Abstract- In this contribution, the control of Reverse Osmosis (RO) desalination plant using PID controllers is presented. The tuning of PID controllers is accomplished by minimizing the Integral-Square-Error (ISE). The ISEs are minimized using the Luus–Jaakola (LJ) optimization algorithm. LJ procedure is simple, yet powerful method, available in literature. In this approach, first the feed forward controllers are designed and then the PID controllers are tuned for pH and conductivity using ISE minimization. For the simulation purpose, the DOHA reverse osmosis plant is considered. The results of PID control using LJ method are compared with the Ziegler–Nichol’s (ZN) tuning. The simulation results show that the LJ method performs better than the ZN technique and can successfully be used for tuning of PID controllers for RO desalination plant.

Keywords: Luus–Jaakola(LJ) optimization, Reverse osmosis (RO), ISE, PID tuning.

I. INTRODUCTION

The demand of fresh water is increasing day by day due to the industrial and population expansions. Due to this, the under-ground sources of fresh water are not ample enough to meet these requirements. As most of the water is salted that cannot be used for above mentioned applications. Hence, the desalination of sea water is the only solution for this problem.

A lot of research is going on to extract the fresh water from the salted water. The reverse osmosis is used for this purpose. The most important requirements of the desalination methods are: reasonable cost, addressing automation, and cost optimization. Large scale direct sea water reverse osmosis plants are known to be a cost-effective solution to produce fresh water from underground and sea water to meet the requirements in terms of quality of water production [1].

Reverse osmosis is a membrane based filtration process. It uses pressure to force a solvent, which is being purified, through a semi-permeable membrane. This membrane checks the impurities and allows the solvent to pass through another side [4]-[6]. More eventually, it is the process of forcing a solvent from a region of high solute concentration through a membrane to a region of low solute concentration by applying a pressure greater than normal osmotic pressure of the solution. The portion of water that passes through the semi-permeable membrane is pure solvent called as permeate. The remaining waste water is discharged by the waste pipeline attached before the membrane side. The membrane used in the reverse osmosis process has a dense barrier layer in the polymer matrix where most separation occurs. The membrane is designed in such a way that allows only pure water to pass through this membrane layer while preventing the passage of solutes (such as salt ions).

The membrane assembly consists of a pressure vessel with a membrane that allows feed water to be pressed against it. The membrane must be strong enough to withstand maximum pressure applied against it. RO membranes are made in a variety of configurations. The two most common configurations are spiral-wound and hollow-fiber. These configurations suffer the problem of formation of concentration polarization layer near the membrane and scaling formation due to high pH value of the raw water used at the feed side. Due to this the membrane life is reduced and the operational cost increases as the membrane needs to replace frequently [2].

The problem of membrane damage can be solved with the adjustment of the pH value and conductivity at the feed side. During last four decades, researchers have proposed many strategies [3]-[5] for pH and conductivity adjustments. Many of these conventional and model based methods have found their way into practice and involve satisfactory results to the spectrum of complex systems under various uncertainties.

In this paper, LJ based PID control technique is presented to regulate the values of pH and conductivity. Two PID controllers are designed to regulate the pH and conductivity. The tuning of these PID controllers is accomplished by minimizing the ISE [12]. The ISE is minimized using the LJ algorithm [13].

The outline of the remaining paper is as follows: section II presents the reverse osmosis plant model, the model of reverse osmosis model is described in section III, the proposed technique is discussed in section IV, section V shows the simulation results while the paper is concluded in section VI.

II. REVERSE OSMOSIS PLANT MODEL

The generalized block diagram of the reverse osmosis pilot plant is shown in the Fig. 1. A reverse osmosis process consists of mainly four major steps: pre-treatment process, high pressure pump, membrane assembly, and post-treatment process [6].
In pre-treatment process, the incoming feed water is treated to make compatible with the membrane by removing suspended solids, adjusting the pH, and adding a threshold inhibitor to control scaling caused by constituents such as calcium sulphate. The function of high-pressure pump is to raise the pressure of the pretreated feed water to the level appropriate for the membrane. The RO membrane assembly consists of two or more than two RO membranes made up of variety of blends or derivatives of cellular acetate, polyamides, etc. Post-treatment consists of stabilizing the water and preparing for distribution.

