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Development of mathematical models for the forecast and evaluation of the performance of hydropower using transfer function modelling

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Abstract*: Poor, inefficient and negligence in the evaluation of the performance of a hydropower plant is the root cause of reduced and inefficient power generation, high maintenance costs and replacement or repairs of machines. With the government's focus on installing and developing new and better renewable sources of energy, it is also necessary to maintain the existing hydropower projects in order to get efficient power from them. Growth of 2.3% annually between the years 1990 to 2017 indicates the importance of hydropower amongst all other energy sources. Thus, this research aims to assess the performance of Indira Sagar Project (ISP) which is an existing hydropower plant during different years of its working and to forecast the power which may get produced, for known values of inputs like discharge provided to the turbines and previous values of output i.e. power generated, using transfer function modelling. The results of this study indicate that the performance of ISP was found to be worst during the financial year 2013-14 where the performance coefficient(ω_0) was -0.0007 and it is inferred that maintenance of the machines was required during that period. This study will help in assessing the performance and scheduling the maintenance of different units. With, the R^2 value 0.997 and Chi^2 0.02013 the transfer function model developed to forecast the power, suggests that the model fits well and can be used to forecast the hydropower at ISP.

Keywords*: Performance evaluation, transfer function modelling, maintenance schedule, forecast.

I. INTRODUCTION

Hydropower has long played an important role in innocuous, steady and efficient operation and power generation and is reasonably established. Hydropower not only produces electricity as one of the largest renewable sources of electricity but also has a large share in the regulation and matching up the charges in many energy systems around the world.

India has one nation-wide network with a capacity of 357.875 GW installed by 30 June 2019 [1].

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Renewable energy projects, which also includes hydropower plants having a capacity greater than 30 MW, forms at around 35% of India's entire power-producing capacity. During the financial year (F. Y.) 2017-18, the gross electricity produced by various sources in India was 1,303.49 TWh and the total power production through utility and non-utility sector in the country was about 1,486.5 TWh [1][2]. The total per-capita electricity that was consumed during the F. Y. 2017-18 was 1.149 MWh [1]. India is the third-largest manufacturer and user of electricity [3]. In F. Y. 2015-16, electricity that was consumed only in the agriculture sector has been recorded as the highest worldwide and found to be about 18% [1]. Despite having cheaper tariff rates, the electricity consumption per capita is very low when compared to most of the other countries.

In F. Y. 2017-18 about 75% of the total power was generated at the thermal power stations based on fossil fuels, indicating clearly about the dominance of fossil fuels, in the energy sector of India. In particular, thermal power plants which are widely used across the country. Conversely, the government and Central Electricity Authority of India (CEA) are emphasising on larger investments in renewable energy sources, as per the planning for national electricity, proposed by the govt. of India for the year 2018, our country might not be requiring additional non-renewable projects in the service segment by the year 2027, with the thermal power projects of about 50,025 MW under construction and attaining an aggregate of 2, 75,000 MW through mounted renewable sources, along with subsequent stepping down of near about 48,000 MW old thermal power plants, India is moving in the direction of becoming a superpower. For the development in multi-directions, along with the planning on the establishment of new renewable sources of energy, attention towards existing renewable sources, especially attention towards the hydroelectric power plants is required. A number of existing hydropower plants are facing a decreasing output due to ageing, negligence and ineffective maintenance. Thus, timely evaluation of the performance of these hydroelectric power projects becomes a must.Conventional approaches of evaluating the performance of a hydroelectric power plant, through measuring the efficiency of power-generating turbines become less effective, as it does not consider the stochasticity in the inputs as well as in the outputs. Hydropower generation system resembles any other classic manufacturing system where the inconsistency is generally observed in the inputs and outputs, resulting in cumbersome processes in establishing the relationship between input and output [4].

Statistical processes are somewhat different from the engineering processes, where many practise of response and pathway adjustments are being used. The statistical processes are applied in the industries which are concerned with the manufacturing of distinct parts, whereas engineering processes controls are mostly used in process and chemical industries [5].

