Development of Generator Transition Rate Matrices for MARS That Are Consistent with the EFORd Reliability Index

Validation and Implementation of Method 2

Final Report

6/1/12

The NYISO would like to thank the following individuals for their contributions to this Report:

John Adams	Principle Planner	NYISO
Gregory Chu	Senior Analyst	Con Ed
Dr. Kelvin Chu	Senior Analyst	Con Ed
Ron Fluegge	Principle	GADS Open Source
Dr. Chanan Singh	Principle	Associated Power Analysts

Contents

Background

GE Multi-Area-Reliability-Simulation (MARS) model is the tool that is used in New York for calculating loss-of-load-expectation (LOLE) which forms the basis for calculating the statewide capacity requirement needed to meet NYSRC and NPCC resource adequacy criteria. Since its adoption as the methodology for this purpose, the MARS model has simulated the random outage of generating using transition rates developed from the generating availability data system or GADS. GADS and its variation is the system that generators use to report their performance. The transition rates calculated from the GADS data have been consistent with NERC concept of forced outage rate or FOR. The FOR or EFOR in practice determines the probability of a generating unit being in a forced outage state. However, it has been recognized in the industry that a better measure for generator performance especially for peaking units and intermediate cycling units is the FOR only when the unit is needed or demanded. This is the known as FORd and in practice becomes the EFORd. The NYISO capacity market uses the EFORd to determine a generating unit unforced capacity value or UCAP, which determines its overall capacity. The better a generating unit performs the higher its UCAP value would be and, therefore, its overall capacity payment.

The Installed Capacity Subcommittee of the New York State Reliability Council decided in 2010 that the EFORd would provide an improved or more accurate measure of generator performance as well as provide a metric that was aligned with what is used in the capacity markets. However, there is no direct way to determine when a unit is being demanded and how to calculate EFORd. The NYISO proposed a methodology that calibrated a generating transition rate matrix or EFOR value to the EFORd value by adjusting the first row of the transition matrix. ConEd proposed an approach, which assigned full capacity to the reserve state with the supposition that in this state the unit is available for service.

In order to have an independent review of both of these approaches and determine which might be superior or whether alternative approaches could be developed, the NYISO contracted with Dr. Chanan Singh, a principal of Associated Power Analysts Inc of College Station Texas. Dr. Singh is a professor in the power program at Texas A&M and a recognized world expert in the area of power system reliability. Dr. Singh's initial observation was that MARS or any similar program is based on continuous load over the year and does not have the capability to put units on reserve and start units when needed or demanded. Therefore, probabilities conditioned on demand need to be used. He concluded that the approaches proposed by NYISO and ConEd were reasonable approaches, but both had shortcomings. He proposed and developed two alternative approaches which would provide transition rate matrices that were consistent with EFORd or probabilities conditioned on demand. ICS reviewed a paper prepared by Dr. Singh at a special meeting and agreed to go forward with his Method 2 proposal. Below are Dr. Singh's overall findings. His complete paper including his proposed equations can be found in Appendix A.

Dr. Singh's Overall Findings

1. Embedded in the $EFOR_d$ calculation are the following three steps:

   - Find number of times spent in various states during demand

   - Convert the number of times into conditional probabilities

   - Adjust the number of times in derated states to equivalent times in the full forced outage state

2. Under the present state of data collection, as a matter of practice, it is appropriate to assume that the conditional probabilities calculated for $EFOR_d$ procedure are the bench mark.

3. For the LOLE calculations using MARS or a similar program to be consistent with the $EFOR_d$ calculations, transition rate matrix should maintain the conditional state probabilities used in the $EFOR_d$ calculation.

4. It should be kept in mind that MARS and similar programs do not have mechanisms for starting or shutting down units in response to demand changes. Therefore, these programs essentially assume the units are running or in service all the time.

5. To be consistent with the assumption that units are running all the time, models should be used that are conditional on demand.

6. The $EFOR_d$ calculation formula is based on the conditional probabilities of the states and these conditional probabilities should be assumed as a good estimate of the performance. So the transition rate matrix should be constructed to maintain these conditional probabilities. The conditional approach used in the 4-state model that forms the basis of $EFOR_d$ calculations was in fact proposed to deal with the assumption of units running all the time.

