Efficiency Analysis of Hydraulic Wind Power Transfer System

Ayana Pusha, Student Member, IEEE, Majid Deldar, Afshin Izadian, Senior Member, IEEE

Abstract—High-pressure hydraulic systems have shown low efficiency in wind power transfer when interface a single-turbine to a ground-level generator. This paper demonstrates that using a central generation unit for a group of wind turbines and transferring the power of each turbine through hydraulic system increases the efficiency of overall system by 17% reaching maximum efficiency of 90.7%. The efficiency enhancement depends on the rotational speed of the hydraulic pumps. Therefore, it is proven that the multiple-turbine hydraulic power transfer system reaches higher efficiencies at lower rotational speed as much as 11.83%. This suggests that the variable speed gearbox can be eliminated from the wind powertrains if multiple turbines are connected to the central generation unit. Computer simulations and experimental results are provided to quantify the efficiency enhancements obtained by adding the second wind turbine hydraulic pump to the system. Adding more wind turbines enhances the integrated hydraulic wind systems’ power delivery profile and efficiency.

Index Terms—Efficiency, wind power, hydraulic energy transfer, multiple wind turbine integration.

I. INTRODUCTION

Wind energy generation using conventional powertrain is intermittent, difficult to control and expensive [1]. It requires many individual components for each tower such as turbine compartment, gearbox, generator and power transformer. These components, the set of gearbox and generator specifically, are expensive, bulky, and require regular maintenance, which makes wind energy production expensive. The dedicated generator to each wind tower also increases the capital and operation cost and decreases the capacity factor of the power plant. Some of these issues can be resolved by shifting the weight from the tower to ground level and interconnecting the system by a hydraulic power transfer unit. A hydraulic transmission system (HTS) consists of a hydraulic pump that converts turbine’s mechanical power into fluid power. Pipelines that connect the hydraulic pump to a hydraulic motor, which converts fluid power back into mechanical power, making the overall system a closed loop [2].

A hydraulic transmission system can transfer large amount of power and has more flexibility than a mechanical and electrical system. However, the hydraulic power transmission has already been tested for wind and resulted in low efficiency [3], [4]. Power transfer efficiency in a hydraulic transmission system is evaluated by examining the pressure losses. There are many variables that significantly affect the behavior of a hydraulic transmission system [2], including 1) the pressure differential across the pump and motor, 2) the rotational speed of the pump, motor and prime mover, 3) volumetric displacement of pump and motor, and 4) density, effective bulk modulus, and dynamic viscosity of the fluid. Examples of hydraulic wind turbine can be found in Mitsubishi plant [3], [4] and Chapdrive [5] with power rating of hydraulic machinery up to 5 MW.

Conventional variable speed hydraulic drives exhibit the ruggedness, weight and controllability required for large wind turbines; however, HTS’s generally have acceptable efficiency at full load and drop efficiency as the loading changes, typically having a peak around 60%, as a result of the loss mechanisms internal to pumps and motors [6] [7]. The wind turbine is of variable speed, which offers increased efficiency of 8-15% in capturing the energy from the wind over a wider range of wind speeds [8] [9]. It also proves to be a better option than the fixed-speed generation system because mechanical rotor power generated by a turbine is a function of the rotor speed for different wind speeds. The power transferred from the wind turbine to the generator is important to balance the system’s active power or compensate for frequency droop, when connected to a network. It has to ensure that the maximum output power is obtained for a certain wind speed [10] [11] [12].

A new hydraulic system configuration has been introduced in our previous research [13], [14]. This paper introduces an efficiency enhancement configuration when multiple wind turbines in parallel are integrated in a central energy generation unit. Parallel configuration allows for a more reliable operation [15]. A mathematical model of the system will be obtained to understand the losses of the system and calculate overall efficiency. The quantitative results obtained from the mathematical model can then be compared with a model designed using the SimHydraulics toolbox, and with experimental. Efficiency of the system will be measured through an experimental setup in two configurations: 1) single-turbine and 2) double-turbine to demonstrate the efficiency enhancement over the range of input hydraulic pump speeds.

