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# Dynamic Modelling and Analysis of a Hydraulic Energy Storage Based Hybrid Power Transmission for Wind Turbine

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***Abstract***

This work discussed the detailed dynamic model of a Hydraulic Energy Storage based Hybrid Power Transmission (HESbHPT) technology. It is an unite operation of two individual power transmission systems, such as gear train and a state-of-art hydraulic energy storage-based hydraulic power transmission. The output power of the turbine rotor is applied as the input power of the gear train whereas the output power of the gear train is supplied to the hydraulic pump that supplies flow to the hydraulic motor of the hydraulic power transmission (HPT). A hydraulic energy storage, i.e., an accumulator and two control valves are incorporated between the hydraulic pump and the motor in order to operate the fixed load by storing or releasing the excess flow supplied from the pump. A Two-step or On-Off controller controls the control valves and ensures the charging and discharging operation of the accumulator. The dynamic bond graph model of the HESbHPT is developed and simulated using SYMBOLS SHAKTI software. The simulation responses of the proposed model indicate that the output speed of the hydro-motor is stable to 8.2 rad/s although the input power to the gear train is variable in nature. Also, the efficiency of the HESbHPT is reported, and found that the overall transmission efficiency is in the range of 90-98%. Moreover, the pressure and energy storage variation into the accumulator is reported.

*Keywords:* Hybrid power transmission; Energy storage, Bond graph; Dynamic modelling; Accumulator.

## 1. Introduction

The availability of wind energy is due to the movement of air masses on Earth caused by the sun's uneven heating of the atmosphere. Wind turbines harness this kinetic energy and convert it into electricity. Wind power is indeed variable and dependent on weather conditions, leading to fluctuations in electricity generation. To address this intermittency and ensure a more reliable power supply, energy storage systems (ESS) are often integrated into wind energy systems. Some of the well-known cutting-edge energy storage techniques are pumped-hydroelectric energy storage system (PHEESS), underground PHEESS, compressed air ESS, ESS using a battery, hydrogen ESS, thermal ESS etc [1]. In wind turbines, the most important technical units are turbine blades model, tower design, power transmission unit, and electric generator. Among all these, the power transmission system plays a crucial role in converting the rotational energy of the turbine blades into electricity and advancements in this area can have a significant impact on the overall performance, efficiency, and maintenance requirements of wind turbines. The gearboxes were indeed the most commonly used power transmission systems in traditional wind turbines [2-3]. Indeed, hydraulic power transmission (HPT) has been explored as an alternative to traditional gear train systems in wind turbines [4]. The gearbox is positioned between the low-speed turbine rotor, which is turned by the wind, and the high-speed electrical generator. The primary function of the gearbox is to increase the rotational speed of the low-speed rotor to the higher speed required by the electrical generator for efficient electricity generation. It is more efficient than HPT, but the probability of failure is higher [5]. Also, the maintenance costs associated with gear train systems in wind turbines, particularly in larger turbines with power ratings exceeding 3 MW, have been a significant concern [6]. Also, the provision to store the excess energy that is generated from the wind turbine during cyclones, storms etc, is absent. Hence, wind turbines with gear train systems waste a large amount of energy during storms or cyclones. Besides, the concept of using HPT in wind turbines involves a hydraulic pump coupled with the turbine rotor and a hydraulic motor or actuator (such as a Pelton wheel) coupled with the electric generator. This arrangement aims to convert the kinetic energy of the wind into hydraulic energy, transmit it to a different location, and then convert it back into mechanical energy for electricity generation [7-9]. Recently, the use of an accumulator in hydraulic power transmission (HPT) systems for wind turbines has been extended, as described by Fan *et al*. and Mahato *et al*. demonstrates an innovative approach to address the challenges of power fluctuation associated with variable wind speeds [10- 11]. Hence, the said approach contributes to reducing the probability of load shedding at wind power supply locations. The stated schemes used a nozzle and a Pelton wheel, which were coupled with the generator. These equipment makes the complete schemes unnecessarily bulky as well as complex in dynamical modelling. The stated scheme can be simplified by using a hydro-motor instead of the Pelton wheel. Moreover, the major issue associated with HPT is lower transmission efficiency as comparison to other power transmissions [12]. In addition, the size of the hydraulic pump is influenced by the speed of the rotor. All these issues hinder the promotion of HPT in wind

