Abstract—Controlling frequency of the generated power is one of the main problem in Small Hydro Power Plants. This paper reviews and proposes a new technique of automatic frequency control of Small Hydro Power Plants based on Fuzzy Sliding Mode Controller. A PSO algorithm is used in order to regulate the membership functions of fuzzy system accurately which results in more proper response. Also the comparison of proposed control strategy with PI controller and conventional sliding mode controller is presented.

Keywords—Small Hydro Power Plant; Fuzzy System; Sliding Mode Control; Particle Swarm Optimization.

I. INTRODUCTION (HEADING I)

In today’s life, electricity plays an important role. In electrical power system, consumers require uninterrupted power at rated frequency and voltage. Due to advantages of electrical energy its demand is increasing rapidly. But due to limits of available conventional energy sources, we have to use the non-conventional energy sources effectively and efficiently to fulfil the increasing energy demands.

The power of running water in small rivers can be utilized for electrical power generation using Small hydro power plants. Small hydro power generation plays vital role in electrification of rural and remote areas in developing countries [3]. The gap between electrical energy demand and supply is increasing day by day and often it is not possible to meet the large industrial load demands. Thus it is necessary to do load sharing by disconnecting low significant loads like small villages from grid for some hours. The dependence of small loads from remote areas on diesel system and on grid supply can be reduced by using stand alone generation units to meet the local requirements in these areas [2]. Some of the areas have huge amount of water that can be used for generation using small hydro power plants.

Moreover, small hydro power has a huge, as yet untapped potential in most areas of the world and can make a significant to future energy needs [2], [3]. Small hydro power generation is already an effective and efficient proven technology, but there is considerable scope for research and development of control for this technology [3]. Keeping the parameters of power plants output power within their permissible limits is very important for appropriate performance and effective use [1]. Voltage of generated power is maintained by controlling excitation of the generator while frequency is maintained by eliminating the mismatch between generation and load demand.

Since frequency is an indicator of energy balance and power quality in the system, the load frequency control is one of the most important subject in power system. Conventionally speed governor with supplementary integral control is used to maintain the frequency constant in case of grid connected as well as isolated power plants [3].

A. Conventional mechanism of Load Frequency Control in Small Hydro Power Plants

In Small Hydro Power Plants for load frequency control generally the generation control mechanism is not used due to high cost [2], whereas frequency is controlled by load management. In case of standalone small hydro power plants due to lack of storage facility, total input power has to be converted into electrical energy irrespective of total load requirement. Any variation in power demand is controlled by a resistive load called dump load.

The dump load is a thyristor controlled heater load as shown in below Fig.1, so that the actual load plus dump load can be always maintained equal to generated power at rated frequency [3]. But limitation on size of available dump load results in avoiding use of small hydro power plants with high capacity [2].
In most of the sites of small hydro plants the primary requirement of water is for irrigation purpose. But if electricity is also available, it may enhance the standards of living. Thus if water to the generator is controlled properly instead of using dump load, both electricity as well as irrigation can be achieved.

**B. Structure of Proposed Control System**

In this method, the dump load at output side is eliminated and the amount of input water to the power plant is controlled by control valve at penstock driven by a small servo motor as shown in below Fig.2.

![Fig. 2 Proposed Frequency control system of Small Hydro Power Plant](image)

Here servo motor is used as it is an accurate electric motor whose rotational movement is adjusted by controlling electrical commands. The advantages of servo motor are as it is compatible with digital computer, it has linear speed-torque characteristics, gives quick response, available in wide ratings, etc. [2].

In this proposed method, a DC Servo motor with armature control is used for controlling input water flow through penstock.

**C. Need of Fuzzy Sliding Mode Controller**

In most of the control schemes, only the linear model of the system at particular operating conditions is considered while designing load frequency controller. However the components of power system are nonlinear in nature and operating conditions are often changing, also there may exists some parameter uncertainties. Generally performance of most of the conventional controllers gets affected due to these nonlinearities and uncertainties in the system. Thus it is very necessary to design a controller which has robustness against parameter changes, external disturbances and uncertainties.

In this paper a PI controller based on Fuzzy Sliding Mode Control is suggested for controlling load frequency of Small Hydro Power Plants. In order to obtain the more proper system response, the Particle Swarm Optimization algorithm is used to accurately regulate the membership functions of Fuzzy System.

