Robust Adaptive Generalized Predictive Control with Multiple Reference Model for Frequency Control In Hydroelectric Power Plants

Korassai, Yeremou Tamtsia Aurelien, and Haman-Djalo,

Abstract—This paper presents a method for the design of a Primary Frequency Controller applied to hydroelectric power plants. This controller is designed to maintain quality, reliability and stability to consumers even in the face of fluctuating power demand. For this purpose, a robust adaptive Generalized Predictive Control with Multiple Reference Model type controller is proposed. Simulation results on Matlab/Simulink show that the Generalized Predictive Control with Multiple Reference Model controller compared to literature cannot only achieve good performance under load disturbances, but also excellent robustness.

Index Terms—Primary Frequency Controller, Generalized Predictive Control with Multiple Reference Model, Hydroelectric Power Plants.

I. INTRODUCTION

Hydroelectric power stations are the third largest source of electricity in the world and the first in Cameroon in terms of electricity production. An electricity network is supposed to provide its consumers with quality and reliability. Quality is linked to the conformity of these parameters, i.e. they must have voltage and frequency values within certain limits. This is important for consumers because machines are designed to operate with fixed electrical values and even small variations in these values can cause premature failure or unwanted operation. Reliability, on the other hand, is linked to the continuity and stability of the power system. Mainly because there are no service interruptions for causes unrelated to generation capacity and the ability to recover from transmission outages. A power system must be able to return to a state of equilibrium even after a disturbance.

In order to maintain frequency stability, generating units automatically change their output power as the system frequency changes to reliance the active power. This is Primary Frequency Control (PFC). PFC is commonly used by power plant units because of the high speed and amplitude of power regulation. However, in spite of the desire to control consumption, demand tends to grow, not only in quantity but also in quality of service, especially in developing countries. Which are often characterized by a strong growth in demand due to rapid urbanization and a recurrent ageing of the production equipment, leading to variations in the parameters of the regulation system. Numerous studies applying different techniques have been carried out to propose long-term solutions to this problem: in particular the classical PI or PID methods [1-6]; methods whose objective is to optimize the proportional and integral coefficients of a PI controller. Many articles offer modified PID controllers, while other articles present controllers with specific characteristics. PID or PI-PD controllers need to set their parameters for each operating point to ensure optimal behaviour. Over the last decade, many of the contributions have been made to there search of the benefits of robust, advanced and intelligent controllers. Their applications in other areas of science and engineering are still being successfully explored, but in the case of hydroelectric power plants, there is still an opportunity to develop a reliable model and design of these controls. In this context, we will deal with the structure of an adaptive frequency predictive control system for hydropower plant that will meet the requirements of globalization in terms of adaptation (stability, time response, precision).

The content of this article is structured as follows: Section 2 presents the related works. Section 3 presents our contributions on the design of primary frequency controllers used in hydroelectric power plants and Section 4 presents the various simulation results in the Matlab/Simulink environment.

II. RELATED WORK

A. Model description

The block diagram of hydroelectric plant, including the speed control system can be divided into three subsystems (Guide Vanes, hydraulic subsystem and Electrical subsystem), as shown in Fig. 1. The functioning of the global system is a reciprocal action between the different subsystems.

Hydropower plant selected for our study is the Songloulou hydropower plant. Cameroon’s largest hydropower project. It is hydroelectric plant without surge tank. The characteristics of the Songloulou hydropower plant are shown in Table I.
Table I
SONGLOULOU HYDRO POWER PLANT PARAMETERS.

<table>
<thead>
<tr>
<th>Element Characteristics</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir</td>
<td>Length</td>
<td>225 m</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>35 m</td>
</tr>
<tr>
<td>Penstock</td>
<td>Length</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>Rated head</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>Flow rate at rated head</td>
<td>Q</td>
</tr>
<tr>
<td>Francis Turbine</td>
<td>Rated speed</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Rated mechanical power</td>
<td>Pm</td>
</tr>
<tr>
<td></td>
<td>Gate position at No-load</td>
<td>Gnl</td>
</tr>
<tr>
<td></td>
<td>Gate position at Full-load</td>
<td>Gfl</td>
</tr>
<tr>
<td></td>
<td>Power Factor</td>
<td>Cosphi</td>
</tr>
<tr>
<td></td>
<td>Rated Power</td>
<td>S</td>
</tr>
<tr>
<td>Generator</td>
<td>Rated Voltage</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>Moment of Inertia</td>
<td>J</td>
</tr>
<tr>
<td>Frequency</td>
<td>f</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

1) Modeling of Electrical subsystems: From [19], the power at the generator terminals as a function of the turbine flow rate is given by:

\[ P_m = \frac{1}{90}(Q - 16)H_b \]  

Where \( H_b \) is the head in m.