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turbine applications [13]. The discussed drawbacks of the gear-train power transmission, as well as HPT, can be overcome by introducing various types of hybrid power transmission technologies [7, 14-15]. In [14-15], a hydro-viscous hybrid power transmission has been introduced for wind turbines, but the complex structure of the hydro-viscous power transmission is limiting its commercial feasibility. Another hybrid approach, i.e., gear train combined with HPT, is discussed in the articles [16-17]. In [16], a gear train is coupled with a low-speed hydraulic pump and transmits wind power from the turbine rotor to the generator. A dynamic model of the stated transmission system is modelled and simulated. Also, developed a prototype of the Hybrid Power Transmission System (HPTS) and subsequently validated the simulation responses through experimental testing. Similarly, in [17], a new continuously variable drive train, which contains a hydrodynamic pressure transmission and a gear train, is developed for wind turbine application. Also, the simulation responses of the continuously variable drive train are validated experimentally. Another recent article was published on hydro-mechanical power technology for wind power application by Kumar *et al*. [18]. It is the primary conceptual work on hydro-mechanical power transmission technology. Furthermore, the detail and expended work is reported in [19]. In this work, a new hydro-mechanical power transmission technology is proposed for power transmission in wind turbine. The work concluded that the wind power output is of a fluctuating nature as the input wind speed is variable in nature. All these hybrid power transmission technologies do not provide the concept of how the power fluctuations of the wind turbine can be reduced using a hydraulic energy storage system by eliminating the frequency converter. The stated deficiency has been overcome by incorporating an accumulator and a special control valve into the HPT unit [20]. Recently, Kumar *et al*. (2023) proposed a hybrid power transmission that consists of an energy storage system to reduce power fluctuation in wind turbines [21]. The work concluded that the wind turbine may always supply stable power to the supply location irrespective when the input wind speed is fluctuating in nature. Still, the hybrid power transmission technology for wind turbine applications proposed by eminent researchers has not been commercialized globally. Hence, it is needed more detailed dynamic analysis of the hybrid power transmission technology and its key equipment, i.e., energy storage device.

The work proposed a detailed bond graph dynamic model of a Hydraulic Energy Storage based Hybrid Power Transmission (HESbHPT) technology and analysed the system performance. Moreover, it is addressed the performance of the accumulator as it is a key equipment of the stated power transmission system.

## 2. Outline of the Hydraulic Energy Storage based Hybrid Power Transmission (HESbHPT)

The outline of the HESbHPT is shown in Fig. 1. It is an unite operation of a gear-train (Single Stage Planetary Gear Train-$_{SS}$PGT) and a start-of-art hydraulic energy storage-based hydraulic power transmission. The gear train increases the rotational speed of the low-speed rotor to the higher speed required by the electrical generator for efficient electricity generation, whereas the HPT provides the scope to store or compensate the excess or shortage flow to or from the accumulator. From Fig. 1, a variable frequency drive (VFD) has been used in place of the turbine blades and rotor to supply variable speed to the gear train is coupled to the gear shaft. The gear train increases the available input shaft low speed to the higher output speed due to its positive gear ratio. The output shaft of the gear is coupled to the hydraulic pump, which converts the mechanical power to the equivalent hydraulic power, and supplies flow to the hydraulic motor, which converts hydraulic power to the equivalent mechanical power. The hydraulic motor is connected to the load, and it operates the mechanical load. Moreover, a suitable hydraulic energy storage system is incorporated into the HPT unit. It stores the excess flow supplied by the pump when it is rotated sufficiently higher speed and compensates the hydro-motor flow when pump rotates at a very low speed. The charging and discharging operations of the energy storage system/accumulator are ensured by closing and opening the control valves (CCV and DCV) that are controlled by a Two-step or On-Off controller. The stated process of the energy storage system or the accumulator helps to diminish the speed fluctuation of the hydro-motor and always operates against a constant load whether the variable frequency drive supply is of a fluctuating nature.

