An Energy Storage Technique for Gearless Wind Power Systems

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Abstract—Hydraulic wind power transfer systems allow collecting of energy from multiple wind turbines into one generation unit. They bring the advantage of eliminating the gearbox as a heavy and costly component. The hydraulically connected wind turbines provide variety of energy storing capabilities to mitigate the intermittent nature of wind power. This paper introduces the hydraulic circuitry and control algorithm for a novel wind energy electrical energy storage technique. The simulation results demonstrate successful operation of the storage to maintain the fluid in the system and control the generator speed at a reference.

I. INTRODUCTION

The hydraulic wind power transfer system consists of a fixed displacement pump driven by the prime mover (wind turbine) and one or more fixed displacement hydraulic motors. The hydraulic transmission uses the hydraulic pump to convert the mechanical input energy into pressurized fluid. Hydraulic hoses and steel pipes are used to transfer the harvested energy to the hydraulic motors [1]. The proposed energy transfer system offers several advantages ahead of their geared counterparts including the replacement of gearbox with a hydraulic transmission system. Unlike traditional wind power generation, this system offers lower operating and maintenance costs and allows for integration of multiple wind turbines to one central generation unit.

The new wind energy harvesting technique incorporates power generation equipment of individual towers in a central power generation unit. With the introduction of this new approach, the wind tower only accommodates a hydraulic pump, which passes the hydraulic fluid through high-pressure pipes attached to the hydraulic motor coupled to a generator at ground level. This will result in enhanced reliability, increased life span, and reduced maintenance cost of the wind turbine towers. Other benefits of this technique include high-rate of energy transfer and size reduction of the power electronics [2-5].

The energy harvesting from intermittent sources, require energy storage units to smooth out the generation of power and frequency stability, which can easily deviate from 60 Hz as the wind speed changes. High-pressure hydraulic systems provide an excellent platform for incorporation of mechanical and electrical energy storage units.

This paper addresses the circuitry needed for energy storage and the control algorithm that can enable it. In general, high wind speeds result in generation of excess flow in the system. The energy of this flow is captured by an auxiliary generator and stored in a storage unit. The stored energy is released back to the system to run the main pump when the wind speed drops. In this case, the flow generated by the wind turbine is augmented by the auxiliary pump flow to maintain the angular velocity demands of the loaded primary generator. A two-loop control system with PI and a rate limit sliding control is designed to maintain the reference angular velocity [13-15], and control the storage charge and discharge power.

II. HYDRAULIC WIND ENERGY TRANSFER SYSTEM

The hydraulic wind power transfer system consists of a fixed displacement pump driven by the prime mover (wind turbine) and one or more fixed displacement hydraulic motors. The hydraulic transmission uses the hydraulic pump to convert the mechanical input energy into pressurized fluid. Hydraulic hoses and steel pipes are used to transfer the harvested energy to the hydraulic motors [1].

Figure 1 displays a schematic diagram of the wind energy transfer and the energy storage system. As the figure demonstrates, a fixed displacement pump is mechanically coupled with the wind turbine and supplies pressurized hydraulic fluid to two fixed displacement hydraulic motors. The hydraulic motors are coupled with electric generators to produce electric power in a central power generation unit. Since the wind turbine generates a large amount of torque at a relatively low angular velocity, a high displacement hydraulic pump is required to flow high-pressure hydraulics to transfer the power to the generators. The pump might also be equipped with a fixed internal speed-up mechanism. Flexible high-pressure pipes/hoses connect the pump to the piping toward the central generation unit.

Fig. 1. Schematic of the high-pressure hydraulic power transfer system. The hydraulic pump is in a distance from the central generation unit.
The hydraulic circuit uses check valves to guarantee the unidirectional flow of the hydraulic flows. A pressure relief valve protects the system components from the destructive impact of localized high-pressure fluids. These units also provide proper path for the energy storage to circulate the fluid in the system without going through the hydraulic pump at the wind tower. The hydraulic circuit contains a specific volume of hydraulic fluid, which is distributed between hydraulic motors using a proportional valve.

Since the electrical energy produced at the central generation unit could only be supplied to the grid at a specific frequency, a velocity control unit is required to maintain the constant angular velocity at the primary motor-generator. The speed regulation is accomplished by regulating the flow through a proportional valve and directing the excess fluid to the auxiliary motor. The operation of the hydraulic system is split into two categories, namely system operation at high wind and system operation at low wind.