In the initial years of investigating the causal relationship between output and input of a system with respect to the statistics begun with regression analysis [6]. Thus, it helped in shaping the origination of the conventional statistical methods for establishing the connection between the input and output for a system. The regression analysis consists of many deficits. For example, it is not suitable for the conditions where the output delays the input, a transitory link is present between the output and input. Also, regression analysis is incompetent in accommodating a substantial extent of noise present in the system [5][6].

In 1970, Box and Jenkins presented a better statistical technique for establishing the relation between input and output in an arrangement. This technique was named after the Box-Jenkins transfer function modelling approach [6].

Many exertions have been made into the transfer function modelling by numerous investigators in order to advance, outspread and abate the efforts in obtaining the model. It is being used in several areas. For instance, it was comprehensively applied to model geographical systems [6]. In econometrics and economic forecasting. The literature review in the coming paragraphs will convey the determinations of various other researchers, engineers and scientists on further extending the utility of transfer function modelling.

An improved and novel method was proposed for the evaluation of the performance of for a brewery which belongs to multi-input and single-output (MISO) system using the combination of transfer function modelling and fuzzy logic for a period of six years. Effective maintenance techniques, defining limits in the consumption of raw ingredients and assessing the efficiency of the MISO system [7].

Parameters of transfer function model were used to optimize the mining operation and forecasting assay values of Fe_2O_3 and P_2O_5 for a single/multi-input and single-output system (SISO/MISO) for extracting iron ores from Bicholim mine in Goa, India [8]. The concept of transfer function model has been successfully applied to many fields for instance; production, engineering, geography, mining, biology etc. The passages to follow explain more about the versatility in the applications of transfer function modelling. Most of the uses of time series analysis and transfer function modelling in the area of production are identified to monitor the quality control of produced goods [9]. Transfer function model was applied to observe and control carbon IV oxide produced as the output of a gas furnace [5].

A methodology was proposed for the wind energy industry, where the wind speed and direction non-stationary data at an existing target site was used to develop the transfer function model for the forecasting of wind-speed and wavelet packet [10]. Proposed to forecast the electricity charges established by considering previous tariffs as well as the demands, mentioning the logic behind the development of the transfer function model [11]. Developed a novel and superior technique for assessing the performance of Kainji hydropower project and to increase its performance using transfer function modelling, considering discharge and power produced data, located in Niger State, Nigeria for over a period 10-year and developing transfer function models of the process for the 10 years, which are used as performance indicators [4].

Transfer function model for a hydroelectric power system will support to evaluate the performance of the system. Good maintenance strategies could be developed, repair and replacement work can be prescribed and also management for the water allocation can be predetermined using the transfer function model. The present research aims to develop a mathematical model for the forecast of hydropower for the known values of discharge being provided to the turbines and previous values power generated, as well as to evaluate the performance of the existing hydropower project during its different years of operation.

In this particular article, the performance of Indira Sagar Project (ISP) has been evaluated. ISP is a multi-purpose project which is capable of irrigating 16900 square kilometres annually along with meeting the industrial demands of 74 million cubic meters (MCM).

The powerhouse of ISP is a surface type one, consisting of 8 turbines of capacity 125 MW each, was commissioned in the year 2005.

The approach presented in this research is sound and easier in comparison with the conventional regression analysis, which fails to provide accurate results when there are multiple inputs as well as when the output lags the input. The remainder of the paper is divided into Section 2 which highlights the methodology followed by the Results and Discussion in Section 3 and lastly, Conclusions are made in Section 4.

II. METHODS AND METHODOLOGY

Forecasting through time series analysis could be done by numerous approaches are available autoregressive models (AR), moving average models (MA), autoregressive-moving average models (ARMA), autoregressive integrated moving average models (ARIMA), transfer function models etc., which stands important for the planning, scheduling of maintenance and forecasting of energy are discussed in the following paragraphs.

1.1. Transfer Function Model

Transfer function model is a numerical model which defines the relationship amongst one or more input and output variables. In most of the cases, the transfer function model is represented as a linear equation [12].