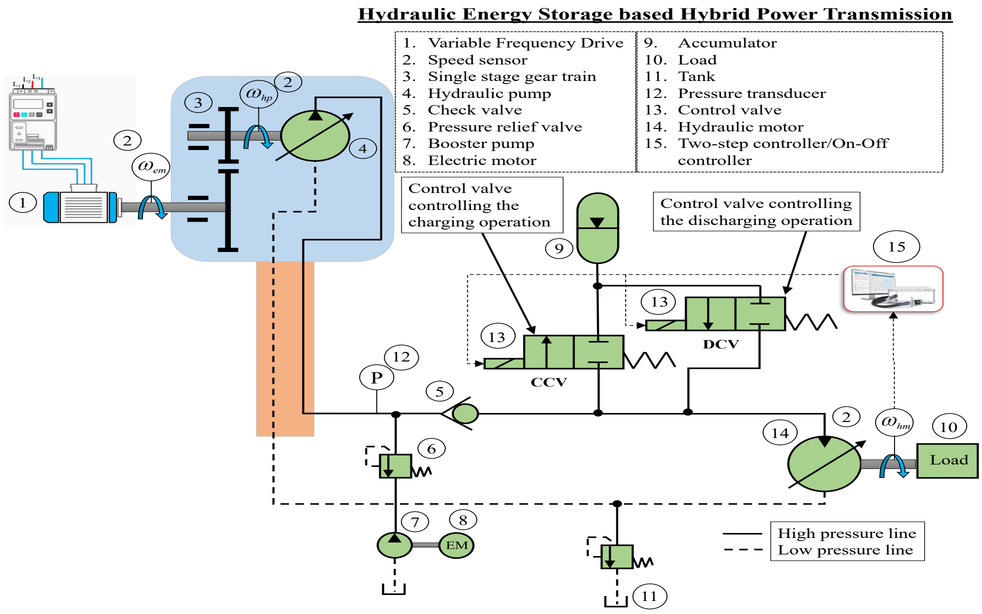



**Fig. 1.** Outline of the physical model of the HESbHPT.

## 3. Bond graph model of the HESbHPT

The bond graph model of the HESbHPT is presented in Fig. 2. The assumptions which are taken into consideration to develop the dynamic bond graph model of the ABHPT are: the working fluid is compressible, and its properties are unaltered with temperature variations, its inertia and turbulence effect on the system are negligible, and negligible frictional loss due to rigid coupling between shafts.

