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ELECTRIFICATION OF HYDRAULIC SYSTEMS USING HIGH-EFFICIENCY PERMAMENT MAGNET MOTORS

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ABSTRACT

In this paper, electrification of hydraulic systems is proposed using high-efficiency permanent magnet (PM) motors and wide bandgap power electronic drives. Direct driven hydraulics (DDH) is selected because of its higher efficiency compared to other conventional technologies such as valve-controlled systems. The DDH is directly driven by a servomotor. The ratings and design guidelines for a servomotor used in DDH applications are provided in this paper. Specifically, a surface permanent magnet synchronous machine (SPMSM) is designed. Finally, a state-of-the-art inverter using silicon carbide wide bandgap devices are designed for high performance operation.

Keywords: Direct driven hydraulics, Electrification, Electric motors, Hydraulic actuator, High efficiency, Permanent magnet synchronous machines

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1. INTRODUCTION

Hydraulic systems are known for their capability of applying large forces with a fast response. The further electrification of hydraulic systems is becoming popular, mainly for increasing the system efficiency. These additional features are attractive in a high-performance application such as heavy-duty mobile or stationary applications.

Electrification of powertrains in off-road mobile applications has been extensively studied [1]. The next step for further improvements consists of the electrification of working hydraulics or implements. Regarding drivetrain systems, electrification can be done by connecting an engine to an electric generator. Thus, a generator provides power to a combination of converters feeding electric motors to drive hydraulic pumps, which complete the electrification of the implements or actuators of hydraulic system.

Many examples of engine/electric generator type of electrification have been reported in the literature [1, 2], where authors demonstrated improvements in both force/position response and efficiency.

Reduced energy consumption and higher efficiency are critical in electric and hybrid off-road mobile applications, such as construction equipment, forest, and mining machinery. The state-of-the-art research demonstrated that significant improvements to the system efficiency can be achieved by switching from valve-controlled to pump-controlled hydraulic systems. Moreover, using a variable speed electric drive with a fixed displacement pump allows further improvements in the hydraulics, making it more energy efficient [3–5].

To provide high-performance electrification to hydraulic systems, high torque-density electric machines are required. Surface permanent magnet synchronous machines (SPMSM), with fractional-slot concentric windings (FSCW) becomes a desirable candidate, due to their high efficiency and high-power density. The main goal of this paper is to design a high-performance and efficient electric drive for further electrification of working hydraulics in off-road machinery with pump-controlled systems such as direct-driven hydraulics (DDH).

2. HYDRAULICS ELECTRIFICATION

In a traditional diesel operated mobile machinery, the energy available in fuel is converted to hydraulic through an internal combustion engine (ICE). In [6], an accurate description of the sources of energy losses in a typical hydraulic system were described. The diagram of **Figure 1** depicts how losses are distributed in a conventional hydraulic system.

Based on **Figure 1**, it is possible to identify several opportunities for increasing the efficiency in hydraulic systems. Although several improvements have been made in the design of ICE and hydraulic components [6], many hydraulics based applications, such as excavators, offer opportunities to recover energy. Typically, in excavator applications there are plenty of possibilities for harvesting and storing the kinetic and potential energy, for example, when bringing down a heavy load on a bucket to the ground or during swing motion. A general diagram of how electrification can improve hydraulic systems is shown in **Figure 2**.

Several examples of energy savings by electrification have been reported in [1]. Most of the focus for energy saving was based on including electrical energy storage, such as batteries or super capacitors. Thus kinetic and potential energy can be recovered through electric drives. Companies have deployed commercial products with a combination of hydraulic and electric systems. Examples of these products can be found for Kobelco, Hitachi, Caterpillar, and Komatsu [1, 2]. Topologies combining hydraulic and electrical systems by several manufacturers are depicted in **Figure 3**.

In the academic side, in [7], energy recovery was proposed for electric hydraulic hybrid electric system by harvesting potential energy from the boom in an excavator. Other examples include the design of novel topologies as the one shown in [8], which combines closed-loop in a hydrostatic transmission circuit and a hydraulic accumulator for energy storage. Many of the efforts have been made in utilizing hydraulic accumulators to recover the potential and kinetic energy of the system. The hydraulic accumulator then drives an electric generator which store the energy in capacitors or batteries. Examples of hydraulic accumulators for energy saving are provided in [9–12].

