Electric Power Market with Intermittent Power Generators

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Abstract—**We are discussing a stochastic market clearing problem to deal with uncertainty in electric power generation. These fluctuations arise due to several imperfections in weather forecast data as well as multiple line loss constraints. These forecast errors can give rise to imbalances in demand or supply or both. The model presented in this paper compares scenarios with variations in power generation from multiple sources. The comparisons drawn are further analyzed in order to compute price variations in all the scenarios**

I. INTRODUCTION

Several years back, when electric power generation was solely a product of conventional sources, a combination of inflexible and flexible generators was used to supply the load. As a result Day-Ahead, commitment was balanced by using real time analysis. But, in the modern world the focus has pivoted from non-renewable to renewable sources of power generation such as wind power, solar power etc. These sources of power generation are considered to be environment friendly and financially stable but the generation by these generators is unpredictable and cannot be controlled manually. This makes scheduling and dispatching of the generators a very difficult task for the system operator.

In Day Ahead (DA), the calculations are performed in advance by predicting the expected load during real time. Dispatching and Scheduling of the generators is carried out to get the optimal power flow Minimizing the cost of generation of electricity as well as maintaining the system stability. As, we need to inform the generating units in advance that their services will be required during the duration of the day because not all the generators can be started or shut down instantly. Whereas, by Real Time (RT), we mean the balancing of the system demand and supply during actual operations.

The predicted day ahead conditions and real time conditions differ from each other because of difference in real time demand from our anticipated demand, due to the unexpected break down of any of our conventional generators or due to the intermittent renewable generators. But, generally to some extent we can as well predict and consider the outage of any one generating plant and the system operator keeps a reserve for the outage by the conventional generator. But, no one can exactly predict the energy generation by the sustainable generators as they are highly unpredictable. Though, we can make a rough estimate of the power supply by these generators but not exactly. So, though this paper we try to highlight the problems which arises due to the unpredictability of the renewable generators and how the cost of energy is being affected by the actual power delivery by our sustainable generators. Our paper resembles that of Pritchard, Zakeri and Philpott: Single-Settlement, Energy-Only Electric Power Market, which apply the similar models to the problem of ensuring system security. We employ a model in which contingencies represent the intermittent electricity generation by the renewable generators rather than just focusing on the system stability. By, studying the above-mentioned paper we found that the modelled described in that paper considered the intermittent power generations and fluctuate demand but did not consider the cost associated with the excess of energy generated by the renewable sources and how to tackle that problem and what are the effects of such a scenario. Because, when these is excess generation of energy, that needs to be absorbed by the system or needs to be spilled. But, since nothing is free, and everything comes with a price, so there is a penalty which needs to be paid for not consuming that energy which we term as spillage cost in our model. And we try to show the effects of under and excess energy generation by these renewable resources on the price of energy for the consumers.

This paper is organized as follows: The next section will introduce the mathematical modelling of the system in which we have considered the cost of electricity being varied by the energy produced by the renewable sources.

II. PROBLEM STATEMENT

As highlighted in our problem statement, the day ahead computations and real time computations are not analogous due to several factors such as inaccuracy in forecast. Consequently, there exists variations in unit commitment and dispatch which in turn increases the total system costs.

In the model presented in this paper, computations are carried out using weighted average for day ahead market in order to minimize the deviation between the day ahead and real time markets.

$$Weighted\ Average = \sum_{i=1}^{n} \mathrm{P(i)} * \mathrm{Power\ Expected}(i)$$

where P(i) is the probability of i^{th} power generation

whereas the real time power is realized in the live scenario (5-

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60 minutes) ahead.

For example, in a grid with solar and wind generation integrated, it will see a maximum generation in a windy day and minimum generation on a typical night, which creates multiple Day Ahead scenarios of generation for every hour (considering load constant for the ease of calculation). The real time realization of these generation may differ from the calculated weighted mean and System operator would like to schedule the generators in such a way which minimizes the cost. By scheduling the costly generation at low during the peak renewable prediction and vice versa. The problem is to find an exact scheduling option dependent on the price of flexible and inflexible generation which minimized the cost (later discussed paper).