7. The NYISO true-up approach may give correct $EFOR_d$, but it does not allow the conditional probabilities of the individual states to stay consistent with those required for $EFOR_d$. Therefore, while it may give correct EFORd, the LOLE calculation using MARS may be distorted. The amount of distortion will depend on the system characteristics and will vary from one study to the other.

8. The ConEd approach assumes a reserve shut down state with full capacity, but without any exposure to failure. To correctly use this model, the program needs to have unit start and shut down capability. As explained in the text, just assigning full capacity to the

reserve state will over estimate the unit availability when used in MARS or similar programs.

9. Two approaches have been proposed to generate the transition rate matrix that will yield conditional probabilities of individual states to be consistent with the $EFOR_d$ formula. Further they have been illustrated using examples from the NYISO and ConEd reports. The underlying philosophy of these approaches is the same, but they differ on the nature of data availability for the derated states. Since in these approaches, the conditional probabilities stay consistent with the conditional approach used for $EFOR_{d,}$ these approaches are suitable for use with MARS.

Methodology Selection

Both of Dr. Singh's proposed methodologies "estimate" the Equivalent Forced Outage Rate during periods of demand and use the relative historical average forced outage, reserve shutdown, and service time (duty) durations to calculate a "discount factor," which approximates how much of the reported forced outage time occurred during actual demand conditions. Method 2 however would find the hours in the fully available and derated state during demand directly and thus did not need to use an Fp estimate. Fp is a NERC defined estimate of the time in which derated events occur during periods of demand. Method 1 requires using the Fp estimate. Although Method 2 requires additional data, the data needed can be derived from the GADS data. A "better" EFORd would be determined by calculating EFOR for only the actual demand periods, but NERC GADS has no way of collecting the actual demand periods for each generating unit. As a result, it was concluded by ICS and NYISO staff that Method 2 would be the preferred approach of the two.

Validation

A process for implementing and validating Method 2 was established. It consisted of the following steps.

1. NYISO creates test data for three units (small, medium, and large thermal units) based on actual performance over a five year period.

2. Dr. Singh performs a hand calculation on the data showing the appropriate variables.

3. At the same time, test data is run through the new GADS Open Source (OS) software and transition rates are calculated from this data.

4. Using results from step 2 as the benchmark, the results produced by the OS software are reviewed.

5. If significant differences exist, the cause is determined and the needed fixes are identified.

6. Once acceptable results are confirmed, the document is reviewed and findings are presented. The findings need to include Dr. Singh's certification of the applied methodology and results.

7. The technical study entitled: "New York Control Area Installed Capacity Requirements For the period May 2012 - April 2013", which evaluates the impact of using EFORd on the study results is updated.

Validation Findings

The recommended Method 2 was implemented in the GADS OS software and the validation process described above undertaken. In the initial phase of the validation process, it was found that there were some unexplainable differences between the variables used to create the transition rates from Dr. Singh's hand calculation and the GADS OS calculations for the three test units. Additionally, it was determined that test unit three had no reserve shut down events reported for 2006 and could not be used in the entire validation process. Total demand hours H1-H4 were the same, but there were differences between the hours in the derated state. Also, the number of transitions did not balance in the GADS OS generated data. As a result, Dr. Singh and Ron Fluegge, the developer of the GADS OS software, worked together extensively over a two week period to resolve the differences. The primary differences turned out to be how certain events were being interpreted, especially the overlapping or 'shadowing' events and ensuring that the transitions into and out of a state balanced. Tables 1 through 4 presents the results for Dr. Singh's hand calculations and for the GADS OS software.

Table 1 shows the hand calculation of the hours spent in each of the 'demand' states. H1 represents the full output state, H2 and H3 are the hours spent in the derated states, and H4 is the time the unit was forced out of service. Note that H4' is a subset of all the hours in the outage state. It represents those hours where the unit would have been asked to perform (demand) and is calculated by multiplying H4 times the full outage factor (Ff). In addition to the hours, the factors Ff and Fp are shown from the hand calculation (APA) and from the GADs OS software.

