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A Practical Approach to Storage Optimisation and Hydro Scheduling In Mixed Market Environment for Distribution Utility Owned Generation Stations

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Abstract: Optimisation of own hydro power generation of distribution utility in a market environment is a major decision making in the power procurement portfolio finalisation on annual basis to daily and real time basis. This involves hydro – thermal coordination problem and market operation optimisation in addition to the normal storage management which are attempted severally in the research world. Most of the studies on hydro power management revolve around the optimisation at station level considering the inflow, storage and the market conditionsresulting in the determination of local optima of profit maximisation. Many studies have been done in optimizing the power procurement cost at utility level and take the approach of optimisation of the hydro – thermal coordination. In a deregulated environment, the profit maximisation of all stake holders is to be considered along with the maximisation of social benefit. From resource planning view of a distribution licensee, the local optima with respect to each generator may or may not coincide with the global optima of ensuring cheapest power and power for all. The returns to the generator need not be the maximum at the maximum operational efficiency at grid level. The advantage of hydro generators such as low start-stop costs, flexibility in scheduling etc. can be better utilised with proper Storage management at the reservoirs for achieving the optimum solution. Several methods like creation of separate market, ancillary support market etc. are implemented and modified to induce the tuned parameters for global optimisation in the scheduling of hydro generators. However, such market parameters are often quite complex and may not be practically amenable for ensuring reliability with seasonal variations in requirement. The method developed here was with specific reference to Kerala Power System, but is applicable to any practical power system. The optimisation of storage management takes care of the spill threat of the reservoirs while ensuring maximum possible storage by the end of the active inflow period. An ingenuous method developed and implemented on control area basis optimisation is presented in this paper. The method is based on statistical observations and deduction of some parameters. The success of the method is vouched in the operation of Kerala Power System and its retail tariff.

Keywords: Hydro Thermal Coordination, Storage optimisation, Spill threat, Control Area Optimisation

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I. INTRODUCTION

Electricity industry is regarded as the mother of all industries. Per capita consumption of electricity is regarded as a measure of the living standard of the people of a country. Ensuring availability of quality electricity at affordable price is one of the main agenda of any government. In India, the reliability of supply and most economic operation of the grid are mandated on the Regional Load Despatch Centres (RLDC) and State Load Despatch Centres (SLDC) [1]. The system operation in India, under the influence of the legacy of the erstwhile the vertically integrated State Electricity Boards, does not fall exactly in the ambit of definition of ISO/TSO as followed in several countries. Further, the power sector is categorised in the concurrent list in the constitution of India, by which the role of state level optimisation is also mandated. Hence there is a need for moving from local optima at generating station level to global optima at control area level.