Forecasting errors and unforeseen real time scenarios impose additional charges on the grid when load is shed (when power generation cannot meet the demand) or power is spilled (when there is over generation). Under these situations, the System Operator (SO) levies additional charges VOLL (Value of Lost Load) and V_{spill} (Grid absorption cost of extra generation). In this paper, the model presented in this paper concludes that over wind generation though might be cheap but presses additional charges on grid. And demand unmet comes with penalty cost VOLL.
In our multi stage optimization from the eyes of SO we tend to solve the problem by minimizing the operational cost of generators, load shedding and power spillage.

A. *Model Statement*

Since it won't' be prudent to form optimization model for all the expected real time scenarios, the DA dispatch is determined as the weighted average discussed above, which can be called as look ahead strategy in a stochastic market clearing mechanism. Now the clearing based on the actual wind realization (which necessary is not equal to any of the wind scenarios) imposes a system cost in real time differing from the day ahead. Hence the SO's optimization problem becomes

$$Min[(system\ cost\ (DA)) + (Expected\ system\ cost(RT))]$$

Subject to:

- Generation Limits (DA & RT)
- Transmission Limits (constant in DA &RT)
- Load Shedding limits (RT)
- Nodal power balance (DA & RT) (Kirchhoff's Law)

Assuming loads are inelastic

$$System\ cost, DA = \sum C(i) * Pgen(i)$$

Where C(i) is cost of Pgen(i) generation

$$System\ cost, RT = \sum P(i) * [C(i) * RT\ adjustment\ ]$$

Where P(i) is probability of renewable scenarios, RT adjustment is adjustment of flexible generator to compensate for i^{th} scenario, C(i) is cost of i^{th} generator.

We also consider the cost of lost load in RT adjustment which is defined as

$$\sum VOLL(i) * Pshed(i)$$

Where VOLL(i) is value of lost load and Pshed (i) is power shed in i^{th} scenario.

These equations are subjected to their defined limits mentioned above.
Using the solution of the above optimization problem, we calculate the power spill (in some cases) by using it in the Real time nodal power balance equation defined below and multiply them with Spillage cost to give us the cost of power spillage later added to calculated system cost to give us the net cost after considering the spillage.

$$Nodal\ power\ balance\ equation\ for\ every\ node, RT:$$
$$\sum RT\ adjustment\ of\ Pgen(i) + \sum [PRR(i) - PDDA - Pspill(i)\ ] - [\sum Load\ shed] - [\sum FRT - FDA] = 0$$

Where PRR is Power realization of renewable under scenario(i), PDD is Power dispatched in Day Ahead for that node, Pspill is spillage under scenario (i) for that node, FRT is Real time flow and FDA is Day Ahead flow from that node.

In the presented model wind dispatched in the day ahead is regulated with weighted constrains rather than the maximum value of Renewable farms. Which regulates the renewable power dispatched in the day ahead market from being less than the maximum, to a preferential equal to the weighted average of renewable generation in given the forecast there by decreasing the operating cost (dependent on the significance of forecast). The Day Ahead (DA) constrain now becomes

$$Renewable\ Dispach, DA = \sum P(i) * Power(k, i)$$

Where P(i) is probabilistic scenario and Power (k, i) is power generated by k^{th} renewable unit in i^{th} scenario

Our model also penalizes the over generation of electricity as that means highly deviating from the Day Ahead calculation and losing power as wastage (in some markets these excess powers are sold in spot market at reduced unit rate and with negative sign, showing influx of revenue, our model can accommodate that). The calculated spillage in optimization is multiplied with the penalty rate to give total cost of spillage.

$$Spillage\ Cost = \sum P(i) * Power\ Spill(k, i) * Penality$$

Where P(i) is probabilistic scenario and Power Spill (k, i) is power Spilled by k^{th} renewable unit in i^{th} scenario and penalty *is penalty cost associated with spillage.*

Note: Penalty cost can be replaced with Spot Market price so that it adds to revenue, if sold.