Table 1: Calculated States' Hours

	HOURS	H1	H2	H3	H4'	FF	FP
UNIT 1	GADS	6857.57	142.72	122.62	1868.08	0.417	0.224
	APA	6857.53	142.72	122.62	1749.30	0.390	0.224
UNIT 2	GADS	15415.03	1238.18	354.92	4361.85	0.715	0.604
	APA	15414.05	1238.18	354.92	4276.00	0.701	0.604
UNIT 3	GADS	10481.23	1.10	0.75	4894.14	0.431	0.335
	APA	10481.23	1.85	0.00	4770.92	0.420	0.335

Table 2 shows the number of transactions that occurred between the demand states over the five year period (2006-2010). Because of unit three's missing data, the number of transitions were not determined. Oddly enough, unit three's selection as a test unit was a poor choice since it only had a couple of transitions to derated states and practically no time in those states.

Table 2: Transactions Between States

# of transitions			N12	N13	N14	N21	N23	N24	N31	N32	N34	N41	N42	N43
UNIT 1	GADS		6	8	11	3	1	2	9	0	1	13	0	1
	APA		6	8	11	3	1	2	9	0	1	13	0	1
UNIT 2	GADS		10	23	21	9	1	2	22	1	1	23	1	0
	APA		10	23	21	9	1	2	22	1	1	23	1	0
UNIT 3	GADS		N/A											
	APA		N/A											

Table 3 shows the unit's calculated output level during the derated states. The values are on a per unit basis and are derived by determining the time weighted mean output of the derated states and using that level to divide the derated events into states 2 and 3. A time weighted mean for the events in state 2 are calculated and represent S2 in the table. S3 represents the mean of the events whose output fell below the dividing mean.

Table 3: Unit output levels (per unit)

Capacity States		S1	S2	S3	S4
UNIT 1	GADS	1.00000	0.82448	0.43425	0.00000
	APA	1.00000	0.78998	0.57520	0.00000
UNIT 2	GADS	1.00000	0.76233	0.42523	0.00000
	APA	1.00000	0.75325	0.53252	0.00000
UNIT 3	GADS	1.00000	0.87500	0.18750	0.00000
	APA*	1.00000	0.05469	0.00000	

* The hand calculation performed by APA resulted in a three state model. This was due to rejecting an event that less than 1 hour long over the period (43,800 hours).

Finally, Table 4 displays a comparison of the resultant equivalent forced outage rates during demand periods. The column labeled 'APA' shows the values hand calculated by Dr. Singh. These values are only measures of a unit's performance if it were represented on a two state basis. Since the model we've created is a four state model, its prediction of the unit's behavior under demand is much more realistic.

Table 4: EFORd Comparisons

	EFORd (%)		
	Market	GADs OS	APA
UNIT 1	21.36	21.83	20.64
UNIT 2	21.87	22.74	22.31
UNIT 3	37.69	32.00	31.27

In step 7 above, the GADS OS software was used to update the transition rate matrices to be consistent with conditional probabilities based on the units being demanded or EFORd. The result when calibrated to 0.1 days per year resulted in a base case (BC) IRM of 15.2% or a reduction in the BC IRM of 0.9%.

The final validation step that was carried out by the NYISO was a comparison of the average EFORd calculated by the NYISO ICAP market software, and those that result from the GADS OS software. These calculations were performed for all thermal units (except land fill gas units). Table 5 shows the results of the calculations with the upstate's zones being aggregated for confidentiality reasons. The 2012 BC values are those from the 2012 IRM Study's BC. The column labeled 'Market' come from the formula used by the NYISO to calculate each generator's UCAP value, but determined over a five year period instead of an eighteen month period. The column labeled 'GADS OS' shows the values from using the new GADS open source software to derive transition rates based on Dr. Singh's methodology (described in appendix A).

Table 5: Zonal EFORd Comparisons

All Units EFORd (%)			
	2012 BC	**Singh w/ GADS OS**	**Market**
A-E	4.38	4.66	3.19
F-I	9.54	8.81	7.57
J	12.81	9.46	9.07
K	11.30	10.77	10.23

Table 5 also indicates that the EFORd values from the new methodology are higher than those from the market calculations. This is due to the desire to include additional derated and full outage events in determining the system reliability. These events include those for which the generator is not responsible, but nonetheless cannot deliver power to the grid when needed. These are deemed 'outside of management control' and identified in the data as cause code 9300. In addition, there are some events coded D4 (postponable derates), DEs (derated event extensions), and PEs (planned outage extensions) that need to be captured in the new model because the unit is susceptible to being under demand during these periods. The 2012 transition rates were based on capturing the code 9300 outages, but did not take into account the D4s, DEs, and PEs. The fact that Zones A-D's GADS OS value is above the 2012 BC is an indication that the impact of these events was greater than in the other zones.