III. MODEL OF REVERSE OSMOSIS SYSTEM

In this simulation, the multivariable model given by Doha Reverse Osmosis Plant (DROP) [7] is used that is described as:

\[
\begin{bmatrix}
F \\
C
\end{bmatrix} =
\begin{bmatrix}
G_{p11} & G_{p12} \\
G_{p21} & G_{p22}
\end{bmatrix}
\begin{bmatrix}
P \\
pH
\end{bmatrix}
\]  \hspace{1cm} (1)

where, \(F\) is flux, \(C\) is conductivity, \(P\) is pressure, and \(pH\) is the pH value of water. The general form of \(G_{p11} , G_{p12} , G_{p21} , \) and \(G_{p22}\) is given as:

\[
G_p = \frac{K(r_s + 1)}{(r_s^2 + 2s + 1)}
\]  \hspace{1cm} (2)

For DOHA RO plant, \(G_{p11} , G_{p12} , G_{p21} , \) and \(G_{p22}\) take the form:

\[
G_{p11} = \frac{F}{P} = \frac{0.002(0.056s + 1)}{(0.003s^2 + 0.1s + 1)}
\]  \hspace{1cm} (3)

\[
G_{p12} = \frac{F}{pH} = 0
\]  \hspace{1cm} (4)

\[
G_{p21} = \frac{C}{P} = -0.51(0.36s + 1)
\]  \hspace{1cm} (5)

\[
G_{p22} = \frac{C}{pH} = 0.6s^2 + 1.8s + 1
\]  \hspace{1cm} (6)

The Table I shows the allowable ranges of flux, pressure, conductivity, and pH.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Linear Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux(F), gpm/(m²/s)</td>
<td>0.85-1.25 (0.2-0.3)</td>
</tr>
<tr>
<td>Pressure(P), Kp (psig)</td>
<td>800-1000 (5500-7000)</td>
</tr>
<tr>
<td>Conductivity(C)</td>
<td>400-500</td>
</tr>
<tr>
<td>pH</td>
<td>6-7</td>
</tr>
</tbody>
</table>

A. The Block Diagram of Plant:

The block diagram for the RO membrane is given in Fig. 2.

The RO membranes are very sensitive to feed water temperature, fouling, scaling and variation in pressure. These factors degrade the RO membrane and also affect pH and conductivity of the water. A change in feed water pressure causes a negative effect on conductivity. Changing pH has no effect on the flux but there will be a negative effect on conductivity. If there is high pH of water, it will result in loss of efficiency, formation of scaling and polarization layer on the membrane [6].

B. Designing of the control system:

The reverse osmosis system is basically the multi-input multi-output system having two inputs and two outputs. One input affects more than one output. To avoid this problem of interaction, decoupling is used [8] in this paper. For decoupling two feed-forward compensators are designed as given in Fig. 3.
The total structure for the RO system is stable as each subsystem of the block is open loop stable having negative real pole. The feed-forward compensators are represented in Fig. 3 as $G_{r1}$ and $G_{r2}$ are given in the transfer function forms [9], [10] as

$$G_{r1} = \frac{G_{p11}}{G_{p12}}$$ (7)
and
$$G_{r2} = \frac{G_{p22}}{G_{p12}} = 0$$ (8)

The PID controllers now can easily be tuned even if one of the control loops is open.

IV. PROPOSED SCHEME OF PID TUNING

The tuning of PID controllers is completed using ISE minimization. The performance indices of two controllers are given as

$$J_1 = \frac{1}{2} \int_0^\infty e_1^2(t)dt$$ (9)

and

$$J_2 = \frac{1}{2} \int_0^\infty e_2^2(t)dt$$ (10)

The ISE given by $J_1$ is determined as

$$J_1 = \sum_{i=1}^{p} \beta_i^2$$ (11)

where the $p$ is order of $E_i(s)$ and the parameters $\alpha_i$ and $\beta_i$ are determined from the denominator and numerator coefficients [11] of the $E_i(s)$. In similar manner the ISE given by $J_2$ is determined as

$$J_2 = \sum_{i=1}^{p} \beta_i^2$$ (12)

The performance indices given by (11) and (12) are minimized using LJ algorithm. The details of LJ algorithm are given in following section.