The organization of this paper is as: Firstly the model of Small Hydro Power Plant of Nav, Iran with PI control [1] is explained. Then the load frequency control using conventional Sliding Mode Control and its features are discussed. After this the proposed Fuzzy Sliding Mode Controller and its optimization using Particle Swarm Optimization algorithm is presented. Finally the expected simulation results using proposed Fuzzy Sliding Mode Controller are presented at various conditions are presented for a Small Hydro Power Plant of Nav, Iran.

**II. DESIGN OF PROPOSED FUZZY SLIDING MODE CONTROLLER**

The nonlinear model of a Small Hydro Power plant with PI controller [1] is shown in below Fig.3.

![Fig.3 PI Control of Small Hydro Power Plant](image)

The above model consists of a PI controller, the measurement system, model of servo motor, turbine and power system.

The system nonlinearity and parameter uncertainties affects the performance of PI controller at various operating conditions[1], so it is appropriate to use advance control strategies which are robust against these nonlinearities and uncertainties in the system.

**A. Conventional Sliding Mode Controller**

Sliding Mode Control is a type of Variable Structure Control strategy. The main advantages of this scheme are robustness against nonlinearities, external disturbances and uncertainties, quick dynamic response and simplicity of design and implementation [4]. In case of Sliding Mode Controller, the limit of high switching frequency and parameter uncertainties in system cause the system state not to remain on the sliding surface, and oscillate around it. These oscillations are called chattering [1],[4]. The chattering is undesirable phenomenon as it may increase the control activities and excite the high frequency unmodelled dynamics and may destabilize the system [4].

Sliding Mode Controllers are suitable for controlling various non-linear systems.

Here the nonlinear system is considered by following dynamic equation

\[ x^{(0)} = f(x) + b(x) u(t) + D(t) \]  \hspace{1cm} (1)

Where,

- \( f(x) \) and \( b(x) \) are non-linear functions
- \( D(t) \) relates to the disturbance entered in the system and \( x(t) \) is system state vector

If \( x_d(t) \) is desired system state vector then error state vector is given as

\[ \dot{x}(t) = [x(t) - x_d(t)] \]  \hspace{1cm} (2)
The first step of designing the Sliding Mode Control is to define an appropriate sliding surface in state space. This sliding surface is also called as switching function and is given as,

\[ s(t) = (d/dt + \lambda)(x(t) - x_{ref}) \quad \text{and} \quad \lambda > 0 \quad (3) \]

The second step of designing is to determine the control law for controlling the system to selected sliding surface. Here the control law is given as,

\[ u(t) = u_{eq}(t) + u_n(t) \quad (4) \]

In this method the control law consist of two parts \( u_{eq}(t) \) and \( u_n(t) \). Here \( u_{eq}(t) \) is part of the input such that if it is applied to the system when the system states are on sliding surface then \( x(t) \) becomes convergent to \( x_{ref} \) making error state vector zero.

Moreover, \( u_n(t) \) is a part of the input such that if system states are not on the sliding surface, it can make the system state convergent to the sliding level within limited time, in the presence of uncertainties and external disturbances [1]. Conventionally \( u_n(t) \) is given by switch sign function as,

\[ u_n(t) = k(x) \text{sgn}(s) \quad (5) \]

The value of switching factor \( k(x) \) is selected more than maximum value of uncertainty in order to satisfy the sliding condition \( s\dot{s} < 0 \) and ensure the system stability.

The main problem in this conventional SMC is that the irregular largeness of \( k(x) \) produces the undesirable chattering in system response [4], which affects the system stability. This chattering in conventional SMC is removed in proposed Fuzzy Sliding Mode Controller and system response is improved.

B. Design of Fuzzy Sliding Mode Controller

To obtain the proper response from Sliding Mode Controller, the switching factor \( k(x) \) must be increased in same proportion when the system state is away from the sliding level and vice-versa [4]. To remove the chattering while achieving sliding level in Sliding Mode Control, it is proposed here to replace the sign function \( k(x) \text{sgn}(s) \) in control law by fuzzy function \( u_f(t) = K_{fs}(t)u_{fs}(t) \) and the controller is called Fuzzy Sliding Mode Controller. The block diagram of the proposed FSMC is as shown in below Fig.4.