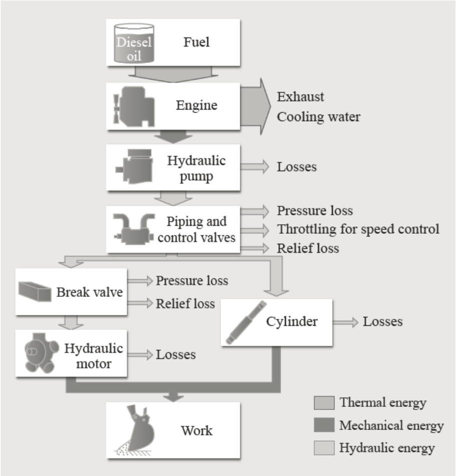


Figure 1: Power flow diagram for a hydraulic system depicting losses in the different stages of power conversion [6].

Industrial applications use open circuit hydraulic systems with large oil reservoirs with a valve to control flow, which is characterized by its low system efficiency. An alternative for valve-controlled hydraulic system is directly applying power in the hydraulic pump and omitting complex servo valves. Thus, a prime mover is connected to the pump, resulting in pump-controlled systems [4]. In pump-controlled systems, a variable displacement pump is controlled by a prime mover. Thus, by running the electric motor at a fixed speed, the control of flow is performed by modifying the displacement of the pump. Therefore, less energy consumption can be achieved.

Further improvements can be made by utilizing an electric drive with variable speed to drive a fixed displacement pump. Thus, directly controlling the flow by modifying the speed of the electric motor. Systems, where a variable speed electric drive is used for directly operate a pump, are referred to as direct-driven hydraulic (DDH) systems [3–5, 13, 14]. A figure of a typical hydraulic system and DDH system is demonstrated in **Figure 4** and **Figure 5**, respectively. By directly driving a pump, DDH systems become more efficient compared to their equivalent valve-controlled, thus improvements in efficiency up to 200 % can be achieved.