II. LITERATURE REVIEW

Power system operation optimisation is a topic with very wide scope and several papers has been published. The uniqueness in this work is the delinking from local optima determination to partial global optima determination where the real time load generation balance, economy of operation, merit order dispatch and water discharge requirements are considered while optimising the storage at the reservoirs. H Ahlborg et al [2] dsicusses the strategies to be adopted to achieve economic viability of hydro generation on public-private-community partnership basis, which gives a clear picture on station level optimisation. Tahanan [3] gives a good review of literature pertaining to unit commitment. The issue discussed in this paper is the unit commitment for economic load dispatching and does not consider the optimum storage management for market operation. Najafi et al [4] proposed a Harmony Search algorithm for unit commitment problem, but this method is also based on the hydro generation capability, but not linked to storage management. Arce et al [5] developed a model highlighting the trade-off between start-up/ shut down of generating units and hydro power efficiency, but takes care of variations in tailrace elevation, penstock head losses and turbine-generator efficiencies only. Arellano et al [6] discusses the market power that can be exercised by hydro generator on account of the storage available, but the management of storage is not considered in detail. Christoforoset la [7] proposed generation scheduling of the hydro production system as a mixed-integer, nonlinear optimization problem and solved with an enhanced genetic algorithm featuring a set of problem-specific genetic operators. But, the annual variation in inflow and storage management is not considered in this approach. Mariano et al [8] proposed short-term hydro scheduling (STHS) solution based on nonlinear programming (NLP), for optimising power generation efficiency. Andres et al [9] models the medium term operation of the system to compute system marginal cost and refinement of hydro scheduling algorithm. The medium term operation planning is done in this paper also, but instead of assuming the hydro generation potential, we intend to go to determination of hydro generation potential itself.Farhat et al[10] gives a literature survey of literature on the various optimization methods applied to solve the Short-term hydrothermal coordination (STHTC) problem. Mario et al [11] presents methodologies and tools being developed to address the new challenges - and opportunities - posed by power sector restructuring in hydrothermal systems: (a) optimal stochastic dispatch of multiple reservoir systems; (b) joint representation of equipment outage and inflow uncertainty; (c) distortion of short-run marginal costs signals when applied to cascaded plants with different owners; (d) economic efficiency and market power issues in bid-based hydrothermal dispatch with reference to Columbian system. Thomas et al [12] describe the Dynamic Unit Commitment andLoading (DUCL) developed for use in real-time system operations at British Columbia Hydro (BCH) to determine the optimal hydroelectric unit generation schedules for plants with multiple units and complex hydraulic configurations. However, the maximum generation capability is taken as a function of head, which is a real time function and not included as a planning figure. Bensalem et al [13] compares the multi reservoir generation plan by the maximisation of reservoir contents at the end of the exploitation period and at the end of sub periods. The paper is based on hydraulically coupled reservoirs, whereas in the present paper we analyse the case for hydraulically independent hydro schemes. Borovold et al [14] proposes a method for implementing enhanced hydropower planning formulation in a long-term expansion planning model. Zhai et al [15] discusses a quadratic program model for optimal scheduling of hydro generation and also the unit commitment among hydro generating units. In this paper also, the control period wise optimisation is not attempted. Bensalem et al [16] proposes a discrete maximum principle to solve the short term hydro management problem, but limited to cascaded schemes. In this paper, we are presenting a model which considers normal statistical figures for expected inflow into the reservoirs, assessment of spill threat to determine the maximum storage that can be achieved during the active inflow period and periodic correction mechanism when the forecast inflow and the actual varies. The model developed in Microsoft Excel predicts the maximum storage that can happen on single day with reasonable accuracy to avoid a spill threat of the reservoir.

Present Status in India

The various studies mentioned above can be classified broadly into local optimisation techniques and global optimisation techniques. In local optimisation problems the maximisation of generation and minimisation of cost of generation at station level with optimum unit commitment is considered. In India, RLDC/ SLDC is not specifying the scheduling of the unit at a station, but insist only on the schedule of power on ex-bus basis [17]. The actual unit commitment within a station is therefore a local optimisation problem to be attended by the generating station itself, considering the local parameters and expected schedule on short term.

Problem definition

The unit commitment problem is attempted in several methods depending on the objectives. The underlining principle from the point of view of grid management is merit order dispatch. In the process of determining the merit order for dispatch, the role of hydro generation is to be considered separately. When control area optimisation is attempted, the merit order has to be fixed on the basis of the price of generation instead of cost of generation. When price is taken as the basis for comparison, the generation from any hydro station gets split into must-run category and free-run category. The must-run is mainly contributed by technical limits of the generators and water discharge commitments for irrigation and drinking water. A cap on generation is imposed by the control area load-generation balance, which is dependent on the availability of power from other sources, which has roots on the nature of such sources. For instance, nuclear plants and renewable sources will have priority in scheduling and the thermal generation cost will be modulated by the heat rate correction when scheduled below a threshold. The start-up and shut down costs also becomes applicable in the case of peaking stations. Considering all these factors, it becomes evident that the cost of generation is not constant, but varies throughout. The electricity industry everywhere has delimited this variation by creating time blocks for fixing such issues. In India, the time block duration is 15 minutes. The cost of energy delivered from all sources together is conventionally represented as a quadratic function of the form

$$\lambda i = \alpha n + \beta n P ni + \gamma_n P_{ni}^2 \qquad (1)$$

Where
P_{ni} = Active power from the nth generation unit during the i^{th} time block
α,β,γ = Cost function of the generating units in service, including the start stop cost under normal pattern of operation

The text book approach is to minimise λi through any standard method. When this process is done, it can be seen that the minimisation correspond to the peak shaving by the hydro units. In this work, the peak shaving by hydro is assumed as the result of this minimisation. The problem attempted here is to determine the hydro generation on daily average basis during each sub control period so that the overall economy is reached.