Conclusions

Dr. Singh has concluded that the GADS OS has implemented Method 2 as intended and the software appears to be producing the expected transition rates. Based on Dr. Singh's findings in conjunction with the EFORd comparisons, the NYISO has concluded that MARS state transition rate matrices whose probabilities are consistent with concept of the unit being demanded as specified in Method 2 has been successfully implemented. The objective of the EFORd calculation is to:

1. Find the time spent in various states during demand
2. Converting these times into conditional probabilities
3. Adjusting the times in derated states to equivalent times in the full forced outage state

This results in the LOLE calculation for MARS being based on EFORd and transition rate matrices that satisfy the conditional state probabilities of the units being demanded. The NYISO recommends that this approach be implemented for the upcoming IRM study.

Appendix A – Dr. Singh's Paper

Development of Generator Transition Rate Matrices for MARS That Are Consistent with the EFORd Reliability Index

April 22, 2011

Chanan Singh PhD, PE

Associated Power Analysts Inc

College Station, TX, 77840

Background

In generating capacity reliability studies, the simplest model is that of a base load 2-state generating unit which has the up state (full capacity) and forced outage state with zero capacity. The transition rate from the up state to the down state is called failure rate, typically denoted by λ and the transition rate from the forced out state to up state is called repair rate and typically denoted by μ. For base load units, the probability of being in the forced out state is called FOR and used as probability of failure. This FOR can be estimated [9] using equation 1,

Full Forced Outage rate (FOR) = FOH/ (FOH+SH) (1)

where

FOH = Forced Outage Hours

SH = Service hours

When a unit is used for peaking or cycling duty with reserve shut down periods followed by in service periods, the forced outage rate calculated by the conventional definitions is found too high. To deal with this situation the concept of FOR given the demand period was introduced [1],

$FOR_d = FOH_{demand} / (SH + FOH_{demand})$ (2)

where

FOR_d = FOR on demand

SH=Service hours

FOH_{demand} = Forced outage hours on demand or during the period of service

It should be noted that FOR_d is a conditional probability of failure given the period of need. Similar definitions for the units with derated states were introduced and the NYISO formula for its estimation is given in Attachment J of NYISO report [2]. The ConEd report [3] provides a very good review of the considerations for development of the formulae for FOR_d and $EFOR_d$.

A few points are emphasized here to keep things in perspective:

1. The concepts of FOR_d and $EFOR_d$ were originally developed for making LOLE calculations for single area studies using analytical methods. In the analytical methods used, there is no mechanism to start the units in response to need and then shut down when not needed. So in the conventional generating capacity reliability studies, units are assumed to run (in service) all the time, unless they are on planned or forced outage. For this reason, it is important to use the

probabilities of unit failure given the demand. These conditional probabilities are assumed to be represented by FOR_d and $EFOR_d$.

2. The peaking or cycling models assume an average duty cycle with duration of reserve shut down time T and demand period D.
3. In reality, the unit duty cycle does change based on its commitment order and change in the load shape. So this assumption of average duty is fine only so long as the nature of the duty cycle does not change significantly. It is, however, the standard practice to use these average duty cycles. References [4,5] introduced methods, analytical as well as Monte Carlo, for calculating duty cycle based on the commitment order of the unit and load shape and also included other issues like the start up delays and outage postponability. **The commercially available programs, however, use an average duty cycle to compute conditional probabilities and then assume these conditional models to run all the time.**

Comments on the Suggested Approaches in NYISO and ConEd reports

The ConEd report [3] recommends an approach using a separate reserve shut down state. The suggested model is reproduced from their document and shown as Fig. 1. If this model or a similar one is used, as shown in the report it will give good estimates of FOR and $EFOR_d$. This is because as explained in Appendix 4 [3] conditional probabilities are used for estimating the $EFOR_d$ and this is the way it should be. However, this model will not give correct results when used in multi-area simulation using the transition rate approach used in MARS or any similar program. The reason for this is that MARS and similar programs do not have the capability to put units on reserve and start when needed. The ConEd report tries to overcome this issue by assigning full capacity to the reserve state 0 with the argument that in this state the unit is available for service. It should be remembered, however, that the unit is not in service during reserve and is thus assumed not to fail. So the problem is that the unit is being given the credit for full capacity without the corresponding exposure to failure. It should be mentioned that it was to avoid this very problem that the idea of using conditional probabilities was first introduced. Mathematically speaking, if we assume P(0) to be fully available state, the equivalent failure rate [7,8] of the unit will become:

$$\lambda_{eq} = P(2)\lambda/(P(0)+P(2)) \qquad (3)$$

which will underestimate the failure rate. In a similar fashion it can be seen that the equivalent transition rates to the derated states will be underestimated. The net effect will be to overestimate the availability of the unit. It should be emphasized again that it is to avoid such problems that the notion of using conditional probabilities or FOR_d was introduced in the first place.

References 5 and 8 implemented similar but more complex models with the important difference that they used mechanisms to shutdown the units when not needed and start when needed. Currently available commercial grade programs unfortunately do not have this capability. Without this capability, the units are essentially assumed to run all the time and in this situation the model conditional on demand is more appropriate to be used.

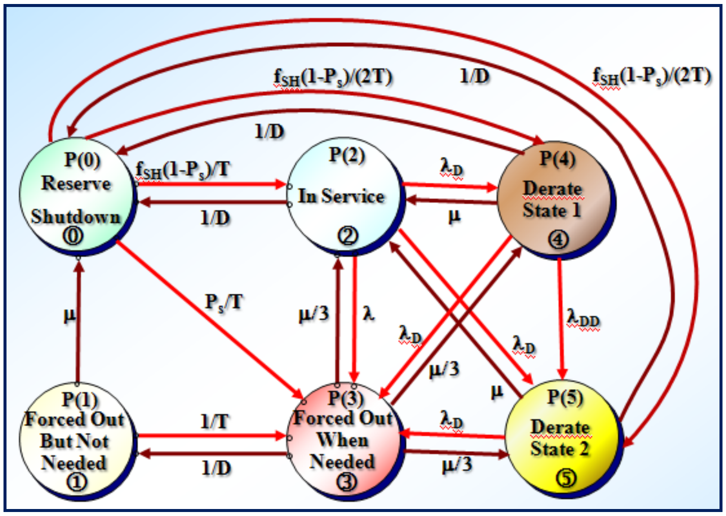


Figure 1. Proposed ConEd Model

The NYISO report suggests an approach based on adjusting the first row of the transition rate matrix by changing the time in the full capacity state. This does give the required value of $EFOR_d$ but as pointed out in ConEd report[3], it arbitrarily changes the state probabilities which may affect the calculated indices. Also in the NYISO approach the reserve shut down state is assumed full capacity state and so the hours spent in this state plus the service hours are used in the denominator for computing the transition rates from the up state to lower capacity states. As stated above the unit is not exposed to failures during reserve shut down and so it is not appropriate to use this time in the denominator [9].

Analysis and Suggestions:

For the ease of discussion, we will consider a unit with two derated states [10], although the conclusions will extend easily to any number of derated states. The model in Figure 2 is a representation of the state space of this unit with two derated capacity levels and one full outage level. The states during the reserve shut down and demand are shown separately at all capacity levels. For example if the unit is in state 5 with full capacity, and it is determined that it is not needed any more, it moves to reserve shutdown state 1. Similarly, if the unit is in derated state 6, and it is not needed any more, it moves to state 2 where it is still in the derated capacity but is not needed. While in state 2, the repair may be completed and the unit moves to state 1 with full capacity but not needed. The service hours SH are then the hours spent in states 5,6 and 7.

The hours spent in state i are denoted by H_i .Some of the terminology used is the same as described in Attachment J of NYISO document [2]. Here we assume that the total time in a derated capacity state is known but its components during demand and reserve shutdown are not known separately. For example, we may know the sum ($H_6 + H_2$) but not H_2 and H_6 individually. Consistent with the approach used for the $EFOR_d$ calculation, the hours in the various derated states and down state during demand can be estimated as:

$H_6 = (H_6 + H_2)f_p$ (4)

$H_7 = (H_7 + H_3)f_p$ (5)

$H_8 = (H_8 + H_4) f_f$ (6)

Knowing the components of derated times during demand,

$H_5 = SH – H_6 – H_7$ (7)

The f factors used in these equations are defined in attachment J [2].