![Fig. 4 Block diagram of proposed FSMC](image)

Now the control law is modified as given by following equation

\[ u(t) = u_{eq}(t) + k_{fs}(t)u_{fs}(t) \quad (6) \]

To implement the FSMC on Small Hydro Power Plant, the system state equations are obtained from bloc diagram of Fig.3 as,

\[
\begin{align*}
\dot{x}_1 &= \frac{-1}{T_p} x_1 + \frac{k_p}{T_p} x_2 + \frac{2k_p}{T_p} x_3 - \frac{k_p}{T_p} \Delta p_i \\
\dot{x}_2 &= \frac{2}{T_p} x_1 + \frac{2}{T_w} x_3 \\
\dot{x}_3 &= \frac{(1+k_k)}{T_v} x_1 + \frac{k_w}{T_v} x_4 \\
\dot{x}_4 &= -\frac{1}{T_m} x_4 + \frac{k_m}{T_m} x_5 - \frac{k_m}{T_m R} x_4 - u \\
\dot{x}_5 &= k_{1} \cdot x_1
\end{align*}
\]  

From equations (3) and (6), the sliding surface and the equivalent control law can be obtained to design FSMC as,

\[
\begin{align*}
\dot{s}(t) &= 1.5(x_1 - x_{ref}^1) + (x_2 - x_{ref}^2) + 2(x_3 - x_{ref}^3) + 3.2 \\
\dot{u}(t) &= u_{eq}(t) - k_{fs}u_{fs}
\end{align*}
\]

C. Variables and Membership Functions

In the fuzzy system the control variables \( s \) and \( \dot{s} \) are used as input variables and fuzzy function \( u_f(t) \) is used as output variable.

Where, \( s = \{N, Z, P\} \)

\( \dot{s} = \{N, Z, P\} \)

And

\[ u_{fs}(t) = \{NB, NM, NS, Z, PS, PM, PB\} \]

The pattern of membership functions of input and output variables is as shown in Fig. 5.

D. Fuzzy rules

Fuzzy logic is an automatic control strategy in which control laws are constructed based on expert’s experience [1]. Fuzzy rules for this controller are derived from the switch function shown in following Fig. 6.

To derive the fuzzy rules for proposed FSMC following necessary conditions are considered.
moving of switch function from sliding level is avoided by applying a small input.

By considering above mentioned conditions, fuzzy rules in the FSMC are obtained as shown in below Table.1.

### Table 1. Rules in FSMC

<table>
<thead>
<tr>
<th>( s )</th>
<th>( u_{\text{sig}} )</th>
<th>( \dot{s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>N</td>
<td>NB</td>
</tr>
<tr>
<td>Z</td>
<td>NS</td>
<td>Z</td>
</tr>
<tr>
<td>P</td>
<td>PM</td>
<td>PB</td>
</tr>
</tbody>
</table>

### III. PARTICLE SWARM OPTIMIZATION ALGORITHM

To obtain the desired response from proposed method, it is necessary to accurately optimize the parameters of fuzzy sets in fuzzy controllers. Here, the parameters of fuzzy sets are \{a, b, c, d, e, f, g, h, i, j, k\} as shown in Fig.5.

If the membership functions of fuzzy sets are not regulated, the Fuzzy Sliding Mode Controller cannot reduce the chattering and may even increase it [1]. So it is necessary to optimally compute the parameters of fuzzy sets by intelligent methods such as Particle Swarm Optimization Algorithm.

The Particle Swarm Optimization algorithm optimizes the position of fuzzy sets in the input and output variables of the fuzzy controller. In this way the fuzzy sets are symmetrically considered towards the co-ordinate origin, which reduces the parameters to half and gives faster performance.

#### A. Structure of Particle Swarm Optimization Algorithm

The PSO algorithm is a kind of evolutionary algorithm proposed by Kennedy and Eberhart in 1995. In PSO algorithm the variables to be optimized are considered as particles. The PSO algorithm is a set of particles (as the optimization variables) that diffuse in the research space. Each particle may be a potential solution. It is obvious that some particles have better position than other particles and the others try to promote their position to the superior particle’s position. At the same time, the superior particle’s position is also changing. The change of each particle’s position is based on the particle’s experience in the previous movements and the neighbouring particle’s experience. Indeed, each particle is aware of its superiority and non-superiority with respect to the neighbouring particles and also toward the total group.