The paper is organized as follows: in Section II, the energy calculations are introduced and the mathematical model of the hydraulic transmission system is designed in Section III. The system’s power losses are discussed in detail in Section IV. Section V evaluates experimental efficiency with the Conclusion being presented in Section VI.

A. Pusha, A. Izadian, and M. Deldar are with the Energy Systems and Power Electronics Laboratory at the Purdue School of Engineering and Technology, Indianapolis, 46202, USA. (E-mail: aizadian@iupui.edu).
II. ENERGY CALCULATIONS

The Bernoulli equation expresses the energy relations in a hydraulic system by analyzing the relationship of fluid mechanics [16]- [17]. It is derived by applying the conservation of energy law along the same streamline as:

\[ z_1 + \frac{p_1}{\gamma} + \frac{v_1^2}{2g} = z_2 + \frac{p_2}{\gamma} + \frac{v_2^2}{2g} , \]  
(1)

Subscripts 1 and 2 denote two distinct locations in the flow where \( z \) is the elevation head (potential), \( \frac{p}{\gamma} \) is the pressure head, and \( \frac{v^2}{2g} \) is the velocity head (kinetic), and \( \gamma \) is the specific weight. There are several restrictions that apply when using Bernoulli’s equation and can only be applied to certain flow conditions. These assumptions require the flow to be steady, incompressible, inviscid (zero viscosity, i.e. the fluid performs no work and has no work performed on it), and flow is along a streamline and is frictionless.

To take into account the frictional losses between two distinct locations along a streamline, and that a hydraulic pump or hydraulic motor may exist between these two locations, a revised Bernoulli equation was applied. The new equation became known as the energy equation or extended Bernoulli’s equation as:

\[ z_1 + \frac{p_1}{\gamma} + \frac{v_1^2}{2g} + H_p - H_m - H_L = z_2 + \frac{p_2}{\gamma} + \frac{v_2^2}{2g} \]  
(2)

Where \( H_p \) is the pump head, \( H_m \) is the motor head, and \( H_L \) is the head loss. All other components of this equation will be discussed in detail in next sections. When a fluid flows through the interior of a pipe, the velocity profile presents a maximum flow at the center as a consequence of the viscosity. The shear stress, \( \tau \), of the pipe wall is directly proportional to the velocity gradient [16], [18]:

\[ \tau = -\mu \frac{dv}{dr} , \]  
(3)

\[ \nu = \frac{1}{4\mu} \left( -\frac{dp}{dz} \right) \left( a^2 - r^2 \right) = \frac{-\Delta p}{4\mu L} \left( a^2 - r^2 \right) \approx \frac{Q}{A} , \]  
(4)

where \( \mu \) is the viscosity of the fluid, \( \nu \) is the velocity of the fluid, \( r \) is any radial location, \( L \) is a finite length of pipeline, \( p \) is the pipe pressure, \( a \) is the radius of the pipe, \( A \) is the area of the pipe, and \( Q \) is the volumetric flow rate. It can be concluded that the smaller the pipe diameter, the larger the value of fluid velocity.

III. POWER TRANSFER SYSTEM

To mathematically model the gearless hydraulic energy transfer system, a hydraulic circuit was created [13]- [14] for individual components. The model and simulation results obtained from this energy transfer system will be verified through simulation as well as experimental data.

A prototype has been built that is capable of mimicking the single-wind and double-wind turbine configurations and was used for model and efficiency calculation verifications. Schematic diagrams of the two hydraulic transmission systems being considered for this work are given in Figures 1 and 2. Interested readers can find the mathematical modeling of the system in the following references [19] [21]-[25].

Figure 1 provides an illustration of the second configuration being investigated to increase system efficiency. A second hydraulic pump, also driven by a wind turbine, has been added to the configuration in Figure 1.

In both configurations, a pressure relief valve is used to protect the system from the damage of excessive pressure. Thus, the relief valve opens occasionally which differs from a typical relief valve operation in a conventional hydraulic circuit. The components of the hydraulic power transfer circuit and their governing equations are illustrated in [21]-[25].