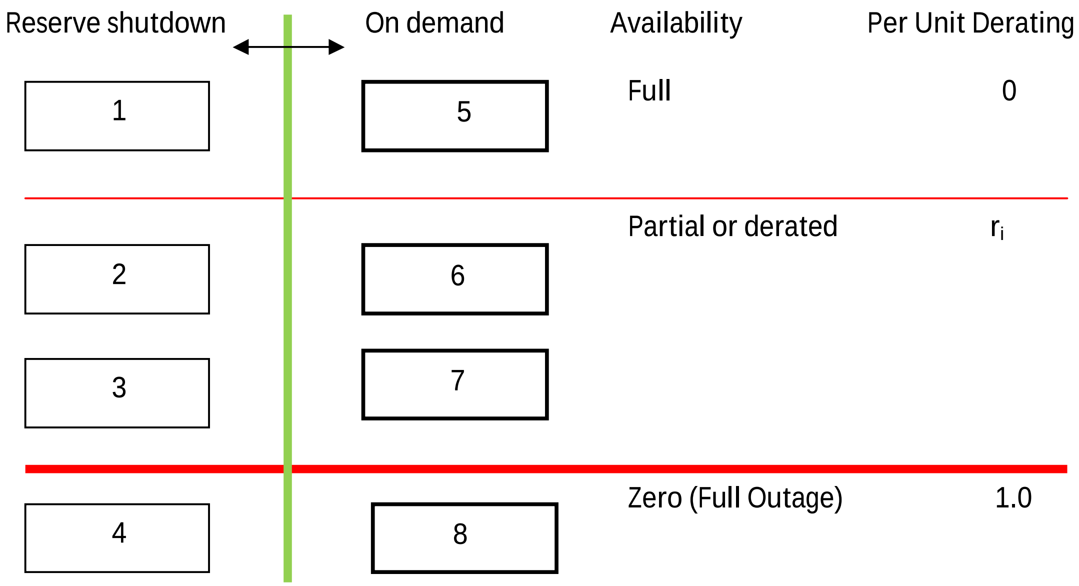


Figure 2. States of a a unit with two derated capacity levels

The conditional probabilities of states, 5 to 8, given demand can be estimated as

$P_{5d} = H_5 / Sum$ (8)

$P_{6d} = H_6 /Sum$ (9)

$P_{7d} = H_7 /Sum$ (10)

$P_{8d} = H_8 /Sum$ (11)

Where Sum = $H_5 + H_6 + H_7 + H_8$

The additional subscript d is used to indicate that these are probabilities given demand.

The $EFOR_d$ can be calculated from these probabilities as,

$$EFOR_d = r_1 P_{6d} + r_2 P_{7d} + P_{8d} \qquad (12)$$

This $EFOR_d$ is basically the same as would be calculated using the Attachment J [2].

It is reasonable to assume that in the absence of the programs to start and shut down units, the use of conditional probabilities given demand (equations 8-11) for the states of the system is the appropriate approach. Since the available multi-area programs do not have capability to start and stop units in response to demand, they basically assume the units to be running all the time, except for periods of forced and planned outages. So we need to create a unit with the conditional states with their probabilities equal to P_{5d}, P_{6d}, $P_{7d,}$ and $P_{8d.}$ These probabilities add up to one, so we end up using a conditional state space for these units. In this example, the new unit with conditional states will have four states with probabilities:

$$P'_1 = P_{5d} \qquad (13)$$

$$P'_2 = P_{6d} \qquad (14)$$

$$P'_3 = P_{7d} \qquad (15)$$

$$P'_4 = P_{8d} \qquad (16)$$

Here the prime indicates the probabilities of unit states in the conditional model.

If the multi-area reliability program was based on using the probabilities ,as some are, then the conditional probabilities P'_i , i=1,2,3,4 can be simply used to sample states in multi-area studies and the results obtained would be consistent with the concepts for calculation of the $EFOR_d$. However, MARS uses transition rates to generate the history of the states of the units and it does not have mechanism to start and shut down units, so we need to have transition rates for this *conditional unit* but probabilities of states must remain the same as given by equations 8-11.