And the swing equation is given by:

\[ J\frac{d\omega}{dt} = T_m - T_r \]  

with:

\[ T_m = \frac{P_m}{\omega_{mes}}T_r = \frac{P_r}{\omega_0} \]  

Then,

\[ J\frac{d\omega}{dt} = \frac{P_m}{\omega_{mes}} - \frac{P_r}{\omega_0} \]  

\( P_r \) represents the power of the load in Watts; \( T_r \) the Resistant Torque due to the load in N.m; \( T_m \) the Motor Torque \( \omega_{mes} \) the Speed measured at the rad/s and \( d\omega \) the disturbance.

And the relationship between the angular speed of the turbine shaft and the output frequency of the generator in Hertz is given by:

\[ f = \frac{p \omega}{2\pi} \]  

where: \( p \) is the number of pole pairs of the alternator; \( \omega \) represents the angular rate of rotation in radians per second

2) Modeling of Hydraulic subsystems: The transfer function of the turbine and the Gate opening \( G \) as a function of the turbine flow rate \( q \) are given by:

\[ G_T = \frac{0.663}{1 + 42.55s} \]  

\[ q = 1.7967G + 0.9874 \]  

3) Modeling of the Guide Vanes: From [19], the transfer function of the guide vanes is:

\[ G_s(s) = \frac{20}{1 + 0.645s + 0.00645s^2} \]
B. Validation of the final model

In order to validate the proposed model, the values of the power produced by the turbo-alternator set were recorded experimentally by varying the gate opening, i.e. the control current. The responses in gate opening and power produced compared with those of the proposed model are shown in Fig. 2 and Fig. 3:

To evaluate our model, we used general performance indicators: bias, RMSE, MSE, variance and Nash-Sutcliffe criteria. These proposed indicators allow us to evaluate: the fidelity, the accuracy and the precision of a model [20]. The results obtained are summarized in Table II.

In view of these results, it is easy to see that the responses of the proposed model are very close to the real responses.

III. Design of GPC/MRM Controller Algorithm

A. Principles

Like the Generalized Predictive Controller (GPC), the GPC/MRM requires a numerical representation model for its operation. This model can be obtained either by discretization of the continuous transfer function of the model (z transform), or by using automatic identification techniques (the MCR recursive least squares method being the most popular) [21].
If the process output \( Y(t) \) follows the reference \( Y_r(t) \) then the system control will follow the reference control. Equation (12) imposes the dynamics of the system, equation (13) then provides a model on the control, this explains the name MRM of this algorithm. The method consists in the resolution of the following criterion:

\[
J_{GPC/MRM}(N1, N2, Nu; \lambda) = \sum_{j=1}^{N2} [\varepsilon_Y(t + j)]^2 + \lambda \varepsilon_t^2(t + j - 1)
\]

Where \( N1 \) and \( N2 \) are the minimum and maximum cost horizons and \( Nu \) the control horizon; these horizons are finite. \( \lambda \) is a weighting sequence in the input. With:

\[
\varepsilon_Y(t + j) = Y(t + j) - Y_r(t + j);
\]

\[
\varepsilon_U(t + j - 1) = \Delta U(t + j - 1) - \Delta U_r(t + j - 1);
\]

\[
\Delta U_r(t + j - 1) \text{ Control increment at the moment } (t+j-1);
\]

\[
\Delta U(t + j - 1) \text{ Control increment at the moment } (t+j-1);
\]

\[
\varepsilon_U(t + j) = 0 \text{ for } j \leq N_u \text{ so } \Delta U(t + j) = \Delta U_r(t + j) \text{ for } j \leq N_u
\]

One can remark that it is not only the variations of control input (like in GPC) which are minimized, but the variations of error between \( U \) and \( U_r \). Moreover, \( N2 \) is the same for both channels. Different \( N2 \) can be used for each channel, but this is very useful if the system has widely varying dynamics. Lastly, one deals with \( m \)-channels square systems (\( m \) inputs, \( m \) outputs).

B. Expression of the quadratic criterion

The predictor generating the output errors as a function of the control errors is given by the expression [22], [23]:

\[
\varepsilon_Y(t + j) = \frac{F_j(q^{-1}) \varepsilon_Y(t) + H_j(q^{-1}) \varepsilon_U(t - 1)}{F_r}
\]

With \( N1 \leq j \leq N2 \), \( T_f \) is the term related to future and \( F_r \) is the free response.