A. Luus–Jaakola Algorithm:

In LJ optimization algorithm, initial test points over some region are chosen arbitrarily. The region sizes are contracted in successive iterations with the best values found in previous iteration. Due to ease of programming and ease of handling constraints, this algorithm has applied in variety of problems [12]-[15]. It is worth mentioning here that LJ algorithm is found to be faster than genetic algorithms and particle swarm optimization in some applications. The steps for LJ optimization are as follow:

Step 1: Choose initial values of all decision variables. Suppose, these are

$$x_i^0, i = 1,2,...,M$$ (13)

Choose initial region size for each decision variable. Suppose, these are

$$r_i, i = 1,2,...,M$$ (14)

The region size should be chosen such that the solution lies in

$$\left[ x_i^0 - \frac{r_i}{2}, x_i^0 + \frac{r_i}{2} \right]$$ (15)

Step 2: Take $R$ sets of random points to be used in each iteration. These are obtained as:

$$x_i(j) = x_i^0(j) + \sigma r_i(j), i = 1,2,...,M, j = 1,2,...,R$$ (16)

where $\sigma = [0.5,0.5]$.

Step 3: Check the feasibility of constraints.

Step 4: Evaluate the performance index, for all feasible points.

Step 5: Now, choose the minimum performance index and corresponding values of variables, $x_k, k \in [1,M]$. Replace $x_k^0$ by this new $x_k$.

Step 6: Reduce the region size vector $r_k$ as

$$r_k(k+1) = \gamma r_k(k)$$ (17)

where $\gamma$ is a region contraction factor such as 0.96, and $k$ is the iteration number.

Step 7: Go to step 2 and repeat above procedure (step 2 to step 6) for $N$ iterations.

V. SIMULATION RESULTS AND COMPARISON

The Table II shows the PID gains for the ZN-PID and LJ-PID. Comparison for performance indices are given in Table III. The Tables IV and V, respectively, show the comparison of performance for flux and conductivity.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ZN-PID</th>
<th>LJ-PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_p$</td>
<td>715</td>
<td>4766</td>
</tr>
<tr>
<td>$K_i$</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td>$K_d$</td>
<td>1.0</td>
<td>1.0</td>
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<table>
<thead>
<tr>
<th>Parameters</th>
<th>ZN-PID</th>
<th>LJ-PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{p11}$</td>
<td>0.0288</td>
<td>0.0392</td>
</tr>
<tr>
<td>$G_{p22}$</td>
<td>0.9378</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ZN</th>
<th>LJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time (sec)</td>
<td>18303</td>
<td>1.9363</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>26255</td>
<td>5.5048</td>
</tr>
<tr>
<td>Peak Overshoot (%)</td>
<td>None</td>
<td>0.0023</td>
</tr>
<tr>
<td>Undershoot (%)</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ZN</th>
<th>LJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time (sec)</td>
<td>0.2222</td>
<td>1.2453</td>
</tr>
</tbody>
</table>
The Fig. 4 and 5, respectively, show the step responses for flux and conductivity.

From the Fig(s), it is clear that the step responses obtained using LJ-PID by minimizing ISE are much better than that of obtained using ZN-PID.

The values of ISE obtained using LJ-PID are smaller than those obtained using ZN-PID. Hence, it can be concluded that the LJ-PID technique proposed in this paper performs better and can successfully be utilized for PID controller tuning for RO system.

**CONCLUSION**

In this paper, PID tuning is presented using LJ optimization method for the reverse osmosis plant. The tuning of PID controllers is accomplished by minimizing the Integral-Square-Error (ISE). MATLAB software tool is used for finding the behavior of flux and conductivity for reverse osmosis membrane. A computer simulation is done to illustrate the results for the flux and conductivity using ZN-PID. Simulation results confirm that the proposed method performs better.

**REFERENCES**