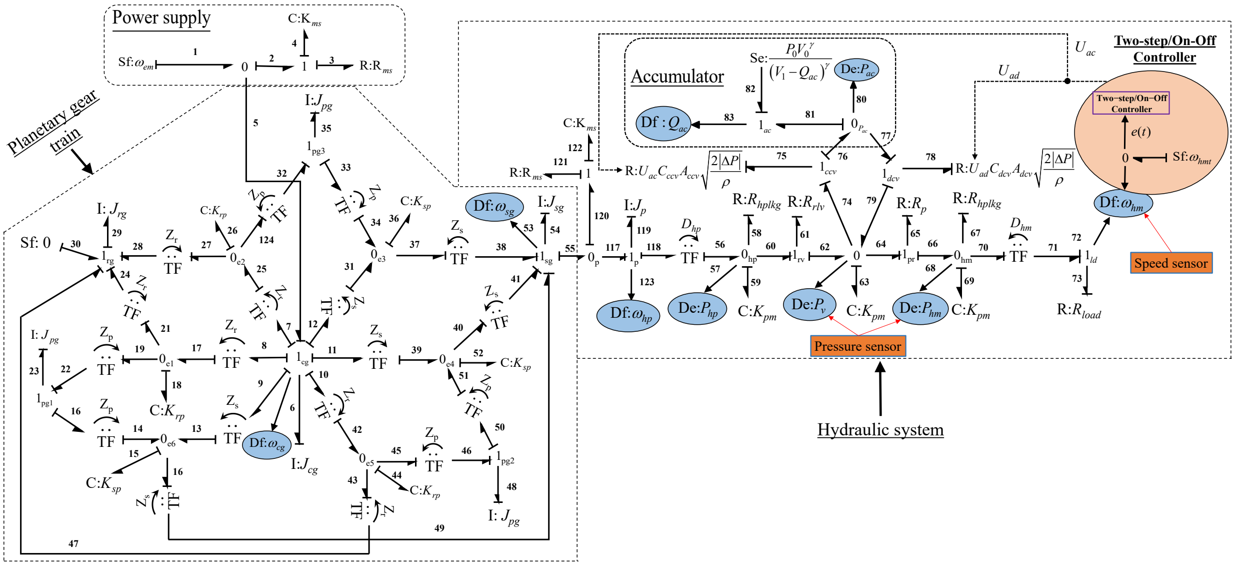



**Fig. 2.** Bond graph model of the HESbHPT.

The dynamic equations of the stated system are derived from the bond graph model of the HESbHPT, and all these equations are simulated using SYMBOLS SHAKTI software. The steady state equations are as follow:

$$\left[(R_{ms}+K_{ms})(\omega_{em}-\omega_{cg})\right]-3Z_s\tau_{sg}-3Z_r\tau_{rg}-J_{cg}\dot{\omega}_{cg}=0 \quad (1)$$

$$Z_p\tau_{rg}-Z_p\tau_{sg}-J_{pg}\dot{\omega}_{pg}=0 \quad (2)$$

$$3Z_s\tau_{sg}-D_pP_p-J_{sg}\dot{\omega}_{sg}=0 \quad (3)$$

$$Z_r\omega_{cg}-Z_r\omega_{rg}-Z_p\omega_{pg}-\frac{\dot{\tau}_{rg}}{K_{rp}}=0 \quad (4)$$

$$Z_s\omega_{cg}+Z_p\omega_{pg}-Z_s\omega_{sg}-\frac{\dot{\tau}_{sg}}{K_{sp}}=0 \quad (5)$$

$$D_p\omega_{sg}-\frac{P_{hp}}{R_{plkg}}-\frac{(P_{hp}-P_v)}{R_{rlv}}-\frac{\dot{P}_{hp}}{K_{pm}}=0 \quad (6)$$

$$\frac{(P_{hp}-P_v)}{R_{rlv}}-Q_{ccv}+Q_{dcv}-\frac{(P_v-P_{hm})}{R_p}-\frac{\dot{P}_v}{K_{pm}}=0 \quad (7)$$

$$\frac{(P_v-P_{hm})}{R_p}-D_{hm}\omega_{hm}-\frac{P_{hm}}{R_{hmlkg}}-\frac{\dot{P}_{hm}}{K_{pm}}=0 \quad (8)$$

The accumulator pressure is estimated from $0_{P_{ac}}$junction and it is expressed as

$$P_{ac}(\forall_i-Q_{ac})^{\gamma}+P_i{\forall_i}^{\gamma}=0 \quad (9)$$

## 4. Speed control model

The proposed system works against a fixed load, and hence it needs a threshold speed ($\omega_{hmt}$) of the hydraulic motor. However, the hydraulic pump supplies variable flow to the hydraulic motor as the frequency of the VFD is variable. When VFD rotates with high speed, the hydraulic pump supplies excess flow, and the hydraulic motor starts rotating with a higher speed than the $\omega_{hmt}$. Concurrently, the speed sensor sends the signal to the Two-step or On-Off controller that allows the CCV to open and hence passes all the excess flow to the accumulator in order to maintain the $\omega_{hmt}$ of the hydraulic motor. Besides, when the VFD rotates with a very low speed, the hydraulic pump supplies less flow to the hydraulic motor, and hence it rotates with lower speed than the $\omega_{hmt}$. As a result, the hydraulic motor is unable to operate the load. At the same time, the Two-step or On-Off controller receives the signal from the sensor, and it allows the DCV to open. Thus, the stored accumulator flow passes through the DCV and compensates the hydraulic motor flow in order to maintain the $\omega_{hmt}$ of the hydraulic motor. The block diagram of the control scheme is shown in Fig. 3.

