Coefficient of volumeric expansion at 15 °C is

$$\alpha_{15} = \frac{K_0 + K_1\rho_{15}}{\rho_{15}^2} \tag{11}$$

where K_0=613.97226, K_1=0. Compression coefficient γ_t is

$$\gamma_t = 10^{-3} e^{-1.62080+0.00021592t+\frac{0.87096*10^6}{\rho_{15}^2}+\frac{4.2092t*10^3}{\rho_{15}^2}} \tag{12}$$

Based on these calculations it is possible to get a lookup table and depict it as a 3D surface plot, that is presented in Fig. 4. The density of hydraulic oil can be found in various viscosity tables, and by employing the pressure depended equations and the Vogel's equation [24], the viscosity at different differential pressures can be computed.

IV. Mathematical model of the test rig

To derive the hydraulic motor characteristics with different hydraulic solutions, a mathematical test rig was developed in Mathworks/Simscape software. It comprises a valve model (PTV), hydraulic motor, generator and its excitation system (Fig. 5).

A control signal is send to the PTV control stage block that defines the valve's dynamic characteristics. It corresponds to the specific opening of the valve, hence to the flow through it, which is defined via the valve's power stage block. By controlling the flow, and consequently a pressure drop across the motor, it is possible to control its velocity and torque. The torque is transmitted to the generator's rotor via the coupling between it and the motor's shaft. To generate terminal voltage, the generator's field windings should be energised by the installed and fully programmed (and modelled) excitation system.

In order to find different dynamic characteristics of the motor, hence the generator, the following calculations are performed. The leakage mass flow rate can be derived as [28]

$$\dot{m}_{Leak} = k_{HP}\frac{\Delta p}{\nu_{Avg}} \tag{13}$$

where k_{HP} is the Hagen-Poiseuille coefficient, Δp is the pressure drop across the motor and ν_{Avg} is the average kinematic viscosity.

The pressure loss can be computed by

$$\Delta p = \frac{\mu_{Nom}}{k_{HP}} q_{Leak} \tag{14}$$

where μ_{Nom} is the fluid dynamic viscosity and q_{Leak} is the volumetric leakage flow rate between the hydraulic motor ports. The volumetric leakage flow rate can be found by

$$q_{Leak} = \frac{\dot{m}_{Leak}}{\rho_{Nom}} = D_v\omega_{Nom}(1-\eta_{Vol.Nom}) \tag{15}$$

where $\dot{m}$ is the mass flow rate through the motor, ρ_{Nom} is the nominal liquid density, ω_{Nom} is the shaft's velocity at nominal conditions, D_v is the volumetric displacement per unit shaft rotation and $\eta_{Vol.Nom}$ is the volumetric viscosity at nominal conditions (Fig. 6). The Hagen-Poiseuille coefficient is derived by

$$k_{HP} = \frac{\mu_{Nom}D_v\omega_{Nom}}{\Delta p_{Nom}}\left(\frac{1}{\eta_{Vol.Nom}} - 1\right) \tag{16}$$

In a steady-state, the leakage mass flow rate ranges from $2\cdot10^{-5}kg/s$ to $2.5\cdot10^{-5}\ kg/s$. It can be used to estimate the total loss (leakage mass in kg) of the motor over a specific period of time. This is important information with regards to hydraulic drives that operate with frequent starts (unlike CAESS).

The testing also involves acceleration of the generator to its nominal speed of 157 rad/s (4 poles generator at 50Hz) in order to find a difference in its acceleration time (Fig. 7). This difference can reach 0.2-0.4 s, depending on the control system and the load of the hydraulic motor. In the presented case, the fastest response time is obtained with hydraulic mineral oil as a hydraulic media. Different hydraulic blends also influence the generator's power output, which is presented in Fig. 8. The maximum power output can be obtained with mineral oil during the start-up of the system. However, the difference between the power outputs with various hydraulic fluids is negligible when the output reaches 1 pu.

V. Conclusion

The above described conclusions prove that a water-glycol solution is an effective alternative to hydraulic oils as a hydraulic fluid. Water-glycol mixtures provide better fire-resistive properties, hence do not impose serious health and safety risks for operating staff. Also they are proved to be environmentally friendly and do not have any toxic influence on people and animals. To reduce negative effects like oxidation and a low-viscosity index, a thickener can be added.

In terms of the dynamic characteristics, mineral oil enables slightly faster acceleration of an electro-hydraulic drive. This is mainly achieved due to the highest kinematic viscosity and the lowest leakage mass flow rate during the start up of the drive train. However, in terms of the generator's power output, the difference between presented fluids is not significant.