Modelling

Having considered the requirement of hydro generation during peak, the assessment of the hydro available for daily generation other than peak is the task. The appropriate decision to operate the hydro plants for the period other than peak is the task in optimisation. The method developed shall be simple to implement and transparent enough to accommodate the queries related to commercials. Further, quick decision is required for rescheduling by the operator when the system conditions changes within the control area or when the changes outside the control area are strong enough to create market movements. The reservoir storage management comes at this stage. By proper management of storage and modulating the generation so as to maintain the storage at optimum level brings out the solution. This requires detailed analysis of the hydrology and weather pattern. The remaining part of the paper is with respect to the case study of Kerala Power System.

III. THE MONSOON

The Monsoon is a characteristic weather phenomenon unique in India, with strong influence in South India. The Monsoon starts in Kerala by June 1^{st} with south westerlies and retrieves after the North-East monsoon in November. Almost 65 -70% of the annual inflow is received during this period from June to November in Kerala. The inflow to the reservoirs after December is nominal and the storage at the end of November is a key indicator on the performance of system operation. The inflow for the period from December to May is not very significant. Further, this period correspond to high demand also. As a result, the planning is to conserve water during the monsoon period upto November and to utilise the stored water from December to May. Hydro generation planning is based on water management and is based on reservoir modelling.
Reservoir wise modelling can be expressed by the general water balance equation

$$\Gamma_0 = \Gamma_{-1} + I_{-1} - \vartheta_{-1} - \zeta_{-1} - \delta_{-1} \qquad (2)$$

Where the suffix -1 stands for the previous control period, and the control period can be one day, or week or month depending on the planning horizon.
Γ_0= Present storage
Γ_{-1}= Storage at the beginning of the control period, can be one day, month or year as the case ofanalysis
I_{-1}= Inflow during the control period
ϑ_{-1}= Depletion of water during the control period (Same as the water equivalent of generation during the control period)
ζ_{-1}=Spill during the control period
δ_{-1}= Evaporation and other losses of water from the reservoir during the control period
During monsoon period, water conservation in the reservoir is possible by keeping the rate of depletion $d\vartheta/dt$ below the rate of inflow dI/dt. In practical consideration, the evaporation and other losses $\delta_{-1}$are negligible compared to the other terms and can be omitted. The water level in the reservoir increases to spill level when (ϑ_{-1}) remains negative consistently, say for η days such that

$$(\Delta I - \Delta\vartheta) > \Delta\Gamma \qquad (3)$$

Where Δ indicates the change in η.days and ΔΓ is the difference from the Full Reservoir Level (FRL) and the reference day's level. Maximum storage occurs when the level reaches FRL and can be sustained if the depletion required ϑ per day is not more than the depletion capability of the generating station given by the product of installed capacity with 24 hours. With the given conditions, the storage can be increased by reducing the depletion to the 'safe level' such that (ΔI−Δϑ) remains under control and spill do not occur. The objective function is to avoid or minimise ζ_{-1}. Taking the derivative of equation (1) with respect to time, we can see that the spill minimisation occurs when the rate of inflow and rate of depletion is equal and storage approaches FRL. Mathematically,

$d\vartheta/dt = dI/dt$ and $\Gamma \rightarrow FRL$ (4)

$d\vartheta/dt$ depends on the availability of generation capacity at the station and I is the hydrological parameter of the reservoir, including the catchment area, rate of rainfall etc. The conditions in equation (3) lead to classification of hydro stations based on reservoir capacity and depletion capability for the purpose of storage optimisation.