A. System Operation at High Wind

The wind speed fluctuates over time. Therefore, utilization of fixed displacement pumps result in flow variation in the system. If the wind speed is higher than the reference that generates 60 Hz voltage in the output, the condition is called high wind. If the excess flow of power and its energy is not captured, the generator’s voltage frequency will deviate from 60Hz. The proportional valve is regulated such that the required flow is delivered to the primary hydraulic motor, and the excess energy is captured by the auxiliary hydraulic motor. The auxiliary hydraulic motor is coupled with an electric motor/generator. At high wind, the auxiliary hydraulic motor runs the electric generator. The electric generator converts the mechanical energy of the rotating shaft into electric energy and stores it in batteries. The primary motor is coupled to the main generator and supplies electricity at a specific frequency to the load. Figure 2 illustrates the hydraulic circuit of the energy transfer system at high wind. To regulate the amount of energy captured by auxiliary motor a rate limit controller is utilized.

![Fig. 2. Operating configurations of the system at high wind.](image)

B. System Operation at Low Wind

If the wind speed drops below a threshold speed, the condition is considered low wind. In this condition, the flow generated by hydraulic pump is not sufficient enough to maintain the reference angular velocity at the primary motor. In order to compensate for the flow deficiency, the energy stored in the storage should be released back to the system. The storage in any form can run the auxiliary hydraulic pump to generate an augmented pressurized fluid in the system. Figure 3 illustrates the system operation at low wind. In this configuration, a PI controller regulates the storage discharge rate such that the main generator maintains the rated frequency.

C. Hydraulic Circuit Dynamics

The complete mathematical model of the hydraulic wind energy transfer system is represented in [2-12]. Hydraulic pumps deliver a constant flow determined by

\[ Q_p = D_p \omega_p - k_{L,p} P_p, \]  

(1)

where \( Q_p \) is the pump flow delivery, \( D_p \) is the pump displacement, \( k_{L,p} \) is the pump leakage coefficient, and \( P_p \) is the differential pressure.

The flow and torque equations are derived for the hydraulic motor using the motor governing equations. The hydraulic flow supplied to the hydraulic motor can be obtained by

\[ Q_m = D_m \omega_m + k_{L,m} P_m, \]  

(2)

where \( Q_m \) is the motor flow delivery, \( D_m \) is the motor displacement, \( k_{L,m} \) is the motor leakage coefficient, and \( P_m \) is the differential pressure across the motor. Torque at the motor driving shaft is obtained by

\[ T_m = D_m P_m \eta_{mech,m}, \]  

(3)

The total torque produced in the hydraulic motor is expressed as the sum of the torques from the motor loads and is given as

\[ T_m = T_i + T_f + T_L, \]  

(4)

where \( T_m \) is total torque in the motor and \( T_i, T_f, T_L \) represent inertial torque, damping friction torque, and load torque, respectively. This equation can be rearranged as

\[ T_m - T_L = I_m (d\omega_m/dt) + B_m \omega_m, \]  

(5)

where \( I_m \) is the motor inertia, \( \omega_m \) is the motor angular velocity, and \( B_m \) is the motor damping coefficient.

D. Hose Dynamics

The fluid compressibility model for a constant fluid bulk modulus is expressed in [9]. The compressibility equation represents the dynamics of the hydraulic hose and the hydraulic fluid. Based on the principles of mass conservation and the definition of bulk modulus, the fluid compressibility within the system boundaries can be written as

\[ Q_e = (V/\beta)(dP/dt), \]  

(6)

where \( V \) is the fluid volume subjected to pressure effect, \( \beta \) is the fixed fluid bulk modulus, \( P \) is the system pressure, and
\(Q\) is the flow rate of fluid compressibility, which is expressed as
\[Q_v = Q_p - Q_m.\]  
(7)

Hence, the pressure variation can be expressed as
\[dP/dt = (Q_p - Q_m) \beta/V.\]  
(8)

**E. Storage Dynamic**

Without loss of generality, in this paper we consider the storage as a battery. The excess energy which is captured by the auxiliary motor is transformed to electrical energy through a generator. The charge current is calculated as
\[I_B = \frac{\tau_{p/m} \alpha_{p/m} \eta_{gen}}{V_B}.\]  
(9)

where \(I_B\) is the battery current, \(\tau_{p/m}\) is the auxiliary pump/motor torque, \(\alpha_{p/m}\) is the auxiliary pump/motor angular velocity, and \(V_B\) is the battery voltage.