A linear model indicates that the relationship between an output (Y) and input (X) is direct and both X and Y are linear signs of progress. Mathematically it is expressed as (1)

$$Y_t = v_0 X_t + v_1 X_{t-1} + v_2 X_{t-2} + \cdots \quad (1)$$

Where,

$v_0, v_1, and\ v_2, \ldots$ are constants indicating the influence of X_{t-j} on Y_t and are referred to as impulse response weights.

can be rewritten as

$$Y_t = v(B) X_t \quad (2)$$

Where B is a backward shift operator.

For the model in (1) to be feasible, the function $v(B)$ must be defined using autoregressive integrated moving average (ARIMA) model [13].

$$Y_t = \frac{\omega(B)B^b}{\delta(B)} X_t \quad (3)$$

Where,
b is a non-negative integer, and is defined as delay time,

$$\omega(B) = \omega_0 + \omega_1 B + \omega_2 B^2 + \ldots + \omega_s B^s$$

$$\delta(B) = 1 - \delta_1 B - \delta_2 B^2 - \ldots - \delta_r B^r$$

The transfer function model may also be defined as the ratio of Laplace transformation of the output variable (Y) to the Laplace transform of the input (X), with a supposition that the initial conditions are to be zero [14].

In exercise, the output Y_t is not a deterministic function of X_t. In most of the cases, it is disturbed by the noise (N_t). The noise may be associated with ARIMA (p, d, q)) process.

A transfer function model is mathematically represented as;

$$Y_t = c + \frac{\omega(B)B^b}{\delta(b)} X_t + \frac{\theta(B)}{\phi(B)} a_t \quad (4)$$

Where c is a constant
$\theta(B)$ is the coefficient of MA
$\phi(B)$ is the coefficient of AR

The transfer function model represented in (4) is a SISO type model.

1.2. Procedure for the formulation of the transfer function model

The procedure for the development of a transfer function model is discussed in the following steps:

Model Identification
To form the graphs of available input/output data.
Attain stationarity of Y_t and X_t.
To estimate α_t by fitting a univariate model to x_t.
To estimate possible noise N_t by fitting a univariate model to y_t as a datum.
Calculate Cross-Correlation Function for different lags (k) $\beta_t \alpha_{t-k}$ to identify r, s and b.
For r = Autoregressive order of function,
s= Number of ω terms,
and b= Delay of impact.
Examine Cross-Correlation Function for r, s and b.
Model Estimation
Using Y_t and X_t estimation of the transfer function model.
Using the residuals of the transfer function to find N_t.
Estimating the full model.
Confirm all estimation procedures converged.
Model Diagnostics
Confirm significant, non-redundant parameters in model.
Modify the transfer function or noise model as needed.
Confirm that the fit and forecasts are reasonable.
Confirm stationarity, invariability and stability.
Confirm model parsimony.
Over fit model.
Experiment with the transfer function.
Confirm model intuitive appeal.
Forecasting
Confirm forecasts are reasonable.

1.3. Development of SISO forecast transfer function model

The data consists of 1461 observations for 4 years i.e. F. Y. 2013-14 to 2016-17 of (i) Daily discharge being provided to the turbines (Q_t) as input and (ii) Daily Power generated (P_t) as output. The time interval for the input and output series is 24 hours. For the available data set an adequate transfer function model is developed for the forecast. For the statistical analysis of the input and output time series and developing the Transfer Function Model, R-Software/R-Studio (version 3.6.0 dated 26-04-2019) is used.