IV. CLASSIFICATION OF HYDRO GENERATING STATIONS

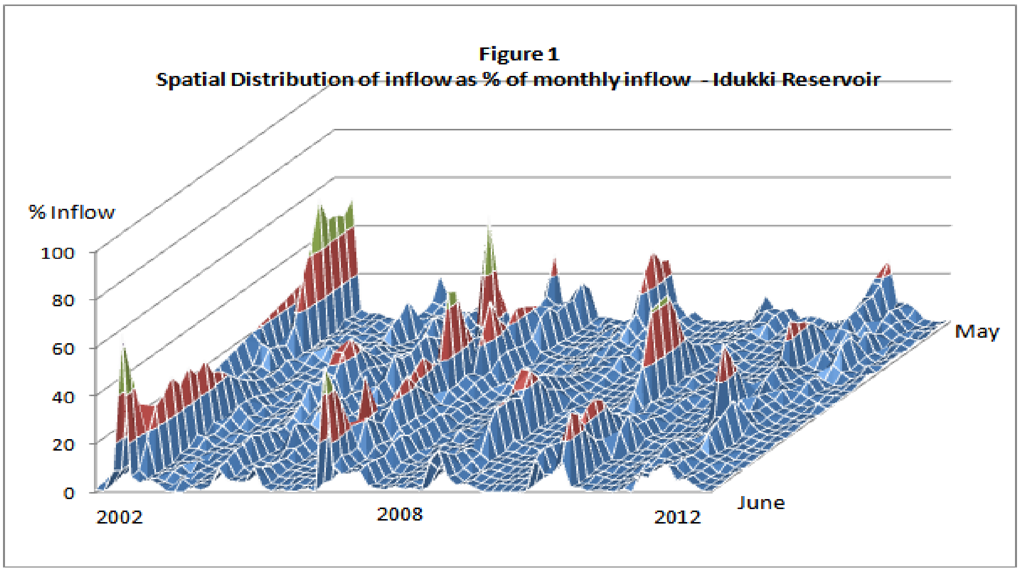
The water balance is satisfied when $\Delta\Gamma \leq (I_{-1} - \vartheta_{-1})$ under maximum storage conditions to avoid spill ζ. Conservation of water (storage) is maximised when $\Delta\Gamma$ is minimum. The storage can be increased if ϑ is comparatively higher than the expected I. Thus the characteristics of the reservoir are determined by the catchment area, rain yield and the generation capability (or more precisely, depletion capability). Based on these the reservoirs in Kerala were classified into three categories.

The expected inflow is variable over time. During the peak of Monsoon, the value of I could be very high and dI/dt changes sign very frequently. When dI/dt is positive, the ϑ_{max} shall be the limiting factor. However, ϑ_{max} is fixed with respect to the annual yield and the minimum load factor for the economy of operation. Spatial variation of I is the next important parameter and the modulation of ϑ with respect to the anticipated movement in the variation of I can bring in good results.

V. ANALYSIS OF PARAMETER VARIATIONS

The daily inflow into the reservoirs for the past 15 years was analysed in detail. Though various methods for daily inflow forecast are attempted, the forecast results have not been satisfactory for the entire Monsoon period. The meteorology department also has not been able to forecast the Monsoon availability for the whole season with satisfactory accuracy. The forecast for the next 4-8 days as given by the meteorology department with reasonable accuracy is not sufficient to optimise the storage as the storage optimisation is to be done on the seasonal basis with maximum storage attained towards the end of the active Monsoon period. The reason for the errors in the overall monsoon prediction being cited is that the Monsoon is a complex process with umpteen parameters, all of which are not even identified. Another issue is that the accuracy of the weather forecast reduces as the foot print reduces. The prediction for the entire India may not match with that of Kerala. Even within the state, cases of monsoon starting normal and later weakening due to cyclonic movements resulting in uneven distribution of rain is observed. Alternate methods for inflow forecast include 10-year moving average (MA) [18] which has some correlation with cyclic nature of monsoon. An attempt was made with 20 year moving average forecast, but the results are almost similar. The 10 year MA forecast is found to be deliveringreasonable results when correction factor is applied during the progress of the season based on the current trends. This 10-year MMA (Modified Moving Average) method is adopted for study in this paper and is currently used in KSEB for inflow prediction.

The impact of the spatial distribution of inflow was further analysed. Figure 1 shows the 3D graph of the inflow to one of the reservoirs in Kerala. The Idukki reservoir has been chosen for case study as it is the largest in terms of capacity, catchment area and depletion capability in Kerala. The application of the proposed methodology can be best illustrated with the reservoir chosen.



From figure 1, it can be seen that the inflow is not uniform throughout the year. Further, it can be seen that the inflow has peaks in between followed by lean period even during high inflow period. Further statistical analysis was carried out on the data for 10 years.