The flow through the control valves $Q_{ccv}$ and $Q_{dcv}$are

$$Q_{ccv}=U_{ac}C_{ccv}A_{ccv}\sqrt{\frac{2|\Delta P|}{\rho_o}} \quad (10)$$

$$Q_{dcv}=U_{dc}C_{dcv}A_{dcv}\sqrt{\frac{2|\Delta P|}{\rho_o}} \quad (11)$$

where $U_{ac}$ and $U_{ad}$ are the output of the Two-step or On-Off controller and it is expressed as

$$\left.\begin{matrix}U_{ac}=1\\U_{dc}=0\end{matrix}\right\}\ if\ e(t)\geq 0 \quad (12)$$

$$\left.\begin{matrix}U_{ac}=0\\U_{dc}=1\end{matrix}\right\}\ if\ e(\mathrm{t})<0 \quad (13)$$

The $\{e(t)=(\omega_{hmt}-\omega_{hm})\}$ is the deviation signal or error signal of the hydraulic motor speed. The error signal helps to operate the CCV or DCV.

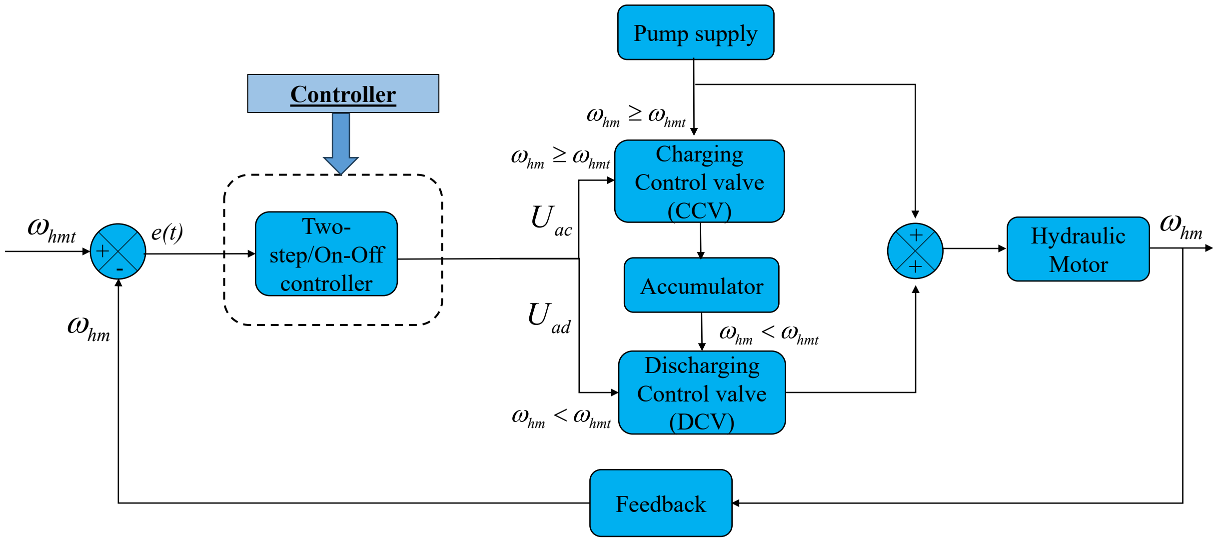



**Fig. 3.** Block diagram of the speed control scheme.

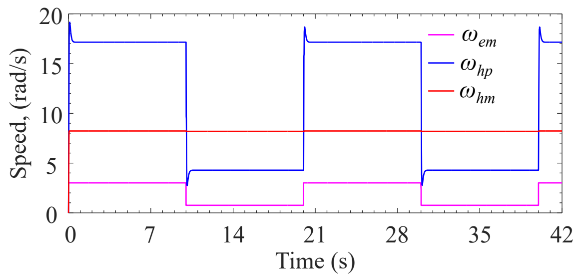
## 5. Results and Discussions

The steady-state equations (1-13) are simulated using SYMBOLS SHAKTI software. A well-known Runge–Kutta Gill method is used to solve these differential equations, and the relative truncation error is chosen to be minimum, i.e., 5 $\times10^{-6}$. The input parameters are listed in Table 1.

