Stability Analysis of DC-link Voltage Control on Autonomous Micro Hydro Power Plant System

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ABSTRACT
Micro Hydro Power Plant has become one of the interesting topics to be researched nowadays. This paper deals with the stability analysis on control system of excitation voltage in Micro Hydro Power Plant. The control of this voltage can be achieved by controlling the Permanent Magnet Synchronous Machine (PMSM) with particular algorithm so the voltage on the DC-link part of the system can be controlled. Without knowing the exact specification of system parameters, the system will be most likely unstable. The DC-link control system is modeled, simulated, and mathematically analyzed so the parameter specification for the stable system can be obtained.

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INTRODUCTION
Micro Hydro Power Plant has been one of the most increasing uses of power generation system in the world. This type of Power Plant has high potential especially on developing country that has many rivers. The autonomous system on Micro Hydro Power Plant can be achieved by using Doubly Fed Induction Generator (DFIG) and Permanent Magnet Synchronous Machine (PMSM). Block diagram of the system is shown in Figure 1.

Figure 1. Microhydro DFIG generation system with PMSM exitation.

The system shown in Figure 1 can be divided into two independent control systems. The first system is regulating the stator voltage to load by controlling DFIG and the second system is regulating the excitation...
voltage by controlling PMSM. On this study, we are focusing on the control of excitation voltage on the system. Therefore the second system is mainly used for easier analysis that will be performed in this paper. The simplified system can be done by replacing the excitation load (DFIG) system by pure resistive load. Figure 2 shows the simplified system that is used in this study.

Stability problem arise in the excitation voltage control system without using an appropriate value of parameters such as water velocity, voltage reference, load resistance, etc. For example, Figure 3 shows the excitation voltage (DC-link voltage) result when a simulation is performed with random value of mentioned parameters. The simulation is performed by using MATLAB’s Simulink.

From simulation result shown on Figure 3, it is noticed that unstable system condition could occur if an inappropriate value of certain parameters is used. To clarify this issue, it is necessary to examine this control problem deeply. The system is modeled and then simulated and analyzed mathematically in order to know the exact value of those parameters. By using this method, the parameter’s value required to achieve stable system can be noticed.

2. SYSTEM MODEL
The whole system is composed of PMSM, shafts, turbine, inverter, DC-link, and controller. Each one of these components is mathematically modeled to ease the analysis process.

2.1. PMSM Model
Electrical model of PMSM is expressed by (1) and (2).

$$\frac{d}{dt}i_d = \frac{1}{L_d} v_d - \frac{R_s}{L_d} i_d + \frac{L_q}{L_d} \omega_r i_q$$

(1)

$$\frac{d}{dt}i_q = \frac{1}{L_q} v_q - \frac{R_s}{L_q} i_q - \frac{L_d}{L_q} \omega_r i_d - \frac{p \phi_m}{L_q}$$

(2)

Where p is pole pairs, $\omega_r$ rotor speed, $R_s$ stator resistance, $L_d$ and $L_q$ the direct and quadrature axis inductances, $v_d, v_q, i_d, i_q$ are the direct and quadrature axis voltage and current components, and $\phi$ is the permanent magnet flux.

Mechanical model of PMSM will be discussed on shaft subsection because the state (rotor speed) on PMSM is the same as rotating speed of the shaft.

2.2. Shaft Model
Differential equation of the shaft is expressed as:

$$\frac{d}{dt} \omega_r = \left(-B \omega_r + T_e - \frac{T_m}{R}\right) \left(\frac{J_m}{R^2} + \frac{1}{R}ight)$$

(3)

$$T_e = p \phi_i q$$

(4)
Where B is internal damping, $T_e$ is electrical torque from PMSM, $T_m$ is mechanical torque from turbine, K is gear ratio, $J_m$ and $J_p$ are inertia of turbine and PMSM.

### 2.3. Turbine Model

Turbine component does not have its own state. This component just continuing rotor speed’s feedback state from shaft and water velocity from its input. Output of this component is mechanical torque to shaft as expressed in (5).

$$T_m = -\frac{0.5 \rho \omega_r s v_w^3}{\omega_r}$$ (5)

Where $\rho$ is water density, $s$ is turbine swept, $v_w$ is water velocity, and $c_p$ is turbine constant.

### 2.4. Inverter Model

The inverter is assumed as an ideal power conversion machine with an efficiency factor $\eta$. The power conversion expression of inverter model for analysis purpose is expressed as:

$$\eta V_d i_{in} = v_d i_d + v_q i_q$$ (6)

In the analysis the inverter is assumed to be ideally efficient, therefore $\eta = 1$.