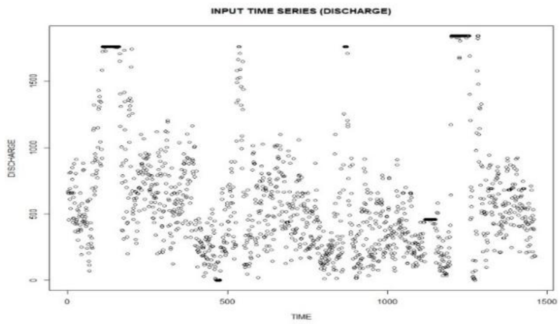

Fig. 1 Input (Q_t) Time Series for ISP for 4 years

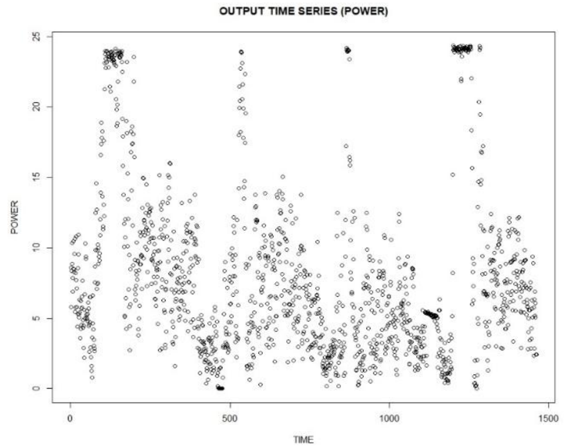

Fig. 2 Output (P_t) Time Series for ISP for 4 years

From Fig 1 and 2 it is found that there is some non-stationarity in the input (Q_t) as well as output (P_t) time-series, which is to be removed by differencing.

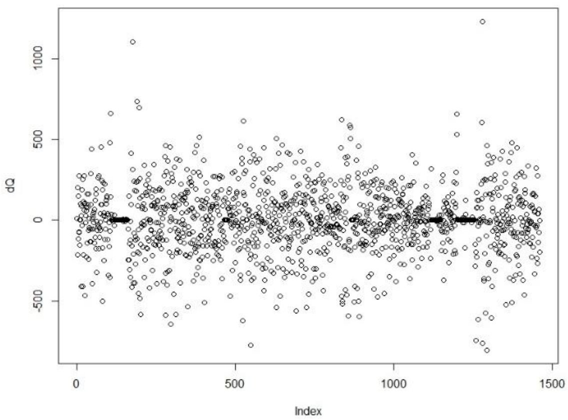

Fig. 3 Differenced Input (dQ_t) Time Series for ISP

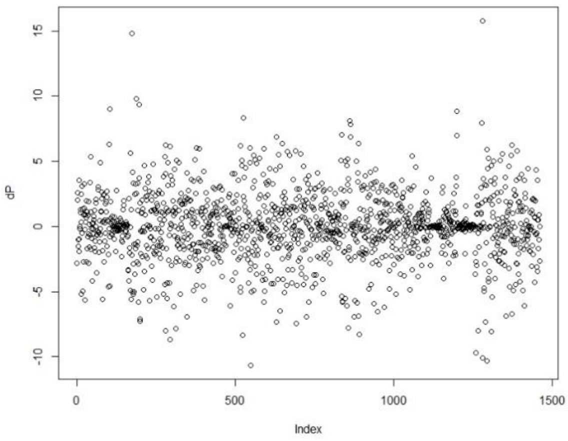

Fig. 4 Differenced Output (dP_t) Time Series for ISP

The time series obtained after first differencing of Qt and Pt are defined as differenced input (dQt) and differenced output (dPt) respectively. Plot for dQt and dPt with respect to time, Fig. 3 and 4 respectively it can be observed that the non-stationarity has been removed and the input and the output time series have become stationary with a zero mean and σ^2 standard deviation. For making further decisions in the direction of model development plot for autocorrelation function and partial-autocorrelation function for different lags are prepared.