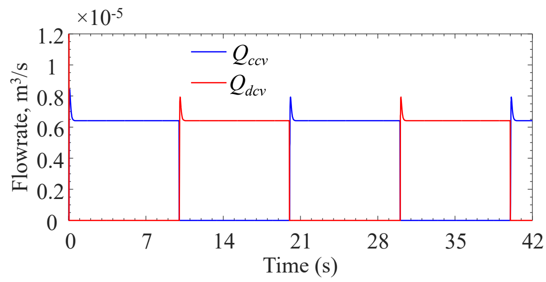
**Table 1.** Parameters for simulation

| Parameters | Value |
|---|---|
| $D_{hp}$: Volume displacement rate of the hydraulic pump | $1.0\times10^{-6}$ $m^3$/rad |
| $D_{hm}$: Volume displacement rate of the hydro-motor | $1.31\times10^{-6}$ $m^3$/rad |
| $R_{hplkg}$ and $R_{hmlkg}$: Pump and motor Leakage resistance | $1\times10^{18}$ N.s/$m^5$ |
| $R_{rlv}$: Relief valve resistance | $7\times10^{10}$ N.s/$m^5$ |
| $R_p$: Pipeline resistance | $5\times10^{8}$ N.s/$m^5$ |
| $K_{pm}$: Bulk stiffness of the fluid | $1\times10^{12}$ N/$m^2$ |
| $P_i$: Initial pressure of accumulator | $9.48\times10^{6}$ Pa |
| $\forall_i$: Initial volume of accumulator | $530\times10^{-3}$ $m^3$ |
| $A_{ccv}$ and $A_{dcv}$: Area of control valve | $2\times10^{-6}$ $m^2$ |
| $C_{ccv}$ and $C_{dcv}$: Discharge coefficient of the control valve | 0.56 |
| $R_{load}$: Load resistance | 150 N.m.s/rad |
| $\rho_o$: Working fluid density | 870 kg/$m^3$ |
| $Z_p$: Planetary gear teeth | 39 |
| $Z_s$: Sun gear teeth | 21 |
| $Z_r$: Ring gear teeth | 99 |
| $J_{pg}$: Rotary inertia of the planetary gear | 3.2 |
| $J_{sg}$: Rotary inertia of the sun gear | 3.2 |
| $J_{rg}$: Rotary inertia of the ring gear | 144.2 |
| $J_{cg}$: Rotary inertia of the carrier gear | 59.1 |
| $K_{rp}$: Mesh stiffness between planetary and ring gear | $19.2\times10^{9}$ |

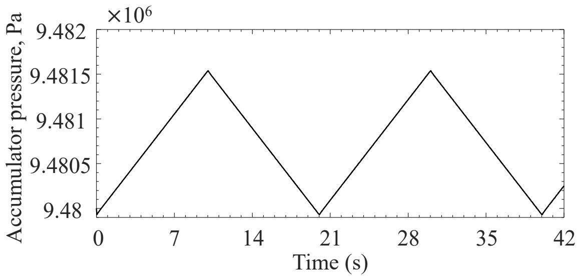
The input speed to the gear rain varies from 3 rad/s to 0.75 rad/s by changing the frequency of the VFD (refer Fig. 4a). The output speed of the gear train is increased due to its positive rear ratio, and it varies from 17 rad/s to 4 rad/s. The proposed system works under a fixed load, i.e., 150 N. To operate the stated load, the torque developed by the hydraulic motor at 1-10s, 20-30s, and after 40s are surplus, and the excess hydraulic energy is stored into the accumulator. Besides, the torque development at 10-20s and 30-4 0s is not sufficient to operate the same load. In such a situation, the accumulator compensates for the flow to the hydro-motor in order to develop constant torque or to maintain the constant speed of the hydraulic motor. In Fig. 4a, it is clearly shown that the output speed of the hydraulic motor $\omega_{hm}$ is stable to 8.2 rad/s although the input speed to the gear train is variable in nature. In Fig. 4b, it is showing the flow rate through the charging and discharging control valves. The charging control valve is opened, and the accumulator is in charging operation at 1-10s, 20-30s, and after 40s when the hydraulic pump supply flow is surpluses. Similarly, the discharging control valve is opened and allows the discharging operation of the accumulator at 10-20s and 30-40s when the hydraulic pump supply is insufficient to develop constant torque. Fig. 4c represents the pressure at the accumulator.