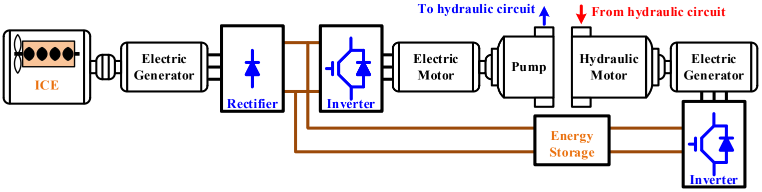
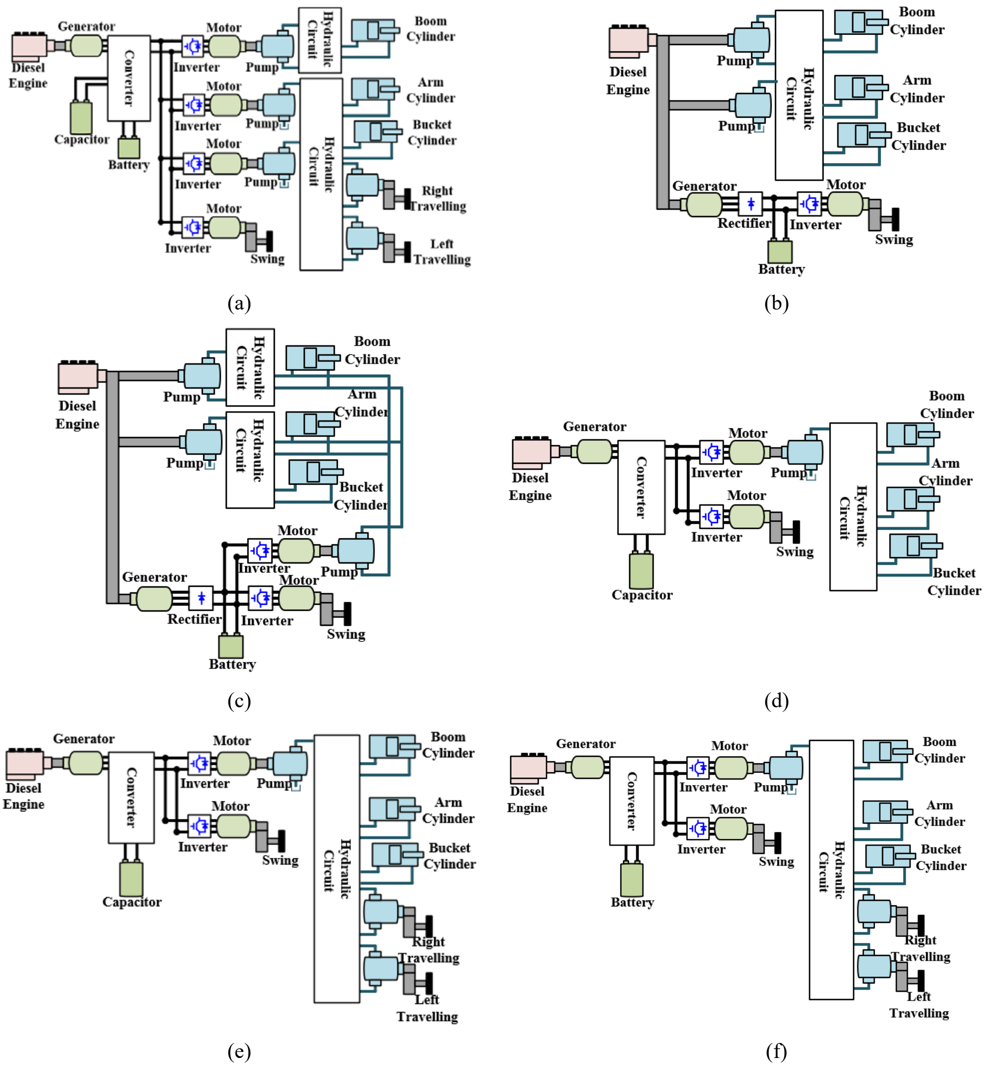


Figure 2: Generic scheme of how electrification allows to recover and store energy from hydraulic systems.



(a) (b) (c) (d) (e) (f)

Figure 3: Examples of commercially available electrified excavators [1], (a) Kobe Steel series-parallel hybrid excavator, (b) Doosan series-parallel hybrid excavator, (c) Komatsu series-parallel hybrid excavator, (d) Hitachi parallel hybrid excavator, (e) New Holland parallel hybrid excavator, (f) Kobelco parallel hybrid excavator.

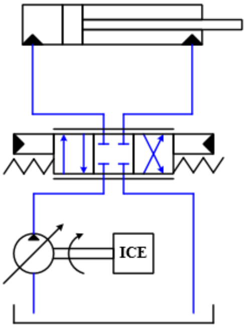


Figure 4: Simplified example of valve-controlled system.

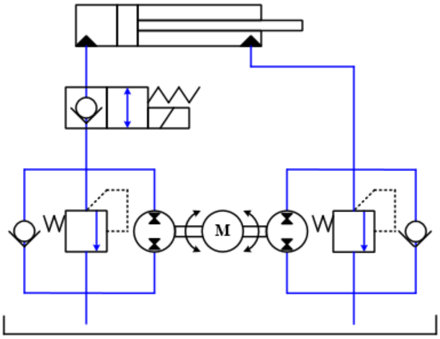


Figure 5: Direct driven hydraulic system.

Nowadays, electric drives can achieve a precise torque/speed/position control with minimal losses compared to hydraulic systems. One of the main objectives of this paper is to describe the design of a combination of an electric machine and an inverter for DDH systems. Based on the applications studied for DDH in [3, 5, 14], the ratings depicted in **Table 1** are used as a baseline for sizing and designing an electric machine. The details regarding the electric machine and drive are discussed in the following sections.