The realistic Electric Market also faces transmission side constraints, the transmission carrying capacity of the lines will not only impact the power flow between the two nodes but also the nodal marginal price at each node (in most cases). In a DC OPF optimization, these constraints are regulated by under mentioned equations.

$$|\frac{1}{Xij}(\theta i - \theta j)| \leq Fij, max$$

$$\sum_{between\ All\ Nodes} B.\theta = \sum_{Node}(Pgen - D)$$

Where X_{ij} is the reactance of i^{th} and j^{th} line and $(\theta i - \theta j)$ is the nodal voltage angle difference between i^{th} and j^{th} node. B is the susceptance of the line, Pgen the generation is generation at i^{th} node and D is demand attached to same node

III. MODEL ANALYSIS

The system designed in this paper constitutes of two conventional generators G1 and G2 where G1 is the inflexible generator whereas G2 is the flexible generator. There are two renewable sources of power generation K1 (Wind Power Generator) and K2 (Solar Power Generator). The power generated in DA and RT from these renewable and non-renewable sources of generation is used to feed the inelastic and inflexible demand D1 and D2. The specifications of the model elements are mentioned in the Table 1.

S. No	Elements	Type	Capacity (MW)
1	G1	Inflexible	600
2	G2	Flexible	400 ± 80
3	K1	Unpredictable	400
4	K2	Unpredictable	400
5	D1	Inelastic	400
6	D2	Inelastic	600

Table 1. Specifications of Generation and Load
**Data is taken from EIA*

Three cases have been considered for analyzing the effects of variations in the generation of electrical power by the unpredictable renewable energy generators. In the model, the effects on the cost have been considered and a conclusion has been drawn. The design of the system is as shown in Figure 1.

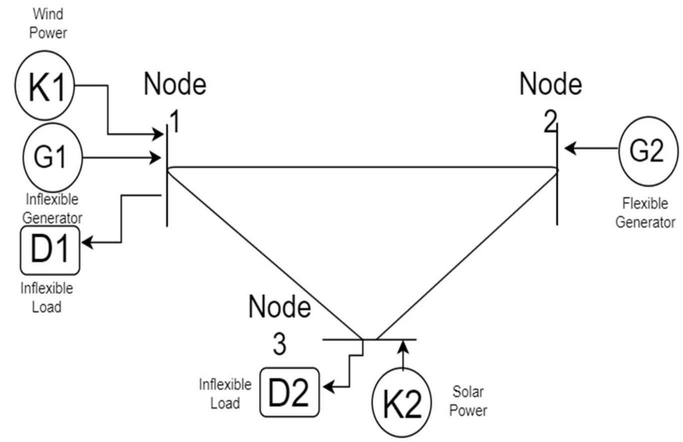


Figure1. Three Node System

Figure 1 shows that there are three nodes in the system with random generators and loads connected on different nodes. Node 1 comprises of generation units G1 & K1 and load D1.

Node 2 comprises of generation unit G2 and Node 3 comprises of generation unit K2 and load D2. Transmission line capacity has been considered high enough to avoid any hindrance in power flow from one node to the other. Equal susceptance has been considered for all the transmission lines.

Generation/Probability	S1	S2	S3	S4	S5
K1	0.2	0.2	0.2	0.2	0.2
K2	0.2	0.2	0.2	0.2	0.2

Table 2. Probability of scenarios happening

A. Case I (80-20)

In this case, conventional generators provide 80% of the demand and 20% of the demand has been provided by the Renewable sources. When the system is formulated as per these specifications, the simulation yields a result with a system cost of $23640. The final system cost including the spillage cost is given as $23640. In this case both the cost functions with and without spillage are analogous. This phenomenon occurs because the adjustment ability of the flexible generator in real time is more than enough to balance any wind scenario realizations (from s1-s5). The wind power realization in DA is scheduled to be 80 MW with locational marginal prices (LMP) at all nodes as $36.