The PSO concept consists of changing the velocity of each particle toward its \( p_{\text{best}} \) and \( g_{\text{best}} \) positions at each time step. Velocity is weighted by a random term, with separate random numbers generated for velocity toward \( p_{\text{best}} \) and \( g_{\text{best}} \) positions. The process of the PSO algorithm can be described as follows:

1. Initialize a population (array) of particles with random positions and velocities on d dimensions in the problem space.
2. For each particle, evaluate the desired optimization fitness function in d variables.
3. Compare particle’s fitness evaluation with particle’s \( p_{\text{best}} \).
   - If current value is better than \( p_{\text{best}} \), then set \( p_{\text{best}} \) position equal to current position in d dimensional space.
4. Compare fitness evaluation with the population’s overall previous best. If the current value is better than $g\text{best}$ then reset $g\text{best}$ to the current particle’s array index and value.

5. Change the velocity and position of particle using following equations (9) and (10) respectively:

$$v_{i}^{(k+1)} = w v_{i}^{(k)} + c_1 r_1 (p\text{best} - x_i^{(k)}) + c_2 r_2 (g\text{best} - x_i^{(k)})$$ (9)

$$x_{i}^{(k+1)} = x_i^{(k)} + v_{i}^{(k+1)}$$ (10)

Where, $v_{i}$ is velocity vector, $v_{i}^{(k+1)}$ is modified velocity and $x_{i}$ is position vector and $x_{i}^{(k+1)}$ is modified position of particle $i$ at iteration (generation) $k$.

$c_1$ and $c_2$ are cognitive and social coefficients that affect the velocity of particles. In many algorithms the values of $c_1$ and $c_2$ are selected such that $c_1 + c_2 < 4$.

In above equations it is found that the largeness of $v_{\text{max}}$ may pass the particles over the minimum point and it’s smallness may rotate the parcels rotate around its position, thus the size of $v_{\text{max}}$ is selected between 10-20% of the range of variables.

The appropriate selection of $w$ causes the optimization in less iterations. In PSO algorithm the value of $w$ is reduced from 0.9 to 0.4 using following equation (11):

$$w = w_{\text{max}} - \frac{w_{\text{max}} - w_{\text{min}}}{\text{iter}_{\text{max}}} \text{iter}$$ (11)

Where, iter and $\text{iter}_{\text{max}}$ are the current value and maximum value of iteration respectively.

6. Return to the step 2 and repeat the iterations until a required criterion is met, such as good fitness or maximum number of iterations are achieved.

### B. Fitness Function

The fitness function in the PSO algorithm comprises of a summation of three parts as:

1) The steady-state error $E_{\text{ss}}$ of switch function,
2) The amount of overshoot $\text{OS}$ of switch function, and finally
3) The integral of the absolute value of the switch function ($\int_{0}^{t} |s(t)| \, dt$) as Equation (12).

$$F_{\text{obj}} = W_1 \cdot E_{\text{ss}} + W_2 \cdot \text{OS} + W_3 \cdot \int_{0}^{t} |s(t)| \, dt$$ (12)

Where $W_1$, $W_2$ and $W_3$ are weighting coefficients of the evolution function.

The flowchart of PSO algorithm in proposed Fuzzy Sliding Mode Controller to compute its membership functions is as shown in below Fig. 7.

### IV. Simulation Results

In this section the simulation results of proposed control strategy as well as conventional control strategies for frequency control in small hydro power plant in Nav, Iran at various operating conditions are studied. The simulation model is based on the model of power plant as shown in Fig. 3 and the operating parameters are given in Appendix.

#### A. System Response by only PI Controller

In this only PI controller is used for frequency control of the power plant. The system Step response $x_1(t)$ obtained for 0.1pu change in load is as shown in Fig.8.

![Fig. 8 Frequency response of Power plant with PI Controller](image)

From above response, it is seen that the settling time of response is 80 seconds and the amount of overshoot is 3.3.

This is not a appropriate response, and the better control is needed to improve settling time and overshoot.