(a)



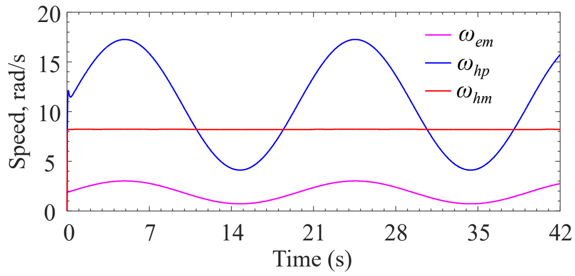

(b)



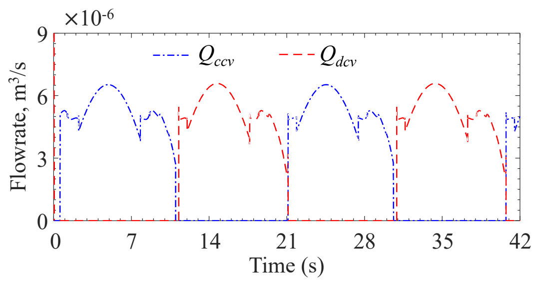

(c)

**Fig. 4.** Rectangular variable input (a) Speed of the VFD ($\omega_{em}$), Speed of the gear train/hydraulic pump ($\omega_{hp}$), Speed of the hydraulic motor ($\omega_{hm}$) (b) Flow through control valves (c) Accumulator pressure

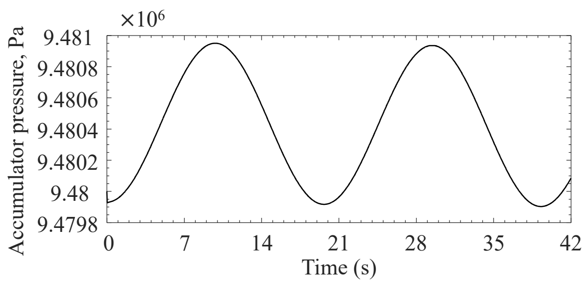
When the input speed to the gear train is sinusoidal, the corresponding speed at the pump shaft and the hydro-motor shaft is shown in Fig. 5a, whereas the corresponding flow rate through the control valves is shown in Fig. 5b and accumulator pressure variation is shown in Fig. 5c.




(a)




(b)




(c)

**Fig. 5.** Sinusoidal variable input (a) Speed of the VFD ($\omega_{em}$), Speed of the gear train/hydraulic pump ($\omega_{hp}$), Speed of the hydraulic motor ($\omega_{hm}$) (b) Flow through control valves (c) Accumulator pressure

### 5.1. Accumulator pressure and energy variation

The accumulator pressure variation is reported when the gas compression process is different. From Fig. 6, it is clear that the pressure development is higher in the accumulator when the gas is compressed in an adiabatic process. Therefore, with the decrease of the specific heat index of the air, the pressure development of the accumulator decreased.