The polynomials \( F, H \) and the matrix \( G \) define by:

\[
F = \begin{bmatrix} F_{N1}(q^{-1}) & \cdots & F_{N2}(q^{-1}) \end{bmatrix}^T
\]

\[
H = \begin{bmatrix} H_{N1}(q^{-1}) & \cdots & H_{N2}(q^{-1}) \end{bmatrix}^T
\]

\[
G = \begin{bmatrix} G_{N1}^{N1} & G_{N1}^{N1} & \cdots & \cdots & \cdots & \cdots & G_{N1}^{N1} \\
G_{N2}^{N1} & G_{N2}^{N1} & \cdots & \cdots & \cdots & \cdots & G_{N2}^{N1} \\
\vdots & \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\
G_{N2}^{N2} & G_{N2}^{N2} & \cdots & \cdots & \cdots & \cdots & G_{N2}^{N2} \\
\end{bmatrix}
\]

\( \varepsilon_Y, \varepsilon_U \) are \( m+1 \) vectors with \( i^{th} \) row \( \varepsilon_Y(t) = y_i(t) - y_r,i(t) \), \( i^{th} \) row \( \varepsilon_U(t) = \Delta u_i(t) - u_r,i(t) \).

Equation (15) can be put in the following form:

\[
\hat{\varepsilon}_Y = G \varepsilon_U + F \varepsilon_Y(t) + H \varepsilon_U(t - 1)
\]

C. Control law

Minimizing the cost function (Equation 19) compared to \( \varepsilon \) gives the optimal solution:

\[
(\varepsilon_U)^{opt} = -M(F \varepsilon_Y(t) + H \varepsilon_U(t - 1))
\]

Where

\[
M = [G^T G + \lambda I_{N_u}]^{-1} G^T = \begin{bmatrix} m_1 \\ \vdots \\ m_{N_u} \end{bmatrix}
\]

Only the first control of the optimal sequence is to be applied to the system, the procedure is then repeated at each sampling period.

\[
U_{opt}(t) = U_{opt}(t - 1) + \Delta U_r(t) - m_1(F \varepsilon_Y(t) + H \varepsilon_U(t - 1))
\]

D. Equivalent polynomial controller

The Equation (22) can be put on the following form:

\[
(1 + M_1 H q^{-1}) \varepsilon_U(t) = -M_1 F \varepsilon_Y(t)
\]

The polynomial structure is introduced in order to obtain a relationship linking the output to the control and the setpoint according to the following Fig. 5:

The control \( U(t) \) is applied to the process through the following difference equation:

\[
S(q^{-1}) \Delta(t) = -R(q^{-1}) Y(t) + T(q^{-1}) W(t)
\]

By identifying the terms of equation (23) with those of equation (24), the following linear polynomial controller can be synthesized:

\[
S(q^{-1}) = (1 + M_1 H q^{-1})
\]

\[
R(q^{-1}) = M_1 F
\]

\[
T(q^{-1}) = A_{r}^{-1}(q^{-1}) B(q^{-1}) R(q^{-1}) P(q^{-1}) + A_{r}^{-1}(q^{-1}) \Delta(q^{-1}) S(q^{-1}) A(q^{-1}) P(q^{-1})
\]
Where,
\[
deg \left[ S(q^{-1}) \right] = deg \left[ B(q^{-1}) \right] \\
deg \left[ R(q^{-1}) \right] = deg \left[ A(q^{-1}) \right]
\]

E. Choice of the reference model

We recall some equations necessary to understand the method. The basic model of the process is given by equation (9). The principle of the method is first to choose the polynomials \( A_r(q^{-1}) \) and \( B_r(q^{-1}) \) and then to minimize at each sampling period the criterion \( J_{GPC/MRM} \). Thus, the dynamics of the system are translated by:

\[
A_r(q^{-1})y(t) = B_r(q^{-1})w(t)
\]

Then, from the new scheme of the GPC/MRM equivalent polynomial structure (Fig. 5), we can write:

\[
u(t) = \frac{T(q^{-1})}{\Delta S(q^{-1})}w(t) - \frac{R(q^{-1})}{\Delta S(q^{-1})}y(t)
\]

The polynomials \( R(q^{-1}) \), \( S(q^{-1}) \) and \( T(q^{-1}) \) are polynomials to be calculated. From equations (9), (28) and (29), we can write [12]:

\[
A_r(q^{-1}) = A(q^{-1})\Delta S(q^{-1}) + B(q^{-1})R(q^{-1})
\]

\[
B_r(q^{-1}) = B(q^{-1})T(q^{-1})
\]

with \( T(q^{-1}) \) defined by equation (27).