The battery state of charge (SOC) which is defined as the percentage of the initial battery capacity is calculated as
\[SOC = \frac{C_i}{C_0}.\]  
(10)

where \(C_i\) is the available charge of the battery, and \(C_0\) is the nominal capacity of the battery.

The auxiliary motor/pump is coupled with the electric generator/motor. The dependency of the angular velocity of the auxiliary pump to the extracted battery current is expressed such that
\[\omega_{p/aux} = k I_B.\]  
(11)

where \(k\) is the current coefficient of the electric generator which is coupled with the auxiliary pump.

**III. SYSTEM OPERATION AND DYNAMIC MODEL**

1. **System Operation at High Wind**

The overall hydraulic system can be connected as modules to represent the dynamic behavior. Block diagrams of the hydraulic transmission system using MATLAB Simulink are demonstrated in Figures 4. The model incorporates the mathematical governing equations of individual hydraulic circuit components. The bulk modulus unit generates the operating pressure of the system.

Figure 4 shows a block diagram of the wind energy transfer system in high wind. According to the figure, the wind turbine supplies power at a specific angular velocity to the main hydraulic pump. The hydraulic pump supplies pressurized hydraulic fluid to the proportional valve which distributes the hydraulic fluid between the motors based on the reference primary motor angular velocity. The auxiliary motor captures the surplus energy of the flow and drives the electric generator to charge electrical storage. The generated electrical energy is stored in a battery through the power electronic converters. The primary motor is coupled with the main generator and supplies electricity to the grid.

2. **System Operation at Low Wind**

The model of the wind energy transfer at low wind is similar to the high wind condition. However, in this configuration, the transfer system is driven by the energy stored in the battery when released back to the system. The current extracted from the battery is regulated to accommodate the primary motor angular velocity demands. The auxiliary motor can be driven as a pump by the electric motor and flows pressurized fluid augmented with the main pump flow. The compressibility block calculates the gauge pressure along the pumps and hydraulic motor terminals. Figures 5 show the block diagram of the mathematical model of the hydraulic transfer system at low wind conditions [10][11].

![Fig. 4. Hydraulic transmission schematic diagram in gasoline configuration.](image)

![Fig. 5. Hydraulic transmission schematic diagram in electric configuration.](image)

**IV. CONTROLLER DESIGN**

This section introduces the design of the controllers which are required to maintain the reference primary motor angular velocity at both high and low wind conditions. A rate limit controller regulates the position of the proportional valve at the high wind operation to maintain tracking of the reference speed. A PI controller is also utilized to regulate the battery discharge current at low wind operation.

A. **Rate limit Controller Design**

The rate limit controller directs the flow of the hydraulic fluid from wind turbine at high wind, and from wind turbine and auxiliary motor at low wind to the main hydraulic motor. The controller adjusts the position of the valve towards the primary motor path to maintain tracking of the reference angular velocity. Figure 6 illustrates the diagram of the rate limit controller.

At the high wind operation, the rate limit controller measures the error between the reference angular velocity and the primary pump angular velocity. If the error value is positive, then the controller sends a number of negative fixed
displacement step signals to the valve, to regulate the flow and track the reference velocity. If the error value is negative, the controller opens the valve by sending a fixed positive step displacement signal to the valve. Figure 7 shows the structure of the rate limit controller. The step values are designed to maintain system stability while both fast response and error mitigation criteria are fulfilled.

![Fig. 6. The diagram of the rate limit control closed loop system](image)

**B. PI Controller Design**

At low wind conditions and when the battery is being discharged, a PI controller is utilized. In this case, the PI controller regulates the angular velocity of the auxiliary pump to maintain velocity reference of the primary motor. The PI controller regulates the amount of battery discharge current to run the electric motor/generator coupled with the auxiliary pump. Figure 8 represents the closed-loop diagram of the PI control system.

![Fig. 7. The rate limit controller structure](image)

![Fig. 8. The diagram of the PI control closed loop system](image)

The proportional gain adjusts the response time characteristics such as settling time and rise time. At higher proportional gains (within the region of stability) a faster system response is obtained. A proper integral gain mitigates the steady state tracking error.

**V. SIMULATION RESULTS AND DISCUSSION**

In this section, the mathematical model of the hydraulic wind energy transfer with the storage unit behavior is simulated and the performance of the control system to maintain the reference angular velocity is evaluated. The simulation parameters are listed in Table 1.