IV. POWER LOSSES

An important cause of energy losses in fluid power systems is produced by friction. For this research, friction can be defined as the resistance to flow, which is a measure of the viscosity of fluid. The greater the viscosity of fluid, the less readily it flows and the more energy needed to move the fluid. This energy loss is transformed into heat, which dissipates into the surrounding air. It results in a loss of potential energy and surfaces as a loss in pressure or head [19].

The loss in head is the decline in the overall head or pressure (sum of the elevation head, velocity head, and pressure head) of the fluid as it moves through a fluid system. Head associates the energy in an incompressible fluid to the height of an equivalent static column of that fluid. Head loss is separated into two main components, losses in pipes and losses in valves, bends, and
fittings [19]. Head loss in pipes can be computed with the use of the Darcy-Weisbach equation as:

\[ H_L = f \left( \frac{L}{D} \right) \left( \frac{v^2}{2g} \right), \]  

(5)

where \( f \) is the friction factor, \( L \) is the length of pipe, \( D \) is the pipe inside diameter, and \( g \) is the acceleration of gravity. Frictional factor \( f \) is a dimensionless quantity that is used to illustrate the frictional losses in pipe flow. It is associated with the shear stress applied to the walls of the pipe. For laminar flow, this equation can be reduced to a simpler equation as seen below [16]:

\[ f = \frac{\tau_w}{\rho v^2} = \frac{16}{RE}, \]  

(6)

where \( \tau_w \) is the shear stress applied to the pipe wall, \( \rho \) is the fluid density, and \( RE \) is the Reynolds Number. The ratio between inertial forces and viscous forces is the dimensionless Reynolds Number. It is utilized to determine the conditions governing the transition from laminar flow to turbulent flow [19] as:

\[ RE = \frac{vD}{\mu} = \frac{vD}{\nu}, \]  

(7)

where \( \mu \) is the absolute viscosity, and \( \nu \) is the kinematic viscosity. Table 1 illustrates the flow characterization based on the value of the Reynolds Number [16].

It is assumed that if the Reynolds number lies within the transition or critical zone, the flow is considered as turbulent. Turbulent flow results in a larger amount of losses, therefore hydraulic systems are generally designed to operate in a laminar flow region as in this paper. Table 1 also indicates that when there is restriction in the flow, there is a pressure drop across the component. This loss depends on the geometry of the restriction and has been observed to be proportional to the flow rate squared [18].

<table>
<thead>
<tr>
<th>Approximate Value of Reynolds Number</th>
<th>Flow Regime</th>
<th>Pressure Gradient is Proportional to</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2,000</td>
<td>Laminar</td>
<td>( Q )</td>
</tr>
<tr>
<td>2,000 - 4,000</td>
<td>Transition</td>
<td>Variable</td>
</tr>
<tr>
<td>&gt; 4,000</td>
<td>Turbulent</td>
<td>( Q^{1.8} - Q^2 )</td>
</tr>
</tbody>
</table>

The main source of energy loss in system occurs in valves and fittings. This is due to the change in the cross section of the flow path and in the flow direction change [10]. The head losses in fittings and valves are proportional to the square of the velocity of the fluid [19] [20] as:

\[ H_L = K \left( \frac{v^2}{2g} \right), \]  

(8)

where \( K \) is the constant of proportionality (loss coefficient) of the fitting or valve. With the use of the Darcy-Weisbach equation it can be illustrated that the head loss in a pipe is proportional not only to the square of the fluid but also to the length of the pipe due to fluid friction. The length of a pipe is regarded as the equivalent length of a particular fitting or valve. For the equivalent length technique, the head loss for a fitting or a valve is set equal to the head loss of the pipe as:

\[ K \left( \frac{v^2}{2g} \right) = f \left( \frac{L_e}{D} \right) \left( \frac{v^2}{2g} \right), \]  

(9)

Where \( L_e \) is the equivalent length of a fitting or valve with proportionality factor \( K \) and \( L_e = \frac{KD}{f} \). Pump head or motor head can be determined using the following equation. \( H_L \), pump head, represents the energy per pound of fluid added by the pump, while \( H_m \), motor head, represents the energy per pound of fluid removed by the hydraulic motor as:

\[ H_L = H_m = \frac{3950(HHP)}{Q(gpm)\gamma}. \]  

(10)

The loss in pressure for each component of head loss can be determined as:

\[ p_L = \gamma H_L = (SG \gamma_{H2O})H_L, \]  

(11)

where, \( \gamma \) is the specific weight of the fluid, \( SG \) is the specific gravity of the fluid, and \( \gamma_{H2O} \) is the specific weight of water.