Generation/Scenario	S1	S2	S3	S4	S5
K1	100	90	80	70	60
K2	100	90	80	70	60
Weighted Average		160 MW			

Table 3. Values considered under case I

B. Case II (50-50)

This scenario splits the load requirement as 50% by the conventional generators and the other 50% in the form of renewable generators. Upon realization the system cost is computed to be $16086. The spillage cost computed for this case is $50. The final system cost that includes the spillage cost turns out to be $16136. Even though the supply from the renewable sources has been increased, in total it does not reduce the entire system cost heavily. This discrepancy arises because the flexible generator cannot account for all real time adjustments since it has limited flexibility. The extra power which is left in the system is either absorbed by the grid or returned to the generator at an additional cost. The power that is spilled can also be sold in a spot market, but the price received for this power is considerably lower than the actual marginal price of the system.

Generation/Scenario	S1	S2	S3	S4	S5
K1	250	225	200	175	150
K2	200	225	200	175	150
Weighted Average			400		

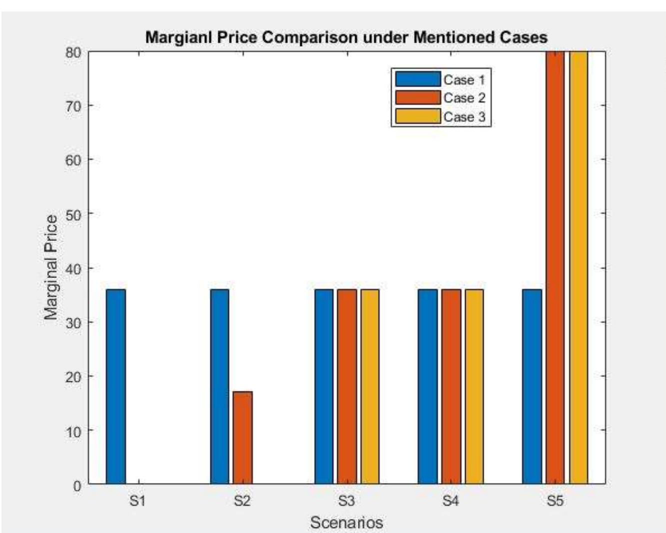
Table 4. Values considered under case II

C. *Case III (20-80)*

Evidently here, 80% of load is supplied by wind and solar power generators whereas only 20% is supplied by the non-renewable generators. As the data suggests, the system cost without considering any spillage adds to $11160 however the system cost with spillage amounts to $11240. The spillage cost as per this scenario is $80. This variance between the two costs increases as more wind power is realized during real time scenarios. Whereas the flexibility of the generator remains the same, making it infeasible for the generator to adjust its output. Hence, the system operator, in order to maintain the system security must adjust the supply of the energy. The supply can be adjusted by either spillage of the extra energy or by selling it in the spot market. Neither of which is free rather comes with the additional cost which in this model we have considered as the spillage cost.

Generation/Scenario	S1	S2	S3	S4	S5
K1	400	360	320	280	240
K2	400	360	320	280	240
Weighted Average			320		

Table 4. Values considered under case III



The above graph compares the marginal cost of total power in all the five scenarios of three cases listed to show how the marginal cost at each node varies due to unpredictable wind power generation.

D. *Case IV (Transmission Constrains in Case II)*

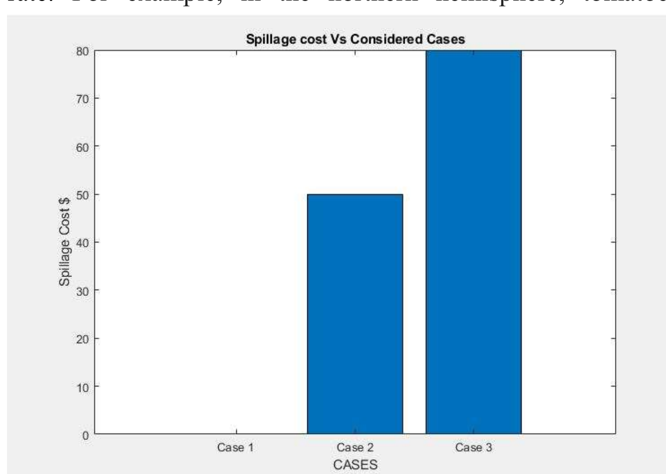
To exhibit the effect of line constraints, we restricted each line capacity to 225MW in the above-mentioned Case II. After running our optimization model, the system cost without spillage turned out to be $17823 and the Day Ahead marginal on all the three nodes were different unlike any of the cases mentioned above. The nodal price of Node 1 is $25, Node 2 $36 and Node 3 is $47. Which introduces us to the concept of Locational Marginal pricing (LMP) where line flow limits have significant impact on nodal equations.
The real time scenario is quite intriguing as given in table below