IV. Simulation Results and Discussion

The discrete transfer function of the corresponding Power Plants with the sampling period \( T_e = 1s \) and a Zero-Order Hold (Zoh) is:

\[
G(q^{-1}) = q^{-1} \frac{0.01603 - 0.05686q + 0.01249q^{-2}}{1 - 2.603q^{-1} + 2.2q^{-2} - 0.6065q^{-3}}
\]

For different values and parameters of the equivalent polynomial regulator, using equations (31) and (32) respectively, we can obtain:

\[
A_r(q^{-1}) = A(q^{-1})S\Delta q^{-1} + B(q^{-1})R(q^{-1})
\]

\[
B_r(q^{-1}) = A(q^{-1})\frac{A_r(1)}{B(1)}
\]

The other adjustment parameters being fixed at \( N_1 = N_u = 1 \) and \( \lambda = 5 \), We vary the maximum value of the prediction horizon \( N_2 \) for the value of the power of the load equal to 48 MW, the value corresponding to the nominal production of a turbine generator group at our hydroelectric plant. This variation of \( N_2 \) leads to several varieties of the response of power output, gate opening and frequency. The results are presented in the following Fig. 6 and Fig. 7.

We notice in figure 6, the value of \( N_2 = 5 \) allows to obtain the frequency closer to the range [49.5 - 50.5] Hz with a short settling time and short undershoot. The more the value of \( N_2 \) increases, the longer the settling time becomes. In Figure 7, a value of \( N = 5 \) gives a better result because it produces a quick response with a modest overshoot. So we choose \( N_2 = 5 \).

The value of the prediction horizon being set at \( N_2 = 5 \), several simulations were carried out to determine the weighting sequence value for the input \( \lambda \) (Fig. 8 et Fig. 9).

The low values of \( \lambda \) accelerate responses and also increase both undershoot and overshoot, (Fig. 8 and Fig. 9). The value of weighting sequence directly affects the value of the control signal in the quadratic cost function of GPC/MRM. So we choose \( \lambda=0.2 \). Table III below summarizes the parameters of our controller.

And the corresponding reference model parameters are:
We simulate the response of the system to a disturbance due to multiple loads. At a time equal to 1600s, the power demand is first 16 MW, then 40 MW and finally 50 MW. We obtain the results below.

We remark that the control current in Fig. 10 increases rapidly and stabilizes at 1.5 mA for the 16 MW load, 3 mA for 40 MW and 3.6 mA for 50 MW. We obtain the results below.

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we used the specifications presented in [9]. The most important are: the P1 test, which gives the time it will take for the power to reach at least 90% of its reference value, the P2 test, which evaluates the overshoot, and finally the P6 test, which gives the information about the undershoot. The values obtained from the different tests are summarized in Table V.

**Table V**

**SPECIFICATION OF POWER PRODUCED RESPONSE AT SONGLOULOU HYDROELECTRIC POWER PLANT.**

<table>
<thead>
<tr>
<th>Test</th>
<th>Criterion</th>
<th>PID</th>
<th>IMC</th>
<th>GPC/MRM</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Primary response (sec)</td>
<td>430</td>
<td>426</td>
<td>13.20</td>
</tr>
<tr>
<td>P2</td>
<td>Overshoot</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>P3</td>
<td>Setting time (sec)</td>
<td>915</td>
<td>915</td>
<td>36.2</td>
</tr>
<tr>
<td>P4</td>
<td>Time to steady state (sec)</td>
<td>1045</td>
<td>1045</td>
<td>51.2</td>
</tr>
<tr>
<td>P5</td>
<td>Rise time (sec)</td>
<td>422.1</td>
<td>424.7</td>
<td>11.2</td>
</tr>
<tr>
<td>P6</td>
<td>Undershoot</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

From Table V, it can be seen that the GPC/MRM controller provides a result on the power response produced with an estimated response time of 36.2 s and a rise time of 11.2 s. The results compared with those of [24] are promising. It can be seen that the GPC/MRM controller has significantly improved the power response compared to that obtained by Modified PID and Modified IMC in [24].

So, we introduce the real operating conditions of our Hydro Power Plant: the nominal load is 48MW and a white Gaussian noise (average 48MW, variance 10). The results are shown in Fig. 14, Fig. 15, Fig.16 and Fig.17.

It can be seen that, despite the disturbances the frequency (Fig. 17) remains within the recommended operating range ([49.5Hz-50.5Hz]). Thus the power produced is whatever the disturbance is equal to the power demanded (Fig16). We remark also that the evolution of the control current in Fig.14 will cause a moderate variation in the gate opening (Fig.15).

**V. CONCLUSION**

In this paper, the frequency control system using Adaptive and Predictive Control of the hydro power plant was developed. Its application on the Songloulou hydroelectric power plant has been modeled and simulated. The different simulations showed a good correspondence between the real system and its model. Moreover, the proposed GPC/MRM control gives appreciable results and can be easily synthesized. It would be interesting to implement new types of robust controllers in order to increase the efficiency of the system.

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REFERENCES


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