Efficiency equals to the ratio of output power over the input power. The overall efficiency of the system is related to mechanical loss and volumetric loss which is due to the fluid’s viscosity. Volumetric losses take place when there is internal leakage as the fluid travels through the gear teeth of a pump or motor. Mechanical efficiency accounts for the mechanical losses caused from gears, bearings, and mating parts. There is a reduction in the power transferred from the shaft to the fluid in the pump or from the shaft of the motor to the pump. The efficiency of a pump or motor can be calculated as follows:

\[ \eta_{overall} = \eta_{vol} \ast \eta_{mech} = \frac{HP_{output}}{HP_{inpt}} \ast 100 \]  

(12)

Where, \( \eta_{vol} \) is the volumetric efficiency and \( \eta_{mech} \) is the mechanical efficiency.

V. EXPERIMENTAL EFFICIENCY EVALUATION

In this section, the efficiency enhancement was experimentally measured through a laboratory test bed. Two experiments were conducted to demonstrate the efficiency enhancement in the hydraulic wind power transfer system. In experiment 1, a single-wind turbine generated high-pressure flow to transfer the energy from wind turbine to a generator. In the second experiment, a second wind-driven hydraulic pump was added to the system and the energy was measured at the hydraulic motor output shaft.

The experimental data was collected from the setup shown in Figure 3. During the experiment it was observed that: 1) The pump ramp speed created a ramp response at the motor, 2) It was determined that the flow rate sensor used at the motor could not detect any flow rate for pump velocities below 115 rpm, and 3) The accuracy of the flow readings diminished at velocities lower than 200 rpm. Therefore, experiments were conducted at pump speeds higher than 200 rpm.
**Experiment 1: Single-Wind Turbine.** In Experiment 1, one pump provided hydraulic fluid to one motor in the setup shown in Figure 3. Figure 4 illustrates the velocity profiles of the pump and motor. A ramp velocity was applied at the input shaft of a hydraulic pump so that the system power transfer and velocity responses at the hydraulic motor could be observed. The input velocity ranged from 200 rpm to 650 rpm for the duration of 15 seconds.

Figure 5 illustrates the efficiency of the power transfer system when a single-wind turbine was used. The efficiency of the system was then calculated from these values. At 200 rpm the efficiency of the system was 74%. As the velocity of the wind turbine was gradually increased to 650 rpm, the efficiency increases to its maximum value of 83%. The efficiency of power transfer system increases as the speed increases. For the single-turbine hydraulic wind power system that eliminated the gearbox, variable wind speed cannot be regulated which consequently results in lower overall system efficiency.

To make the system operation economic and highly efficient, there will be need for more wind turbines to pump high-pressure fluid through the system. That way the efficiency of overall power-transfer system is increased. The second experiment is designed to demonstrate and experimentally prove that as a second wind-turbine is connected to the system, the overall efficiency is increased and this can be obtained at lower pump velocities. Experimental setup and flow directions of double-wind turbines are shown in Figure 6.

**Experiment 2: Double-Wind Turbine Configuration.** During this experiment, the flows of two wind-driven hydraulic pumps were integrated and directed to one hydraulic motor. The speed of one pump (pump A) was held constant with an average velocity of 389.04 rpm. While velocity of pump B varied from 185 rpm to 560 rpm in 15 seconds. Since the purpose of this experiment was to investigate the effect of multiple turbine on efficiency, having two pumps with speed variation only for one of them suffices the purpose. If both pumps’ speed had been changed, the motor output power would have increased but the efficiency would follow similar trend. With an additional pump to this experiment, the shaft velocity of the hydraulic motor jumped at a much higher value of 2069 rpm versus the 800 rpm in single-turbine experiment, and reached a maximum velocity of 3333 rpm as shown in Figure 7.