The only state in this component is DC voltage detection of inverter which can be expressed as:

$$\frac{d}{dt} V_{dc det} = -\frac{1}{\tau_{dc}} V_{dc det} + \frac{1}{\tau_{dc}} V_{dc}$$ (7)

Where $V_{dc det}$ is DC voltage detection value, $\tau_{DC}$ is detection time constant, and $V_{dc}$ is DC-link voltage.

### 2.5. DC-link Model

DC-link circuit structure can be seen on Figure 2. Modeling of this circuit can be done by using basic Kirchhoff’s law and can be expressed as:

$$\frac{d}{dt} V_{dc} = \frac{i_{in}}{C} - \frac{V_{dc}}{CR}$$ (8)

Where $i_{in}$ is input current on DC-link circuit, C is capacitor’s capacitance, and R is load’s resistance.

### 2.6. Controller Model

The algorithm and modeling of this controller is expressed by the state equations as follows:

$$\frac{d}{dt} x_d = i_d^* - i_d$$ (9)

$$\frac{d}{dt} x_q = i_q^* - i_q$$ (10)

$$\frac{d}{dt} i_d^{*1} = \frac{1}{\tau_d} i_d^* - \frac{1}{\tau_d} i_d^{*1}$$ (11)

$$\frac{d}{dt} i_q^{*1} = \frac{1}{\tau_q} i_q^* - \frac{1}{\tau_q} i_q^{*1}$$ (12)

$$\frac{d}{dt} x_{dc} = v_{dc} - v_{dc}$$ (13)

$$i_d^* = 0$$ (14)

$$i_q^* = -k_{pdc} v_{dc} + k_{idc} x_{dc}$$ (15)

Where $\tau_d$ is controller’s time constant, $k_{pdc}$ and $k_{idc}$ are DC-voltage controller constants.
RESULTS AND ANALYSIS

Simulation method used in this study is to do a variation of several parameters: water velocity, DC voltage reference, resistive load, and controller constant. Variation is performed by changing one of the parameter as independent variable while keeping others with their initial value. The system is simulated in Matlab and the result is obtained and analyzed graphically and mathematically. Model's parameter is shown in Table 1 and some variable values are initially stated as shown on Table 2.

| Table 1. System Parameters |
|-----------------------------|
| Parameter       | Symbol | Value |
| PMSM inertia     | \(J_p\) | 0.01 [kgm²/s²] |
| Turbine inertia  | \(J_m\) | 0.5 [kgm²/s²] |
| Shaft Internal Damping | B | 0.001 [Nm/s] |
| Gear ratio       | K     | 9     |
| Stator Resistance | \(R_s\) | 0.55 [Ω] |
| Direct axis inductance | \(L_d\) | 16.61 [mF] |
| Quadrature axis inductance | \(L_q\) | 16.61 [mF] |
| Permanent magnet flux | \(\phi\) | 0.121 [Wb] |
| Pole pairs       | p     | 4     |
| Controller time constant | \(T_c\) | 10 [ms] |
| DC-voltage detection time constant | \(T_{dc}\) | 100 [ms] |
| DC-link capacitance | C | 0.1 [mF] |

| Table 2. Initially Stated Variables Value |
|-------------------------------------------|
| Parameter       | Symbol | Value |
| Water velocity  | \(v_w\) | 2 [m/s] |
| DC-voltage reference | \(V_{dc}\) | 60 [V] |
| DC-voltage controller proportional constant | \(k_{pdc}\) | 0.3 |
| DC-voltage controller integral constant | \(k_{dic}\) | 0.7 |
| Load resistance  | R     | 1000 [Ω] |

System stability is reviewed through poles location of the linearized system which is described by state equation and expressed in Appendix. State variables of the linearized system are as follows:

\[ x = [\Delta V_{dc} \Delta i_d \Delta i_q \Delta x_{dc} \Delta x_d \Delta x_q \Delta i_{d1} \Delta i_{q1} \Delta V_{dc, det} \Delta \omega_r]^T \]  \hspace{1cm} (16)

The result of the system that has initially stated parameters is shown in Figure 4. It shows that when the parameters used on the system equal to the value that was shown on Table 2, the system is stable. Thus these parameters are used as base variables. One of these parameter will be variated for analysis purpose.