A constant primary motor angular velocity of 1000 rpm is used as a reference for both the rate limit controller of the proportional valve, and the PI controller for battery current controller. Figure 9 illustrates the angular velocity profile which is supplied to the hydraulic transmission system. The angular velocity profile is used to determine the system operating modes both at low wind and at high wind. Initially, a 400 rpm step angular velocity is supplied to the hydraulic pump which simulates the high wind condition. The pump angular velocity is reduced to 100 rpm after 5 seconds to simulate the low wind condition. Then, the angular velocity is increased to 600 rpm to restore the high wind condition at t=10 sec. According to the hydraulic wind energy transfer configuration (High wind or Low wind), the associated controller generates a control command to maintain the tracking of the reference angular velocity. The transmission system switches between these two configurations based on the wind speed.

![Fig. 9. Hydraulic pump angular velocity profile.](image)

![Fig. 10. Flow generated by the hydraulic pump.](image)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_p$</td>
<td>Proportional Gain</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>$k_i$</td>
<td>Integral Gain</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Figure 10 displays the flow passing through the main pump when the angular velocity profile of Figure 10 is applied. According to this figure, the wind speed is initially high enough to maintain the reference primary motor angular velocity, and the pump flow is distributed between the main and auxiliary motors through the proportional valve. The wind speed drops after 5 seconds and the system switches to the low wind configuration, at which the main pump flow is
augmented with the auxiliary pump flow. The high wind conditions will occur in 5 seconds from this event.

Fig. 11. Primary motor flow.

Fig. 12. Auxiliary motor/pump flow.

Figures 11 and 12 show the primary motor and auxiliary motor flows. According to these figures, the rate limit controller initially controlled the system flow distribution by regulating the proportional valve position. In this configuration, the auxiliary motor captured the excess flow energy and stored it in a battery through the electric generator. At low wind condition, the PI control regulated the current from the battery and ran the electric motor to compensate for the main pump flow and maintain the reference velocity. According to Figure 12, since the motor angular velocity was proportional to the flow, the controller maintained the fluid flow at a certain rate to maintain the reference velocity. The system switching between these configurations resulted in an instantaneous variation in the system shown as spikes at time 5 and 10 seconds.

Fig. 13. Comparison of the primary motor angular velocity and the reference angular velocity.

Figures 13 and 14 illustrate the angular velocities of the primary motor and the auxiliary motor/pump. As demonstrated in Figure 13, the controller successfully adjusted the valve position at high wind with decremented rate to reduce the flow of main motor and maintain the required velocity. The simulation results illustrate a rise time of 0.135 sec and an overshoot percentage of 15.2%.

Fig. 14. Hydraulic Transmission Auxiliary motor/pump angular velocity.

Figure 15 illustrates the rate limit control effort to maintain the fluid in the system by regulating the proportional valve position. The controller effort is zero while the system runs in low wind condition between 5 to 10 seconds. The controller effort was either 0.0001 to open the valve or -0.0001 to close the valve. The simulation results demonstrate a high performance system operation.

Fig. 15. Control effort of the rate limit controller to regulate the proportional valve position.

Figure 16 illustrates the position of the proportional valve which was regulated by the rate limit controller. According to the figure, the valve was immediately closed enough from the initial position to reduce the flow of the primary motor at high wind. The valve was completely opened in low wind to direct the entire flow towards the primary motor path and augment with the auxiliary motor flow.

Fig. 16. Proportional valve position to distribute hydraulic flow between the motors to maintain the reference angular velocity.
Figure 17 illustrates the effort of the PI controller in discharging the battery. The controller effort was zero when the system was in high wind condition. As soon as the wind condition changed to low wind speed, the PI controller adjusted the battery discharge current to maintain the primary motor angular velocity. The charging process was determined by the amount of fluid redirected from the proportional valve to the auxiliary motor. Figure 18 displays the battery charge/discharge current.

Figure 19 shows the battery state of charge variation as the system operation mode changed. As the figure illustrates, the SOC increased in high wind condition. Figure 19 illustrates battery charge/discharge current controlled by the PI. The current is negative during charge cycles and positive when the battery is being discharged. The figure demonstrates a high performance control of the battery charge and discharge process.

VI. CONCLUSION
This paper presented an energy storage technique to capture the excess energy of hydraulic wind transmission system. The stored energy was released to the plant when the wind speed dropped below a certain threshold. A mathematical model of the storage system was represented for both high wind and low wind operating conditions. A rate limit controller was designed to regulate the valve position opening to track a reference angular velocity at high wind. A PI current controller was utilized to regulate the plant operation at low wind condition. The simulation results demonstrated successful operation of the energy storage and release and its effects on the hydraulic wind energy system operation.

REFERENCES