Table 1: Rating of Electric Machine

Rated values	Value
Rated speed, RPM	2000
Rated torque, Nm	25
Rated power, kW	5.2

3. PERMAMENT MAGNET ELECTRIC MACHINES

When selecting an electric motor for industrial and mobile applications, induction motors have been the standard choice due to their construction robustness and low cost. Nowadays, SPMSM are gaining a lot of attention for their superior efficiency and torque density compared to induction machines.

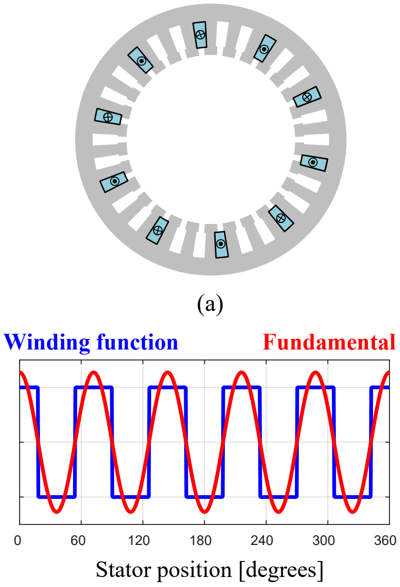
In this section, a SPMSM is proposed for high-performance electrification. The machine is designed to meet required frame size constraints and operate at the desired speed while maintaining high performance. The stator design must be carefully tuned to achieve high performance and fit reasonably small size, thus enabling to be used for electrifying hydraulic actuators.

3.1. Stator Design Considerations

A higher number of poles is desired to achieve higher torque density. However, machines with a higher number of poles typically use a higher number of stator slots to allocate the windings.

The function of the windings is to provide a sinusoidal magneto motive force (MMF) creating a rotating magnetic field. The magnets in the rotor will align with the stator rotating magnetic field, thus producing torque and making the rotor to spin. However, distributing the winding in a sinusoidal pattern in the stator is not practical. Alternatively, the winding can be distributed through the stator in such a way that a fundamental component of the rotating MMF is dominant compared to the rest of the harmonics.

In **Figure 6** a distributed winding (DW) for 10 poles is shown. The dots and crosses depict where the current is coming into or leaving the stator plane. Typically, for a 3-phase machine, generating necessary poles in the stator magnetic field involves the winding being distributed to create a repeating square wave whose fundamental component matches that of the rotor. Hence, a 10-pole design requires 30 slots, which in limited volume will result in small slots to accommodate the copper wires. A higher number of slots and small slot area result in lower overall copper fill and higher stator resistance which leads to a decrease in the efficiency. Also, this kind of distributed windings requires large end windings, which makes the machine bulkier.



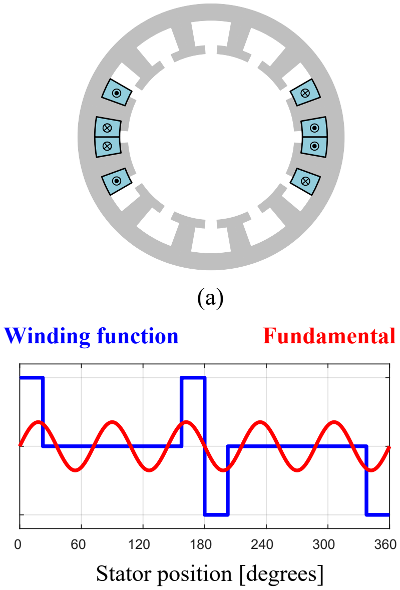
(a)

(b)

Figure 6: Distributed winding configuration, (a) Phase A windings, (b) winding function and fundamental

Alternatively, fractional slot concentrated windings (FSCW) [15–17], as shown in **Figure 7**, can be utilized in designs with a higher number of poles but limited stator volume. In this configuration the turns are distributed such that the dominant stator MMF harmonic matches the desired number of poles. It is to be noted that the dominant MMF harmonic is not necessarily the fundamental harmonic corresponding to the winding distribution.