![Figure 4. DC-link voltage when \(V_{dc} = 60\) V](image)

3.1. DC-Voltage Reference Variation

Simulation results can be seen on Figure 5. Results show that the system can withstand in a certain range of DC voltage reference. On this occasion, if DC voltage reference value is not between 20 and 100 volt, the system will be unstable. To describe this situation, poles location of each system is derived as shown
in Table 3. It is clearly noticed that there is an unstable pole which is located in the Righ Half Plane (RHP) if the DC-voltage reference is out of its certain range.

![Diagram](image1.png)

![Diagram](image2.png)

**Figure 5.** Simulation results when: (a) $V_{dc} = 10\ V$, (b) $V_{dc} = 20\ V$, (c) $V_{dc} = 100\ V$, (d) $V_{dc} = 110\ V$

| Poles      | $V_{dc}$ (Volt) |
|------------|-----------------|
| Pole 1     | 7.43 - 30.66i   |
| Pole 2     | 7.43 + 30.66i   |
| Pole 3     | -0.394          |
| Pole 4     | -0.452          |
| Pole 5     | -9.661          |
| Pole 6     | -16.27 + 15.07i |
| Pole 7     | -16.27 - 15.07i |
| Pole 8     | -52.920         |
| Pole 9     | -87.349         |
| Pole 10    | -100.000        |

### Table 3. Poles Location to $V_{dc}$ Variations

| Poles | $V_{dc}$ (Volt) |
|-------|-----------------|
| Pole 1 | 10              |
| Pole 2 | 20              |
| Pole 3 | 100             |
| Pole 4 | 110             |

3.2. Water Velocity Variation

Simulation results can be seen in Figure 6 and poles locations are shown in Table 4. Results show that system tends to be stable if high water velocity occurred. Low water velocity can cause the system to become unstable. This problem can be resolved by readjusting the given reference voltage to lower value.

![Diagram](image3.png)

**Table 4.** Poles Location to $v_w$ Variations

| Poles | Water Velocity (m/s) |
|-------|----------------------|
| Pole 1 | 1                    |
| Pole 2 | 1.5                  |
| Pole 3 | 2.5                  |
| Pole 4 | 3                    |

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Figure 6. Simulation results when: (a) $v_w = 1 \text{ m/s}$, (b) $v_w = 1.5 \text{ m/s}$, (c) $v_w = 2.5 \text{ m/s}$, (d) $v_w = 3 \text{ m/s}$

3.3. Load Resistance Variation

Simulation results can be seen on Figure 7 and poles locations are shown in Table 5. Results show that system tends to be unstable if the load resistance is small. The system is relatively stable if high load resistance is implemented.

Figure 7. Simulation results when: (a) $R = 100 \Omega$, (b) $R = 1000 \Omega$, (c) $R = 10000 \Omega$
3.4. Controller Constant Variations

Simulation result can be seen on Figure 8 and poles locations are shown in Table 6. Results show that controller constant does not much affect the system stability as long as within the acceptable range. Controller constant only affect system response characteristics.

![Figure 8](image-url)

Figure 8. Simulation results when: (a) $k_{dc}=0.15$, (b) $k_{dc}=1.5$, (c) $k_{dec}=0.35$, (d) $k_{dec}=3.5$

| Poles | $k_{pdc}=0.15, k_{ide}=0.7$ | $k_{pdc}=0.5, k_{ide}=0.7$ | $k_{pdc}=0.3, k_{ide}=0.35$ | $k_{pdc}=0.3, k_{ide}=3.5$ |
|-------|---------------------------|---------------------------|---------------------------|---------------------------|
| Pole 1| -0.326 + 0.239 i          | -0.07                     | -0.191 + 0.089 i          | -0.442 + 0.137 i          |
| Pole 2| -0.326 - 0.239 i          | -0.262                    | -0.191 - 0.089 i          | -0.442 - 0.137 i          |
| Pole 3| -19.619                   | -19.598                   | -19.89                    | -17.068                   |
| Pole 4| -0.477                    | -0.413                    | -0.425                    | -1.075                    |
| Pole 5| -9.808                    | -9.983                    | -9.915                    | -9.859                    |
| Pole 6| -45.512                   | -45.314                   | -45.386                   | -45.359                   |
| Pole 7| -87.046                   | -88.887                   | -88.219                   | -88.277                   |
| Pole 8| -88.231 + 64.441 i        | -212.391                  | -120.976 + 96.613 i       | -121.823 - 89.961 i       |
| Pole 9| -88.231 - 64.441 i        | -561.979                  | -120.976 - 96.613 i       | -121.823 + 89.961 i       |
| Pole 10| -100                      | -100                      | -100                      | -100                      |