	S1	S2	S3	S4	S5
N1	0	36	0	58	58
N2	0	36	36	36	36
N3	0	36	80	80	80

Node 1 under situation 3 witnesses' excess generation of renewable energy due to the fact that the line limit imposes a constraint under which this power cannot be transferred to any other node, thus reducing it nodal marginal price to almost negligible. N1 under scenario S4 and S5 sees a locational marginal price of $58.

SPOT MARKET

A spot market or commonly known as cash market is like a public financial market in which products or financial commodities are bought or sold for immediate delivery. The transactions occur in cash and the price paid is not the same as the one decided at the time of delivery. These prices are called spot prices and are fixed by the market. The spot price can be higher or lower than the original price that is decided at the time of order. Generally, in an electrical market from consumer's perspective, the spot trading takes places in the case of over generation where consumers are incentivized at a lower unit rate. For example, in the northern hemisphere, tomatoes



The above graph shows the comparison between different spillage costs. As the wind power generation increases, the spillage cost also increases which ultimately adds to the total cost of power and would be bear by the consumer.

purchased in the summer will reflect the abundant supply of the commodity, which will contrast with January, when harvests are smaller, and prices are higher. One cannot buy tomatoes for delivery in January at July's prices.

IV. Conclusion

In our model we created an electric market that accommodates not only renewable generation but also constrains the transmission limits in DC optimal power flow scenario. Our model considers loads to be inelastic and is approximate depiction of short run case where load doesn't vary rapidly (in an hour or minute).

In depth analysis of the two-stage model presented in the paper revealed that, even though negligible cost of generation, renewable imposes additional cost on grid during over and under generations (dependent on difference of Real time and Day Ahead realization). These imposes different locational marginal price on each node when transmission limits are considered on the interconnected node. The effect of flexibility of generators can also be explored in our model and how the cost of generating one unit of power will affect the scheduling schematic of the grid can also be visualized.

The effect of several factors that govern the dynamics involved in day ahead (DA) and real time (RT) cost computations are assigned weighted values so that they can be closer to actual value of Cost incurred in a realistic market.
The model presented also can be used in spot market trading, if such market is available to trade the excess generation in certain scenarios.

V. FUTURE SCOPE

The model presented in this paper assumes the demand to be scheduled in day ahead (DA) ignoring any real time adjustments of the demand. Whereas, the load requirement in real time varies daily, even hourly, depending on the usage. This elasticity of demand can be integrated into the objective function designed for the system. Elastic demand can be considered to be a linear function multiplied by any linear operator mu (μ) where μ can be the utilization ranging from 0 - ∞ depending on the real time requirement.

The system has been designed for a finite number of second stage scenarios (s1-s5). Since the scenarios considered are finite, our problem is solved using conventional computation techniques as well as validating the solution by hand. This solution can be extended for more probabilities using the concept of continuous random variable. Moreover, the discrepancies in the system occurring due to forecasting errors and fluctuation errors are not considered along with the objective function (assuming these errors to be rare). But, in practicality these errors can be more prevalent and should be incorporated into the objective function thereby affecting the total system cost.

In a practical implementation, the summation of all the power supplied by the renewable and non-renewable sources is not the same as the total power received because of a considerable amount of transmission line losses. For the purpose of simplicity, the transmission line is taken as a lossless line with a large transmission capacity. This system is based on a DC-OPF model where there are no line losses with only transmission line limits. This system can be extended to an AC-OPF model introducing several new factors like active power, reactive power and line losses. AC-OPF provides a global optimal solution for the market clearing problem.