The advantage of FSCW configuration is that rather than 30 slots, only 12 slots are needed, giving more room to allocate the coils in the stator teeth, thus decreasing the stator resistance. Also, as the coils are wrapped around each stator tooth, thus, the end windings are considerably shorter and require less volume compared to their distributed windings counterparts. The drawback of utilizing FSCW compared to DW is that for the same number of turns per phase the amplitude of the dominant harmonic component of the winding distribution is lower. Thus, more turns are needed to obtain a higher fundamental amplitude. **Figure 8** shows the difference regarding space in between DW and FSCW, showing that FSCW is more compact and easier to manufacture.



(a)

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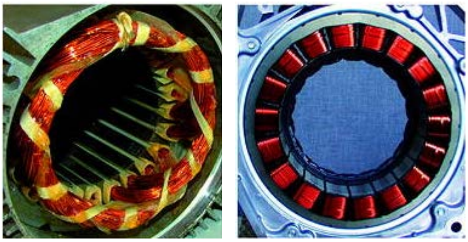
Figure 7: Fractional slot concentrated winding configuration, (a) Phase A windings, (b) winding function and dominant harmonic



(a) (b)

Figure 8: Comparison between stator winding configurations, (a) distributed winding, (b) fractional slot concentrated winding[18].

3.2. Rotor Design Considerations

Typically, for a surface PM rotor design, arc magnets are used in the rotor structure; however, in the proposed design, the magnets are shaped to decrease the ripple torque.

When a motor is designed for high-speed operation, then the rotor design becomes more challenging. However, this is not the case for hydraulic applications. As the machine is aimed to spin at 2000 RPM there are no additional structural requirements for the rotor design.

3.3. Proposed PM Electric Machine Design

The geometric constraints for this machine consider an outer diameter of 150 mm and a shaft diameter of 60 mm. 10 poles were chosen for the design to take advantage of the low-speed requirement and minimize the stator back iron thickness. The rated values obtained from the design are shown in **Table 2**. **Figure 9** shows the proposed design. Finite element analysis (FEA) was performed to obtain the torque waveform at rated conditions as shown in **Figure 10**. It can be seen that although the torque ripple increases slightly at overrated operation due to saturation effects, overall torque ripple is under 2% with a 0.5% ripple at rated operation (15 Arms).

An efficiency map is shown in **Figure 11**. In order to focus on the desired range of operation for this application, i.e. 300 to 3000 RPM and 5 to 25 Nm of torque, the efficiency bands are limited to a lower bound of 80% in **Figure 11**. All the data below 80% is represented by a single color band. From the results it can be confirmed that high efficiency and minimal torque ripple can be achieved within the desired operation range from the designed electric machine.

Table 2: Rating of SPMSM proposed design

Rated value	Value
Rated voltage, Vrms	380
Rated current, Arms	15
Number of poles	10

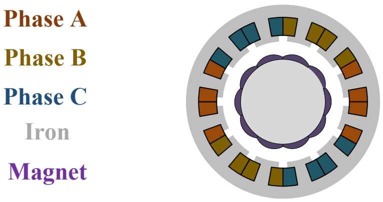


Figure 9: Proposed 12 slots/10 poles SPMSM design.

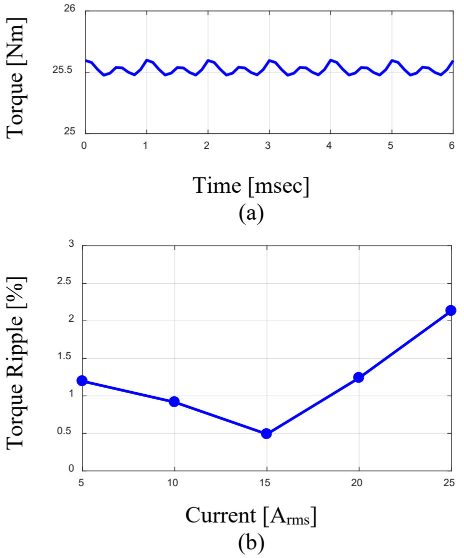


Figure 10: Shaft output (a) Torque at different current levels (b) Torque ripple percentage as a function of the stator current.