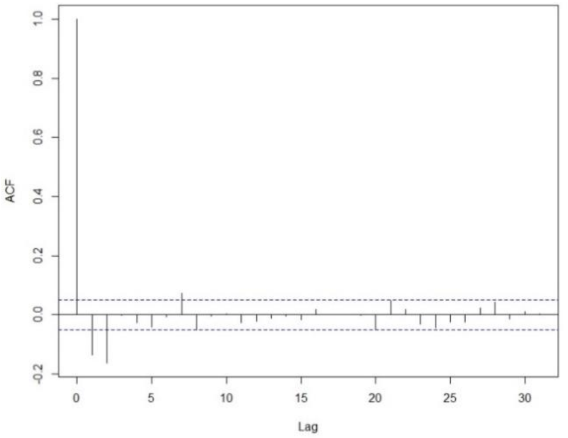

Fig. 5 Autocorrelation Function Plot for dQ_t

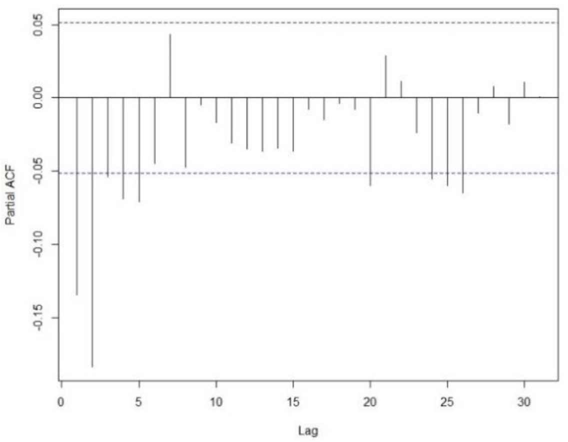

Fig. 6 Partial-Autocorrelation Function Plot for dQ_t

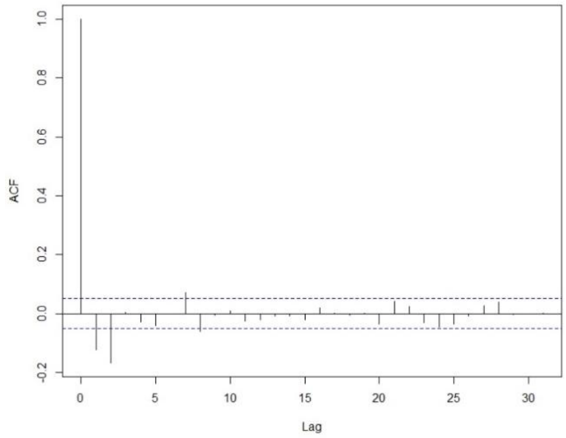

Fig. 7 Autocorrelation Function Plot for dP_t

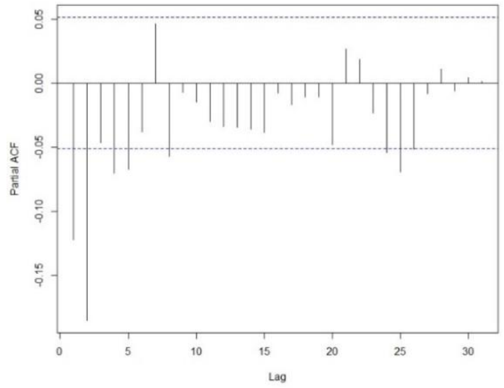

Fig. 8 Partial-Autocorrelation Function Plot for dP_t

Negative values of the significant ACF and PACF plots in Fig. 5, 6, 7 and 8 suggests the order of autoregressive (AR) and moving average (MA) terms as p = 3 and q=3 respectively. Univariate model ARIMA (p, d, q) is fitted for input (Q_t) of order ARIMA (3, 1, 3) and the goodness of fit of the fitted model is then checked.

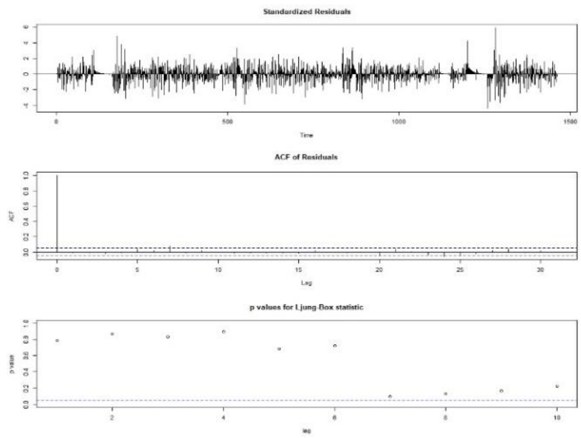

Fig. 9 Goodness of fit for Q_t Time-Series for ISP fitted with ARIMA (3, 1, 3)

The goodness of fit of ARIMA (3, 1, 3) shown in Fig. 9 suggests that the univariate model has fit well to the input time series and may be accepted for further calculations and Transfer function model identification.