VI. References

1) Geoffrey Pritchard∗, Golbon Zakeri, and Andrew Philpott University of Auckland *A single-settlement, energy-only electric power market for unpredictable and intermittent participants (*May 18, 2009)
2) EIA (Energy Information Administration) 2017 average power plant operating expense in US. https://www.eia.gov/electricity/annual/html/epa_08_04.html
3) EIA's procedure of Converting mills per kWh to cents per kWh https://www.eia.gov/tools/faqs/faq.php?id=19&t=3
4) U.S. electricity generation by energy source https://www.eia.gov/tools/faqs/faq.php?id=427&t=3
5) Daniel Kirschen and Goran Strbac: Fundamentals of power system economics

A. *Appendix I (Code)*

```
*Set OutPut Location of gdx File generated
$setglobal location C:\Users\Ashish\Desktop\SMART GRID PROJECT\3node\Smart Grid Project\

*Naming of file and parameters to be written
*$set matout "'TEst.gdx', cost,P_W,P, returnStat ";
$set matout  "fin.gdx"
$set DMULT 0.5

*Defination of Parameters
sets
i      conventional generators /i1*i2/
d      inelastic loads /d1*d2/
n      buses /n1*n3/
s      scenarios /s1*s5/
k      Renewable power generators /k1*k2/

slack(n)        /n1/
Mapi (i,n)      /i1.n1 , i2.n2/
Mapd(d,n)       /d1.n1 , d2.n3/
Mapnm(n,m)    /n1.n2 , n2.n1, n2.n3, n1.n3, n3.n1, n3.n2/
Mapk(k,n)    /k1.n1 , k2.n3/
alias (n,m);

parameters
W_max(k) Renewable's installed capacity
                    /k1 = 400, k2 = 400/;

parameters
Prob(s)                probability of scenarios /
s1  0.20
s2  0.20
s3  0.20
s4  0.20
s5  0.20
*s6  0.1
*s7  0.1
*s8  0.1
*s9  0.1
*s10 0.1
 /

L(d) Load level /d1 400
             d2 600/

V(d) value of lost load /d1 80
                    d2 80  /

TABLE Cost_Excess(k,s)   value associated with spillage
       s1      s2     s3     s4     s5
 k1    5       5      5      5      5
 k2    5       5      5      5      5   ;



*In Case of Spot market uncomment this and Comment out above table
$ontext
TABLE Cost_Excess(k,s)   value associated with spillage
       s1      s2     s3     s4     s5
 k1    -5      -5     -5     -5     -5
 k2    -5      -5     -5     -5     -5   ;

$offtext



TABLE Generation_Para (i,*)  generators' input data
       Pmax     C      Rmax
i1     600     25      0
i2     400     36      80;
Table Renewable_Para(k,s)  Renewable realization under different scenarios
        s1     s2     s3    s4     s5
k1      250    225    200   150    125
k2      250    225    200   150    125     ;
Table Line_Limit(n,n)  Transmission lines capacity
        n1     n2     n3
n1      0      200    200
n2      200    0      200
n3      200    200    0            ;
Table Susceptance(n,n)    Tranmission lines susceptance
        n1     n2     n3
n1      0      500    500
n2      500    0      500
n3      500    500    0            ;

variables
cost               Total expected system cost including Day Ahead and Real Time
theta_DA(n)        Voltage angles in DA
Pflow_DA(n,m)      Power flows in DA
Pflow_RT(n,m,s)    Power flows in RT
theta_RT(n,s)      Voltage angles in RT
PowerAdj(i,s)      Power adjustment of generator i in RT under scenario s;