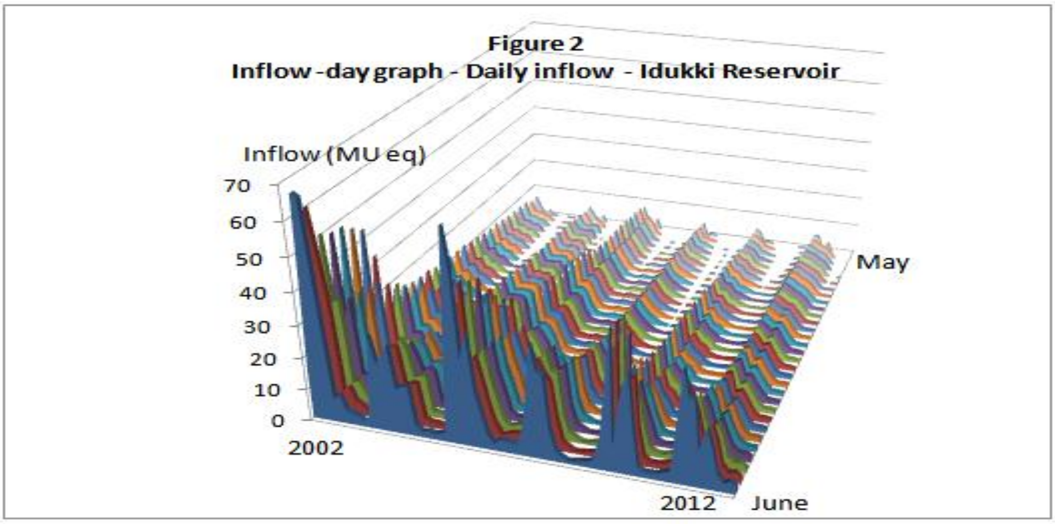
70% - 10 DAYS RULE

Further statistical analysis showed that in a month, the highest inflow can occur at any day and the immediate preceding and succeeding days also show comparable inflow. The credible worst case observed was that about 70% of the monthly inflow is delivered in about 10days. This is clear from figure 2, which is a inflow-day graph, where the daily inflows in each month is plotted from the maximum to minimum. It can be seen that the depth is more during the monsoon period and flattens towards May, the summer period.

From the analysis, it has been concluded that to avoid a chance of spillage while increasing the worst case inflow starting from 1st of any month can be taken for computing the depletion required. It is also established that the inflow after November is comparatively low, except for a few instances in May. The data was validated and it was observed that these instances were during the early onset of monsoon.

The model was created in Microsoft Excel for easiness and acceptability at field level. The basic assumptions made in the model are

i. Active inflow period (Monsoon) starts on June 1st. The previous history as per the details in the meteorology department web site [19] has shown that the maximum delay is 18 days from June 1st for the last 50 years. The earliest onset is 2nd May during this period.



ii. Carry forward requirement at the end of control period is determined on empirical rules. The demand in Kerala control area is having high dependency on the monsoon, partially on account of the consumption pattern of domestic consumers and partially on account of the damages caused to low tension lines during heavy monsoon period, especially during first rain due to heavy vegetation. This leads to a carry forward requirement of storage as on 31st May every year.

iii. The generation is limited by the availability of the generating units in the station. No other constraint such as transmission constraints or load-generation balance constraints prevent generation from the station.
The algorithm used is given below.

Step1: Assume the fixed numbers - carry forward at the end of control period (as on 31st May), actual storage at the beginning of the control period under study (as on 1st June), anticipated inflow month wise (from 10 year Moving Average), minimum generation requirement due to extraneous reasons (irrigation, drinking water commitments etc), minimum generation requirement due to internal reasons like transmission constraints etc.

Step2: With the minimum generation from June (as per LGB requirement), work out the depletion required for spill threat. When generation is to be increased in any month on account of spill threat, recalculate from June again with the additional generation factored along with the minimum already worked out, apportioning the excess uniformly.