For identifying the Transfer Function Model, the impulse response weights $v(B)$ are to be determined. The impulse response weights are either determined by (i) plotting the cross-correlation function between (dQ_t) and (dP_t) and observing the values of r, s and b

Cross-Covariance (for lag k ≥ 0)

$$c_{xy}(k) = \frac{1}{n}\sum_{t=1}^{n-k}(x_t - \bar{x})(y_{t+k} - \bar{y}) \qquad (6)$$

Cross-Covariance (for lag k ≤ 0)

$$c_{xy}(k) = \frac{1}{n}\sum_{t=1}^{n-k}(y_t - \bar{y})(x_{t-k} - \bar{x}) \qquad (7)$$

Cross-Correlation Function

$$r_{xy}(k) = \frac{c_{xy}(k)}{s_x . s_y} \qquad (8)$$

Where,
$c_{xy}(k)$ is determined by using (6) or (7)
s_x is the standard deviation of dQ_t
s_y is the standard deviation of dP_t

Or (ii) Corner method is employed. In the corner method, a two-way table is constructed to demonstrate the patterns of v_j. The table reveals the following pattern to indicate the values of r, s and b [13].

TABLE 1. PATTERN OF v_j BY CORNER METHOD [13]

(i, j)	1	2	⋯	r-1	r	r+1	r+2	⋯
0	0	0	⋯	0	0	0	0	⋯
1	0	0	⋯	0	0	0	0	⋯
⋮	⋮	⋮		⋮	⋮	⋮	⋮	⋯
b-1	0	0	⋯	0	0	0	0	⋯
b	X	X	⋯	X	X	X	X	⋯
⋮	⋮	⋮		⋮	⋮	⋮	⋮	⋯
s+b	X	X	⋯	X	X	X	X	⋯
s+b+1	*	*	⋯	*	X	0	0	⋯
s+b+2	*	*	⋯	*	X	0	0	⋯
⋮	⋮	⋮		⋮	⋮	⋮	⋮	⋯

In the present research, the value of r, s and b for determining the impulse are determined by both the methods. Individuals may use either of the two methods or both.

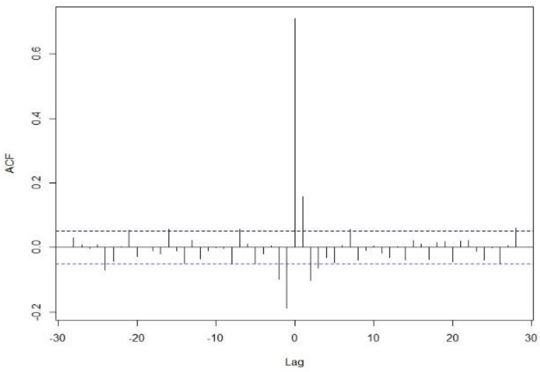

Fig. 10 Cross-Correlation Function plot between dQ_t and dP_t

From Fig. 10 it is understood that the most substantial CCF is at lag (k = 0). Thus, the parameters r, s and b of the transfer function follow the CCF pattern of 0, 0 and 0 respectively [5]. Hence, the CCF supports the following transfer function model:

$$Y_t = \omega_0 X_t + N_t \qquad (9)$$

Where, $\omega_0 = v_j = \frac{s_y . r_{xy}(k)}{s_x}$

The values of v_j are determined at different lags 'k' and are demonstrated in Table 2.