#### B. System Response by Conventional Sliding Mode Controller

In this scheme the conventional Sliding Mode Controller is used to control the frequency. The diagrams of system frequency response $x_1(t)$, control signal $u(t)$ and switch function $s(t)$ at 0.1pu change in load are as shown in Fig.9.
From above figure it is seen that the settling time is considerably reduced to 1.3 seconds and overshoot is reduced to 0.25. But the frequency response obtained consists of undesirable chattering and it doesn’t become stable yet after 10 seconds. Also the control signal is very high, which may excite the high frequency unmodelled dynamics, and even make the system unstable. Such signals require the infinitely fast switching mechanism, but due to physical limits of actuators and delay in control system it is impossible to practically realize such infinite rates of switching. So providing such control signals is impossible in practice.

Therefore it is necessary to remove the chattering problem by using Fuzzy Logic, which makes the control action smooth.

C. System Response by PSO-Fuzzy Sliding Mode Controller

PSO algorithm is used in order to optimize the membership functions of fuzzy system more accurately. The PSO algorithm is performed on the basis of flowchart presented in Fig.7. The values of parameters used in PSO algorithm are as presented in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(c_1)</th>
<th>(c_2)</th>
<th>(w_{min})</th>
<th>(w_{max})</th>
<th>(W_1)</th>
<th>(W_2)</th>
<th>(W_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>2</td>
<td>2</td>
<td>0.4</td>
<td>0.9</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
</tr>
</tbody>
</table>

The number of particles is taken as 50 and the number of iterations performed using algorithm is 30.

Also, the range of variables \{a, b, c, d, e, f, g, h, i, j, k\} are presented in table 3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>(a, d)</th>
<th>(b, e)</th>
<th>(c, f)</th>
<th>(g)</th>
<th>(h)</th>
<th>(i)</th>
<th>(j)</th>
<th>(k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of variable</td>
<td>0-10</td>
<td>0-10</td>
<td>10-14</td>
<td>0-3</td>
<td>2-5</td>
<td>4-7</td>
<td>9-14</td>
<td></td>
</tr>
</tbody>
</table>

Using the available data the values of \{a, b, c, d, e, f, g, h, i, j, k\} parameters of fuzzy sets are obtained as,

\{0.07, 1.51, 10.002, 9.071, 2.035, 14.102, 3.065, 5.086, 6.019, 9.09\}

The frequency response \(x1(t)\) of the hydro power plant and also the control signal \(u(t)\) and the values of switch function \(s(t)\) using suggested control strategy for 0.1pu change in load are obtained as shown in Fig. 10.

From Fig.10, it is seen that using proposed PSO-FSMC method, the chattering phenomenon has been eliminated and smooth control signal is obtained. In this response the overshoot is reduced to 0.58 and the settling time is improved to 6 seconds

D. System Response by PSO-Fuzzy Sliding Mode Controller at changing parameters

At this conditions the \(T_v\) parameter of the system is changed by 25% and the system response is obtained as Fig.11

Here it is seen that the change in parameter doesn’t affect the system response and gives the robustness to the PSO-FSMC system against nonlinearity.
E. Comparison between conventional and proposed control strategies

The performance indices obtained by simulation results are presented in below Table 4 as,

<table>
<thead>
<tr>
<th>Index</th>
<th>Method of control</th>
<th>PI controller</th>
<th>Conventional SMC</th>
<th>Proposed PSO-FSMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling time in seconds</td>
<td></td>
<td>80</td>
<td>1.3</td>
<td>6</td>
</tr>
<tr>
<td>Overshoot</td>
<td></td>
<td>3.3</td>
<td>0.25</td>
<td>0.58</td>
</tr>
</tbody>
</table>

In PI controller, the settling time and the overshoot are big and so the system response is not good.

Using conventional SMC the settling time and overshoot are reduced considerably the chattering problem exists in the system response.

In PSO-FSMC the settling time and overshoot are increased a little, but as it eliminates the chattering problem, still the system response is acceptable. Also the proposed PSO-FSMC is robust against nonlinearities and uncertainties.

V. CONCLUSION

In this paper a Fuzzy Sliding Mode Control based on Particle Swarm Optimization Algorithm is suggested for frequency control in Small Hydro Power Plants and the system response is improved. Particle Swarm Optimization algorithm is used to accurately regulate the membership functions of Fuzzy Controller which reduces the chattering phenomenon. The simulation result gives the effectiveness of the suggested control strategy. Moreover, the suggested strategy is robust against changes in load and parameters, uncertainties and external disturbances occurring in the system.

References