4. INVERTERS

An electric machine driven by variable speed drives (VSDs) provides higher efficiency and better dynamic performance than line-connected fixed speed electric machine. Depending on the types of the input power source, the VSDs can be classified into voltage-, current-, and impedance-source inverters, but the voltage-source inverter (VSI) has been playing a major role in industrial drive applications such as fan, blower, pump, and servo motors since the advent of insulated-gate bipolar transistors (IGBTs).

In this section, VSIs for electrified hydraulic actuators are introduced, and different switching device options are discussed in detail.

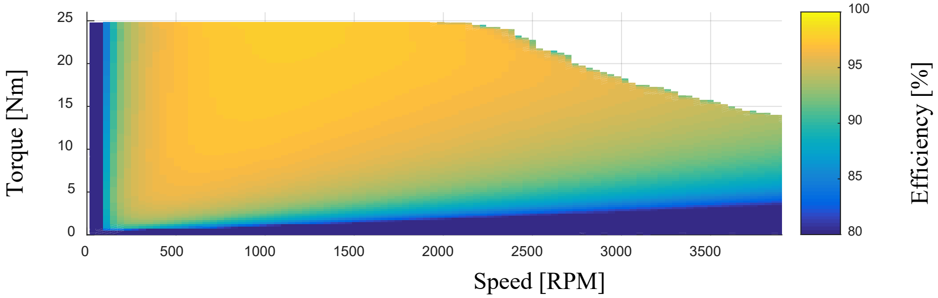


Figure 11: Efficiency map for proposed SPMSM machine with FSCW.

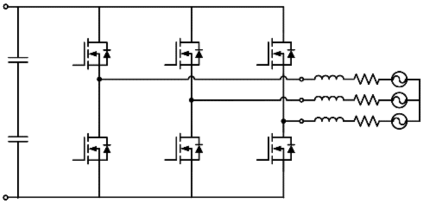


Figure 12: Schematic of 2-level voltage source inverter.

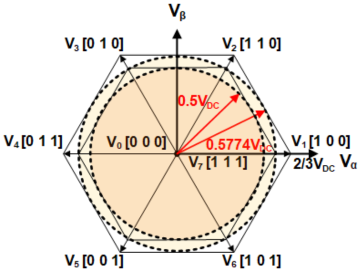


Figure 13: Vector diagram of space vector modulation and sine PWM.

4.1. Two-Level topology with IGBTs

A 2-level VSI has been dominantly used for VSD applications, and it requires a dc-link capacitor, six active switches, and six antiparallel diodes as shown in **Figure 12**. The voltage ratings of the power devices and capacitors need to meet the rated voltage of the electric machine designed in the previous section. Since the rated line-to-line rms voltage of the electric machine is 380 V, the peak phase voltage becomes 310.27 V. When space vector modulation (SVM) as shown in **Figure 13** is utilized the maximum peak inverter output voltage is 57.7% of the dc-link voltage indicating that the minimum required dc-link voltage is 537.7 V. For higher than 550 V dc-link voltage and 15 A rated current, 900 V silicon (Si) IGBT, SiC, and GaN devices are all applicable, and 1200 V Si IGBT and SiC are also available in the market.

Si IGBTs have been around more than three decades in power electronics industry [19], and their device characteristics and behavioral models are well understood. The price of the device is two to three times lower than the equivalent SiC or GaN devices as of 2019 [19], and there are large collections of device ratings and manufacturers. However, it is also well-known fact that IGBTs can only operate within limited switching frequency range (typically less than 20 kHz) due to excessive switching losses. It also generates high conduction loss, which significantly affects the motor drive system efficiency at light load conditions.

4.2. Two-Level topology with wide bandgap devices

The SiC and GaN devices are alternative options to Si IGBTs. These devices can operate over 50 kHz due to its 5 to 10 times faster switching speed and lower on-state resistance. The increased cost due to high device price can ultimately compensated by reduced passive component [20], minimized cooling component design such as heatsink and fan [21], and energy-saving from improved efficiency throughout the operating time [22].