TABLE 2. PROBABLE CROSS-CORRELATION FUNCTIONS AFTER PRE-WHITENING AND IMPULSE RESPONSE WEIGHTS FOR ISP

k	$r_{xy}(k)$	s_x	s_y	v_j	S.E.
-2	0.832			0.01086	0.02616
-1	0.885			0.01155	0.02616
0	0.972	201.598	2.6309	0.01268	0.02616
1	0.932			0.01216	0.02616
2	0.862			0.01125	0.02616
3	0.811			0.01058	0.02616

The final Transfer Function Model (SISO) for Forecasting is obtained from Eq. (9) and is represented as (10)

$$\hat{P}_t = P_{t-1} + \omega_0 dQ_t \qquad (10)$$

Where,

$$\omega_0 = v_0 = \frac{s_y . r_{xy}(0)}{s_x} = 0.012$$

As obtained from Table 2 at lag k = 0.
The Noise term in (9) is neglected as the residuals are representing the white noise refer Fig. 9.

Final SISO transfer function model for the forecast of hydropower of ISP is shown in (11)

$$\hat{P}_t = P_{t-1} + 0.01268 dQ_t \qquad (11)$$

1.4. *Development of SISO transfer function model for the performance evaluation*

The steps discussed in section 2.3 of this article, namely Development of SISO forecast transfer function model, are repeated for evaluation of the performance of ISP for an individual year. Table 3 depicts an overall 5 performance evaluation transfer function models representing performances of ISP during the F. Y. 2013-14 to 2017-18 respectively.

TABLE 3. YEARLY PERFORMANCE TRANSFER FUNCTION MODELS FROM F. Y. 2013-14 TO 2017-18 WITH IMPULSE RESPONSE WEIGHTS

Year	ω_0	Model
2013-14	-0.0007	$\hat{P}_t = P_{t-1} - 0.0007 dQ_t$
2014-15	0.0130	$\hat{P}_t = P_{t-1} + 0.0130 dQ_t$
2015-16	0.0130	$\hat{P}_t = P_{t-1} + 0.0130 dQ_t$
2016-17	0.0129	$\hat{P}_t = P_{t-1} + 0.0129 dQ_t$
2017-18	0.0117	$P_t = P_{t-1} + 0.0117 dQ_t$

2. RESULTS AND DISCUSSIONS

2.1. *SISO forecast transfer function model*

The SISO transfer function model developed using daily data of Q_t and P_t over a length of 1461 days (F. Y. 2013-14 to 2016-17) and is tested and verified for its accuracy using daily data for 365 days i.e. for F. Y. 2017-18. Fig. 11 shows the graphical comparison between the actual power produced at ISP and the power formulated through the model.

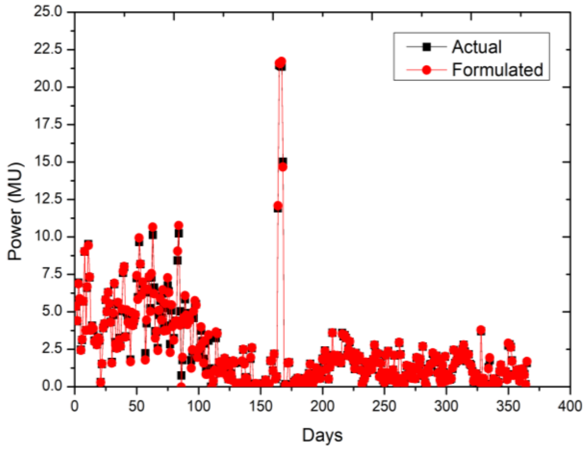

Fig. 11 Actual power vs. power formulated through SISO transfer function model for forecast

Table 4 demonstrates the fit statistics of the SISO transfer function for the forecast.

TABLE 4. FIT STATISTICS OF SISO TRANSFER FUNCTION MODEL

Mean Absolute Deviation (MAD)	$\sum_{t=1}^{n}\frac{\lvert A_t-F_t\rvert}{n}$	0.076
Mean Square Error (MSE)	$\sum_{t=1}^{n}\frac{(A_t-F_t)^2}{n}$	0.022
Root Mean Square Error (RMSE)	$\sqrt{\sum_{t=1}^{n}\frac{(A_t-F_t)^2}{n}}$	0.148
Mean Absolute Percent Error (MAPE)	$\frac{\sum_{t=1}^{n}\frac{\lvert A_t-F_t\rvert}{A_t}}{n}X100$	4.901
Reduced Chi^2 (χ^2)	0.02013	
R-square	0.99756	

The graph is shown in Fig. 11 and the fit statistics listed in Table 4 justifies the SISO transfer function model for the forecasting purpose.