Step3: After attaining initial convergence, check for the balance between load and generation. The peak power requirement may require thermal support on combined cycle, then the energy balance has to be checked again. Go to step 2

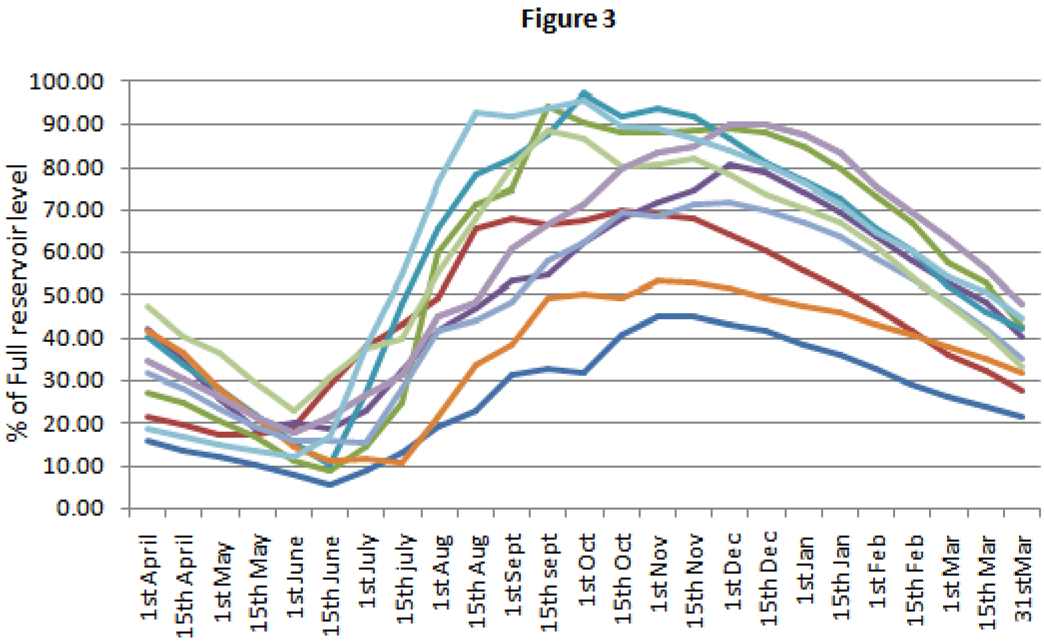
Step4: The annual cost function is worked out at this level including the confirmed market power. To accommodate the hydro generation as per the minimisation requirement go to step 2.

Analysis of results and Conclusion

Table 1
Reservoir: Idukki Gen Station: Idukki

FRL: 2146MU		Balance on May 31 : 341MU			Station figures		
	Water available (MU)as on			Inflow Stn (MU)		Generation possible/Actual	Daily Gen possible/ Actual
	Month end Actual	1st	Month end	Actual/Anticipated	10year average		
June	388	448	388	229.33	323	289.580	9.65
July	780	388	779	590.25	618	198.990	6.42
August	1330	779	1330	701.72	472	150.715	4.86
September	1563	1330	1556	355.85	390	129.995	4.33
October	1646	1556	1640	294.39	256	210.655	6.80
November	1684	1640	1678	211.18	169	173.220	5.77
December	1589	1678	1583	54.19	55	149.570	4.82
January	1460	1583	1453	23.78	24	153.205	4.94
February		1453	1192	18.90	19	280.000	10.00
March		1192	833	31.11	31	390.000	12.58
April		833	574	40.90	41	300.000	10.00
May		574	**331.97**	67.86	68	310.000	10.00
Max %	78.19		Total	**2619**	2465	2736	7.50
Maximum storage computed in %				**Monthly**	78.19%	Daily	92..56%

The implementation of the above algorithm in Microsoft Excel was done using worksheet computations supported by VBA routines embedded. For the purpose of computation, the volume of water in the reservoir is expressed in terms of the generation possible in MU (million kWh). This representation has been followed as it gives a direct feel of the generation for daily monitoring. The results are displayed in excel sheet, which is linked to the computation of load generation balance of the control area. The sample sheet of computation pertaining to Idukki reservoir for the year 2015-16 is shown in table 1.
The management of the generation portfolio by adopting this method of computing the minimumgeneration to avoid spill threat was carried out from 2010. The improvement in the



Maximum storage achieved by adopting this method is depicted in figure 3. The method has been extended to the management of generation from all other hydro generating stations in Kerala with appropriate considerations depending on the water discharge commitments and local transmission constraints in demand management. The results have been satisfactory.

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