Overall, the paper shows a simple engineering approach for the verification of the dynamic characteristics of electro-hydraulic drives. Section II shows the advantages of the fluid change in hydraulic systems, by making them safer during their operations. The main disadvantage of this change is the requirement to add a thickener or polymers to a water-glycol solution. However, even in this case, the employment of a water-glycol mixture has more advantages, than the use of standard hydraulic oils. This research shows mostly positive and some negative consequences of a fluid change, hence every single case should be reviewed individually. For instance, the project "Compressed Air Energy Storage System" [1], [2], requires higher safety standards, therefore the previously employed oil was replaced with a water-glycol solution.

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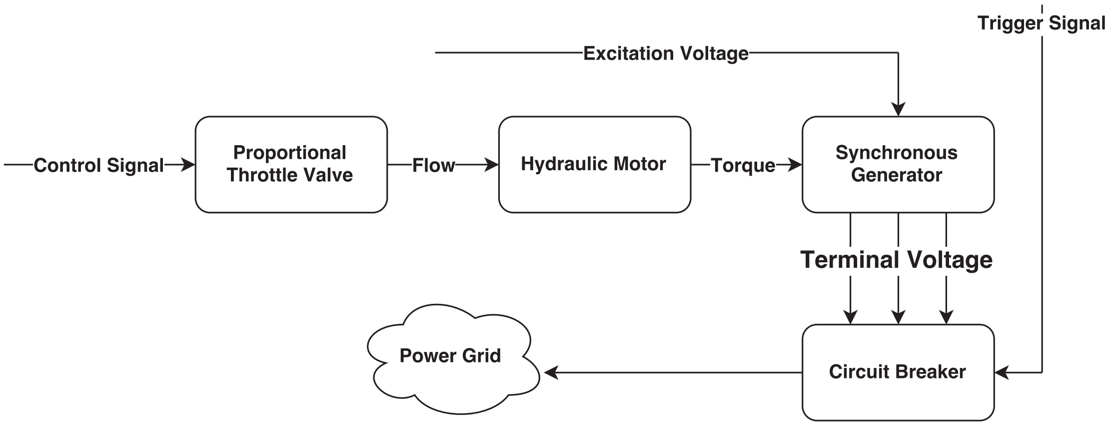

Fig. 5: Block diagram of the mathematical model.

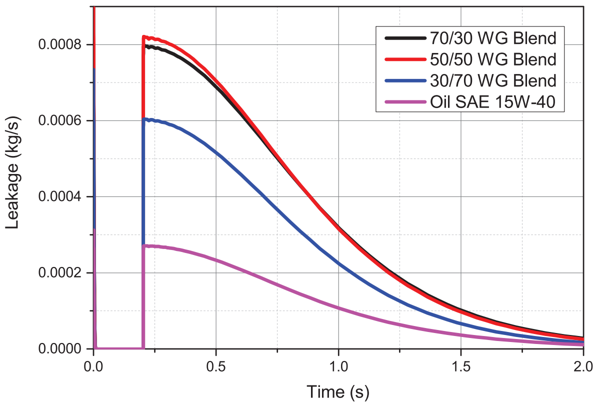

Fig. 6: Leakage of the hydraulic motor with different hydraulic fluids.

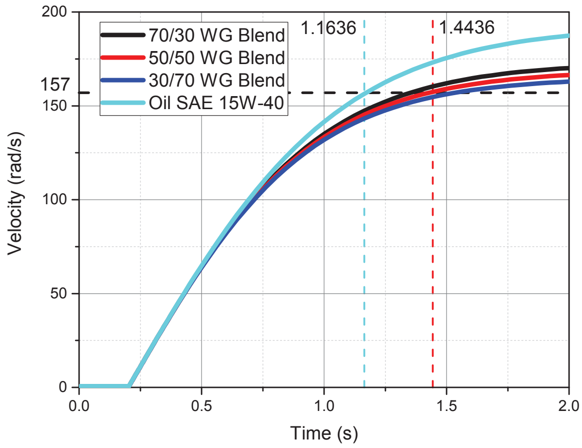

Fig. 7: Velocity comparison of the hydraulic motor with different hydraulic solutions.

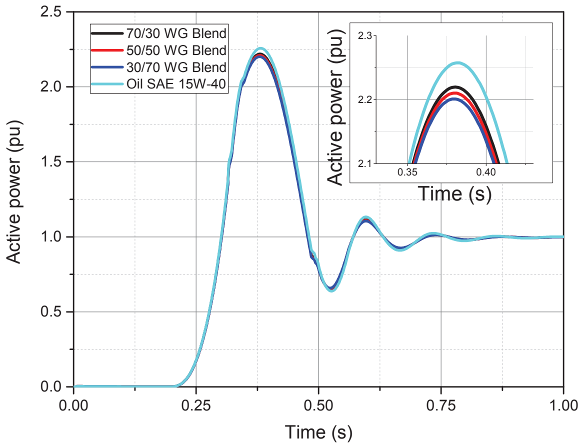

Fig. 8: Power output comparison of the synchronous generator with different hydraulic solutions.

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