2.2. SISO transfer function model for the performance evaluation

The fit statistics of transfer function performance evaluation models for assessing the performance of ISP in the individual F. Y. 2013-14 to 2017-18 are illustrated in Table 5.

TABLE 5. FIT STATISTICS OF SISO TRANSFER FUNCTION MODEL FOR THE PERFORMANCE EVALUATION OF ISP DURING F. Y. 2013-14 TO 2017-18

Year	ω_0	Model	R^2	Chi^2
2013-14	-0.0007	$\hat{P}_t = P_{t-1} - 0.0007dQ_t$	0.999	0.020
2014-15	0.0130	$\hat{P}_t = P_{t-1} + 0.0130dQ_t$	0.998	0.0521
2015-16	0.0130	$\hat{P}_t = P_{t-1} + 0.0130dQ_t$	0.998	0.0342
2016-17	0.0129	$\hat{P}_t = P_{t-1} + 0.0129dQ_t$	0.9996	0.0223
2017-18	0.0117	$P_t = P_{t-1} + 0.0117dQ_t$	0.997	0.02013

The values of R^2 and Chi^2 suggests that these models are good to evaluate the yearly performance of ISP. Considering the basic principle of transfer function modelling and Hydropower generation equation (12)

$$\mathrm{P} = \rho g Q_t H_t \tag{12}$$

Where,

ρ is the density of water being provided to the turbines

g is the acceleration due to gravity, generally 9.81 m/sec^2.

Q_t is the discharge being provided to the turbines

H_t is the operating head

Here, Q_t, i.e. water being provided to the turbines is the pushing function that drives the turbine and generates electricity. The water head h_t is responsible for the flow Q_t.

According to Torricelli's Law, shown in the equation (13)

$$mgH_t = \frac{1}{2}mv^2 \tag{13}$$

Modifying (13), we get

$$H_t = \frac{v^2}{2g} \tag{14}$$

From (12) and (14)

$$P = \frac{1}{2}\rho Q_t v^2 \tag{15}$$

Also,

$$Q_t = A.v \tag{16}$$

Or

$$v = \frac{Q_t}{A}$$

$$P = \frac{\rho Q_t^3}{2A^2} \tag{17}$$

Thus, in the developing the transfer function models for the purpose of forecast and evaluation of the performance for a Single-Input and Single-Output (SISO) relationship discharge being provided to the turbines (Q_t) has been taken as input to the hydropower system not the head (H_t) and power generated (P_t) as output.

III. CONCLUSION

The approach presented in this research is a comprehensive and statistically vigorous technique of assessing the performance of hydropower plants. It is recommended to the hydropower managing authorities in India and across the world to adopt this investigation for the evaluation of the performance of hydropower projects by determining the acute value of the performance coefficient (ω_0) for a hydropower plant. The plant must be considered underperformed if the value is not at par. Present research reveals that Indira Sagar Project (ISP) must have a ω_0 value above 0.0130, the peak value acquired from the present examination as the cautious target for ω_0. A suitable benchmark may be finalized in order to investigate the performance of various other hydropower stations in India.

The financial year (F. Y.) 2013-14 has been observed as the worst-performing having ω_0 = -0.0007, this is because 2013-14 being a flood year, resulted in the higher value of inflows, but the installed capacity of the hydropower project is fixed and thus the coefficient of performance is negative. It is suggested to have a canal bed powerhouse to generate hydropower during the flood years.Single-Input and Single-Output model which is developed for the forecast of the hydropower being produced at ISP suggests that the model is a good fit and could be used to forecast the power known values of previous values of power and presently available discharge.

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