A circuit simulation is conducted to validate the impact of switching frequency on the current waveform as shown in **Figure 14** and **Figure 15**. The dc-link voltage is set to be 600 V and SiC MOSFET C2M0080120D, which has a maximum blocking voltage of 1200 V and a current rating of 36 A is used for the simulation. The output current ripple is reduced by 60% in 50 kHz operation as compared to that of 20 kHz operation. The reduced output current ripple leads to low PWM-induced iron losses [23], low ripple torque [24], and low audible noise.

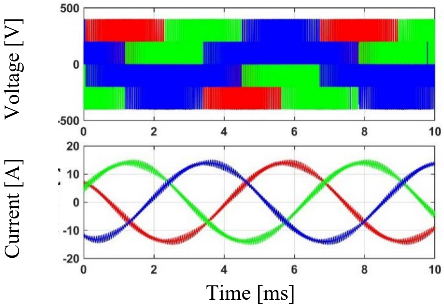


Figure 14: SiC inverter operating at 20 kHz with RL load at 150 Hz fundamental frequency.

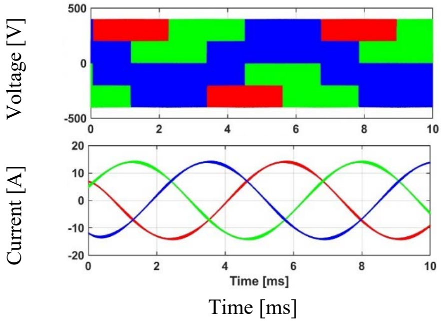


Figure 15: SiC inverter operating at 50 kHz with RL load at 150 Hz fundamental frequency.

5. DISCUSSION

The benefits of electric drives allow to improve efficiency of hydraulic systems by implementing DDH. Hydraulic pumps typically operate in a range between 300 to 3000 RPM [25]. In the DDH, the electric drive is directly connected to the pump where both the pump and the electric motor operate at the same speed. For a range where the operational speed varies between 300 through 3000 RPM the designed electric motor demonstrates a large efficiency, i.e. above 95 %. The efficiency only drops in low torque operation points that are unlikely to occur due to the pump operational characteristics [25].

Regarding controllability, the torque control in an electric drive is very high due to the capability of the inverter to inject current in the stator windings instantaneously. As the torque is mainly dependent in the injected current from the inverter, torque can be achieved extremely fast at any operational speed, thus making the electric drive suitable for deliver torque with good accuracy including the low speed or zero speed region. This last property makes inverter driven motors suitable for electrifying hydraulic systems where the low or zero speed operation can be a challenge otherwise.

Efficiency improvements were obtained when moving from valve-controlled to pump-controlled systems due to high performance servo drive. Moreover, direct-driven hydraulic systems are accepted as a promising technology for hydraulic hybridization which reduces the number of components and the size the overall system.

In terms of electric machines, SPMSM shows superior performance compared to induction machines. Thus, SPMSM was chosen for analysis for the electrification of a hydraulic system. For DDH applications, relatively low speeds, high torque, and limited size are the requirements while keeping the efficiency high. As machines with higher torque require typically more number of poles, a FSCW topology was chosen, thus being able to create the necessary number of poles, to match the torque needed in the limited volume constraint. The designed machine was analyzed with FEA showing efficiency above 95% in almost all the range of operation.

Finally, regarding the inverter, it was shown that higher switching frequencies can lead to small components and better performance in terms of torque and current ripple. However, high-switching frequencies are not achievable with IGBT switches. In this paper, it is proposed to use SiC switches that allow to increase the switching frequency and reduce the switching losses, thus, contributing to higher performance and efficiency.

6. CONCLUSIONS

In this paper, electrification of working hydraulics for off-road machinery application was discussed. The review in electrification of hydraulic system has demonstrated that significant improvements regarding efficiency were achieved by including electric drives.

Surface PM motor with FSCW and SiC-based power electronic inverter were designed and shown as a promising candidate for high-performance and high-power density pump-controlled systems as a way for further electrification of off-road machinery. Features of the propose system include high overall efficiency, compactness, and fast torque response.

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