The energy storage in the accumulator is shown in Fig. 7, and it is estimated from Eqs. (14) and (15) when the gas compression process is adiabatic and isothermal, respectively [23]. It is observed that maximum energy storage in the accumulator at 10 s and 30 s and it is about 585 J and 245 J for adiabatic and isothermal compression, respectively.

$$E = \frac{\forall_i P_i^{\frac{1}{n}}}{n-1}\left[P_{ac}^{\frac{(n-1)}{n}} - P_i^{\frac{(n-1)}{n}}\right] \tag{14}$$

$$E = P_i \forall_i \ln\left(\frac{P_{ac}}{P_i}\right) \tag{15}$$

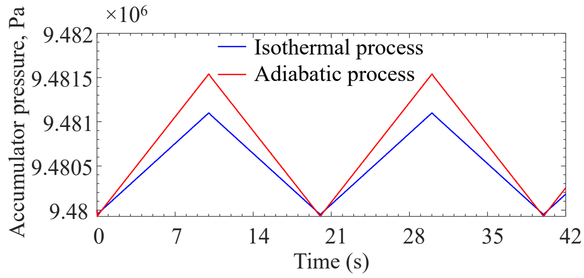



**Fig. 6.** Accumulator pressure variation

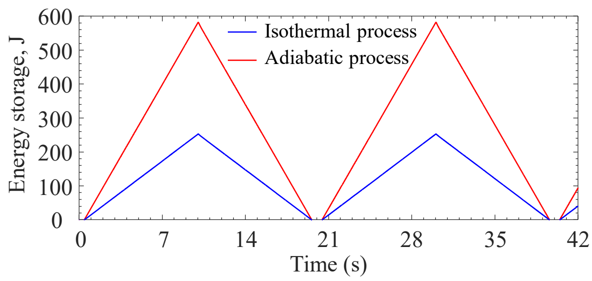



**Fig. 7.** Energy storage variation in accumulator

### 5.2. Transmission efficiency of the proposed system

Figure 8 represents the transmission efficiency of the gear train, HPT, and unite system of both HESbHPT. It is estimated as the ratio of the output power from the output shaft to the input power from the input shaft. The efficiency of the HESbHPT is the ratio of the output power at the hydraulic motor shaft to the input power to the gear shaft. It is found that the gear train has higher efficiency whereas the HPT conserves slightly lower efficiency than that of the gear train due to leakage loss. Moreover, the overall efficiency of HESbHPT is intermediate to the individual efficiency of the gear train and HPT.

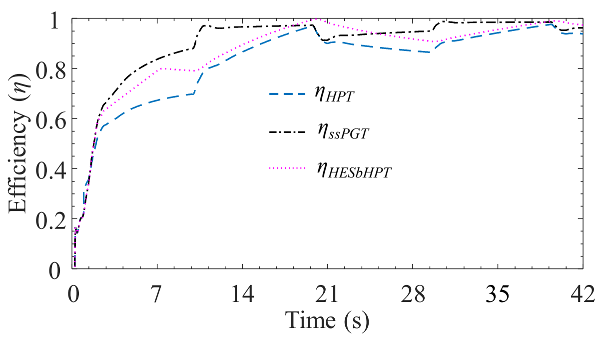



**Fig. 8.** Power transmission efficiency of the HESbHPT.

## 6. Conclusions

A detailed dynamic model of an Accumulator Based Hybrid Power Transmission (ABHPT) technology is proposed. It is an unite operation of two individual power transmission systems, such as gear train and a state-of-the-art hydraulic power transmission (HPT) with an accumulator. The gear train increases the low speed of the VFD shaft, HPT with an accumulator improves the system controllability and energy storage potential. The output shaft of the gear train is coupled to the hydraulic pump that supplies flow to the hydraulic motor of the HPT. An accumulator and two control valves are incorporated between the hydraulic pump and the motor. The control valve operation is controlled by an ON/OFF controller. The study found the following outcomes:

- The output speed of the hydro-motor is stable to 8.2 rad/s although the input speed to the gear train is variable in nature.
- The pressure development and the energy storage into the accumulator are higher when the gas compression of the accumulator is the isentropic process.

In the future, an experimental validation of the proposed scheme can improve the reliability of the technology. Also, a double accumulator-based energy storage system can be introduced to improve the performance of the system.

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