The flows of wind turbines A and B, and their combination passing motor A are illustrated in Figure 8. As the pump speed increased, the flows of wind turbine B and motor A increased linearly. As motor B spun at higher velocity, the output pressure of their point of common coupling (PCC) increased. Therefore,
motor A could pump less fluid at a constant speed. This effect has shown on Figure 8. Wind turbines A and B provided a combined flow of 1.00 GPM to 1.76 GPM as the velocity of motor B increase from 185 to 560 rpm. The hydraulic motor’s flow sensor measured 0.99 GPM to 1.60 GPM for the same range of speed.

![Flow Profile](image)

Fig. 8. Experimental flow measurement in a double-wind turbine hydraulic power transfer setup. Wind turbine A ran at fixed speed 389.04 rpm

The energy transfer efficiency of integrated wind turbines into one central energy generation unit is shown in Figure 9. As the figure illustrates, the overall efficiency of the double-wind turbine system started at efficiency of 86% at 185 rpm, and increased as the wind turbine velocity increased reaching a maximum of 90.7% at around 510 rpm. The single-wind turbine hydraulic power transfer could only reach maximum efficiency of 83.31% at 650 rpm. With an average velocity of 389.04 rpm being produced by wind turbine A, and wind turbine B starting with an rpm of 185, the overall system efficiency reached 89.83% while the overall efficiency of single-turbine hydraulic wind power transfer reached 78% based on figure (5)

These experiments demonstrate two important observations: 1) The maximum efficiency of double-wind turbine system reached 90.7% at a lower speed. 2) At low rotational speeds the efficiency of double-wind turbine system increased by 17%. A comparison of system speed dependent efficiencies in single-turbine and double-turbine systems is shown in Figure 11

![Efficiency Profile Comparison](image)

Fig. 11 Experimental system efficiency measurement comparison of single-wind turbine and double-wind turbine hydraulic power transfer setups. Wind turbine A ran at fixed speed 389.04 rpm

The set of experiments and simulations obtained in Figures 5 and 9 proved that: 1) increasing the number of wind turbines in a hydraulic energy transfer system increased the power transfer efficiency, 2) the increased efficiency occurred at lower rotational velocities suggesting strong prove for elimination of variable speed gearbox from wind turbine drivetrain and high efficiency of multiple-turbine hydraulic wind power transfer. Through the elimination of the gearbox, the overall unit cost of a wind turbine can considerably be reduced.

It was observed that the multi-turbine system provided higher efficiency and delivered more of the power created at the shaft of the hydraulic pumps to the shaft of the motor. The addition of hydraulic wind – driven pump decreased the required rotational velocity at which the maximum efficiency occurred. Running at lower speeds, the multi-turbine system produced a higher efficiency requiring the system to do less work.

Figure 12 shows, as more wind turbines contribute their power to the central energy generation unit, the overall efficiency of the power transfer system is increased. The efficiency of single wind
turbine power system dropped as the load torque increased. However, Figure 12 also demonstrates that multiple-turbine configuration has relatively constant efficiency as the load torque is increased.

![Effect of Multiple-Turbine Operation on Efficiency Enhancement](image)

**Fig. 12** Effect of wind turbine increase and load variation on efficiency enhancement of hydraulic wind power transfer system.

**VI. CONCLUSIONS**

In this paper, a novel efficiency enhancement of hydraulic energy transfer system was introduced. It was observed that the addition of one wind turbine-driven hydraulic pump will increase the efficiency by 17%. Simulations of energy transfer system and energy losses were obtained using two techniques of mathematical modeling. The energy enhancement of these models was 12.04% and 14.45% respectively from a single-wind turbine hydraulic power plant. It was observed that the addition of one wind-driven fixed displacement hydraulic gear pump would decrease the required rotational velocity at which the maximum efficiency occurred. Collection of energy from more wind turbines resulted in increasing of the efficiency and energy generation of the wind power plant.

**REFERENCES**


[22] e. a. K. Wu, "Modelling and identification of a