4. CONCLUSION

There is a stability problem on the Autonomous Micro Hydro Power Plant system caused by low water velocity, out of range DC voltage reference, and low load resistance. In this paper, for 2m/s water velocity and 500 Ohm load resistance, there are stability problems that can be solved by changing the controller constant. However, the constant change only affects the system response characteristics.
velocity, the parameters required to achieve stable system are DC-voltage reference of 20-100 Volt and load resistance of 1000-10000 Ohm. If the water velocity is lower, then readjustment to lower voltage reference is required. The controller constant does not affect system stability as long as within acceptable range. Prospect for further study is adding Doubly Fed Induction Generator (DFIG) to the system so the overall Micro Hydro Power Plant system is completed.

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APPENDIX

Linearized System:

\[
\begin{bmatrix}
\Delta V_{dc} \\
\Delta I_d \\
\Delta I_q \\
\Delta x_{pc} \\
\Delta x_d \\
\Delta x_q \\
\Delta V_{dref} \\
\Delta \omega_r
\end{bmatrix}
= \begin{bmatrix}
Y_{11} & Y_{12} & Y_{13} & Y_{14} & 0 & Y_{16} & Y_{17} & 0 & Y_{19} & Y_{110} \\
Y_{21} & Y_{22} & Y_{23} & 0 & Y_{25} & 0 & Y_{28} & Y_{29} & 0 \\
Y_{31} & Y_{32} & Y_{33} & Y_{34} & 0 & Y_{36} & Y_{37} & 0 & Y_{39} & 0 \\
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-k_{pdc} & 0 & -1 & k_{ide} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & T_d & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & T_d & 0 & 0 \\
1 & -k_{pdc} & 0 & k_{ide} & 0 & T_d & 0 & 0 & T_d & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & T_{dref} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & T_{mech}
\end{bmatrix}
\begin{bmatrix}
\Delta V_{dc} \\
\Delta I_d \\
\Delta I_q \\
\Delta x_{pc} \\
\Delta x_d \\
\Delta x_q \\
\Delta V_{dref} \\
\Delta \omega_r
\end{bmatrix}
\]
Where:

\[
Y_{11} = \frac{i_{q0}v_{q0}}{C_{V_{dc0}}} - \frac{i_{q0}k_{pq}k_{pdc}}{C_{V_{dc0}}} - \frac{1}{L_{R}}; \quad Y_{12} = \frac{v_{d0}}{C_{V_{dc0}}}; \quad Y_{13} = \frac{v_{q0}}{C_{V_{dc0}}}; \quad Y_{14} = \frac{i_{q0}k_{pq}k_{pdc}}{C_{V_{dc0}}}; \quad Y_{15} = \frac{i_{qp}k_{iq}}{C_{V_{dc0}}};
\]

\[
Y_{17} = \frac{i_{q0}P_{pav0}L_{d}}{C_{V_{dc0}}}; \quad Y_{19} = -\frac{i_{q0}P_{p0}}{C_{V_{dc0}}}; \quad Y_{110} = \frac{i_{q0}P_{p0}}{C_{V_{dc0}}}; \quad Y_{21} = \frac{v_{d0}}{L_{d}}; \quad Y_{22} = \frac{v_{p0}}{L_{d}}; \quad Y_{23} = \frac{v_{q0}}{L_{d}}; \quad Y_{25} = \frac{v_{q0}}{L_{d}};
\]

\[
Y_{28} = \frac{L_{d}P_{pav0}}{L_{q}}; \quad Y_{29} = \frac{L_{d}P_{pav0}}{L_{q}}; \quad Y_{31} = \frac{v_{q0}}{L_{d}P_{pav0}} - \frac{k_{pq}k_{pdc}}{L_{q}}; \quad Y_{32} = -\frac{L_{d}P_{pav0}}{L_{q}}; \quad Y_{33} = \frac{k_{pq}k_{pdc}}{L_{q}}; \quad Y_{34} = \frac{k_{pq}k_{pdc}}{L_{q}};
\]

\[
Y_{36} = \frac{k_{iq}}{L_{q}}; \quad Y_{37} = \frac{L_{d}P_{pav0}}{L_{q}}; \quad Y_{39} = -\frac{v_{q0}}{L_{d}P_{pav0}}; \quad Y_{103} = p, \varphi
\]

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