positive variables
Load_shed(d,s)     Curtailed load
Pgen_DA(i)         DA dispatch of generators
Rnew_DA(k)         Renewable dispatch in DA
Power_spill(k,s)   Wind Spillage ;



*Equations Of Optimization

equations
ObjectiveFunction,nodalEq_DA,Pmax,Rmax,flow_DA,flow_max_DA,node_RT,UpperLmt,LowerLmt,generation_min,generation_max,flow_RT,flow_max_RT,shedding,spillage,slack_RT,slack_DA;

ObjectiveFunction..
cost=e=sum(s,Prob(s)*{[sum(i,Generation_Para(i,'C')*PowerAdj(i,s))]+
```

```
[sum(d,V(d)*Load_shed(d,s))]})+[sum(i,Generation_Para(i,'C'
)*Pgen_DA(i))];

*Day Ahead Constrains (subjected to)

nodalEq_DA(n)..
sum(i$Mapi(i,n),Pgen_DA(i))+sum(k$Mapk(k,n),Rnew_DA(
k))-sum(d$Mapd(d,n),L(d))
                                    -
sum(m$Mapnm(n,m),Pflow_DA(n,m))=e=0;

Pmax(i)..
Pgen_DA(i)=l=Generation_Para(i,'Pmax');
*Rmax(k)..
Rnew_DA(k)=l=Renewable_Para(k);
Rmax(k)..
Rnew_DA(k)=e=Sum(s,Prob(s)*Renewable_Para(k,s));

flow_DA(n,m)$Mapnm(n,m)..
Pflow_DA(n,m)=e=Susceptance(n,m)*(theta_DA(n)-
theta_DA(m));

flow_max_DA(n,m)$Mapnm(n,m)..
Pflow_DA(n,m)=l=Line_Limit(n,m);

slack_DA..                    theta_DA('n1')=e=0;

* Real Time Constrains
node_RT(n,s) ..
sum(i$Mapi(i,n),PowerAdj(i,s))+sum(k$Mapk(k,n),Renewabl
e_Para(k,s)-Rnew_DA(k)-Power_spill(k,s))

+sum(d$Mapd(d,n),Load_shed(d,s))-
sum(m$Mapnm(n,m),Pflow_RT(n,m,s)-
Pflow_DA(n,m))=e=0;

UpperLmt(i,s)..
PowerAdj(i,s)=l=+Generation_Para(i,'Rmax');

LowerLmt(i,s)..               PowerAdj(i,s)=g=-
Generation_Para(i,'Rmax');

generation_min(i,s) ..
[Pgen_DA(i)+PowerAdj(i,s)]=g=0;

generation_max(i,s) ..
[Pgen_DA(i)+PowerAdj(i,s)]=l=Generation_Para(i,'Pmax');

flow_RT(n,m,s)$Mapnm(n,m) ..
Pflow_RT(n,m,s)=e=Susceptance(n,m)*(theta_RT(n,s)-
theta_RT(m,s));

flow_max_RT(n,m,s)$Mapnm(n,m) ..
Pflow_RT(n,m,s)=l=Line_Limit(n,m);

shedding(d,s)..               Load_shed(d,s)=l=L(d);

spillage(k,s)..
Power_spill(k,s)=l=Renewable_Para(k,s);

slack_RT(s)..                 theta_RT('n1',s)=e=0;

model Stochastic_clearing /all/  ;

$if exist matout.gms $include matout.gms


solve Stochastic_clearing using mip minimizing cost ;
*time.l = Stochastic_clearing.resusd;

parameters

weightedcostspill             Weighted cost spill
costspill                     Cost of spillage
LambdaN_DA(n)
spill_T(k,s)
costnew                       Cost After considering spillage cost
LambdaN_RT(n,s)       ;
LambdaN_DA(n)=nodalEq_DA.m(n)   ;
LambdaN_RT(n,s)=node_RT.m(n,s)/Prob(s);
Spill_T(k,s)=Power_spill.l(k,s);
*costnew = cost.l+sum((k,s),Spill_T(k,s)*sp(k,s));
costspill =  sum((k,s),Spill_T(k,s)*Cost_Excess(k,s));
weightedcostspill  =sum((k,s),Spill_T(k,s)*Cost_Excess(k,s)*
Prob(s));
costnew = cost.l+weightedcostspill;


display
cost.l,weightedcostspill, costnew, LambdaN_DA,
LambdaN_RT, Rnew_DA.l, Pgen_DA.l, PowerAdj.l,
Power_spill.l, Load_shed.l,Spill_T;


*$libinclude matout cost.l
*$libinclude matout P_W.l
*set stat /cost, P_W,P/;
*parameter returnStat(stat);

*returnStat('cost') = Stochastic_clearing.modelstat;
*returnStat('P_W') = Stochastic_clearing.modelstat;
*returnStat('P') = Stochastic_clearing.modelstat;

execute_unload "%location%%matout%";
```