Some thoughts on adjustment of transition rates:

First let us consider if we can find a unique mathematical solution for transition rates if we want to keep the conditional probabilities unchanged to be consistent with the $EFOR_d$ calculations. If there are n states of the new unit, then the maximum number of frequency balance equations[6,7,11] is n-1 but the number of possible transition rates is n(n-1). Thus in the case of 4 states unit, there will be four *known probabilities* P'_i , i=1,2,3,4 but a max of 12 transition rates to be determined. It should be kept in mind that we should not change these conditional probabilities as these are calculated consistent with the data used. So to find the transition rates that will yield the same probabilities, there can be more than one solution if the number of transition rates to be determined is more than 4, ie, the number of equations. However, it should be noted that the probability based indices like LOLE and EUE will not be affected by the choice of the solution for transition rates as long as they reproduce P'_i , i=1,2,3,4 , defined by equations 13 to 16 as state probabilities. Any frequency based index will, however, be affected by the choice of transition rates. The basic problem with the adjustment approach suggested by NYISO is that it changes the conditional probabilities of states.

So what we need to do is what is done in most optimization problems : use the known constraints. To limit the choice of transition rates to reasonable values, i.e. , to find a good solution, the following ideas are suggested.

If we define an nxn matrix N such that its ijth element N_{ij} is the number of times the unit changes from state i to state j, then the transition rate from i to j is given by

$$\lambda_{ij} = N_{ij} / H_i \qquad (17)$$

where H_i is the time spent in state i.

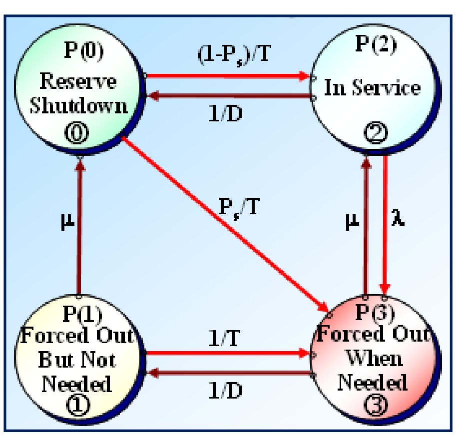
Now the matrix N needs satisfy the following property:

$$\sum_{j,j\neq i} N_{ij} = \sum_{i,i\neq i} N_{ij} \qquad (18)$$

This equation ensures that the frequency of entering a state is the same as frequency of exiting from the state [6,7]. Since in practice, the data may not be collected over long enough time, equation 11 may only be approximately satisfied for every state. It should be noted that the column sum of N is the frequency of entering the state and the row sum is the frequency of exiting the state. So to ensure the frequency balance the column sum for every state should be equal to its row sum.

Now since H_i should not be changed as we want to keep the conditional probabilities unchanged, we should focus on finding an appropriate N matrix that is a reasonable representation of the data.

It should be pointed out that this approach is equivalent to adjusting the transition rates but keeping the conditional probabilities unchanged. In some cases it is simple to make this adjustment. Take the example of 4-state model of peaking unit and its equivalent 2-state conditional model.



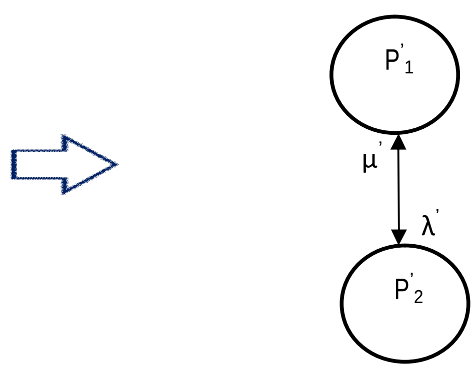


Figure 3. 4-state peaking and its equivalent 2 state model

Differentiating the probabilities in the equivalent model from the original 4-state model by prime,

$P'_1 = P(2)/(P(2)+P(3))$

$P'_2 = P(3)/(P(2)+P(3))$

Since the failure process is assumed to occur during the period of need, we can set

$\lambda' = \lambda$

Then to keep frequency balance between states,

$\mu' = \lambda' \times P'_1 / P'_2$

Now if these new failure and repair rates are used, the conditional probabilities will stay unchanged. This kind of approach may be difficult to use for more than two states. So two simpler approaches are suggested below. The difference in these two approaches is based on how to deal with the availability of data on the derated states. The first approach assumes, as has been done so far in the report that the time spent in a derated state consists of two parts, one attributed to the demand period and the other to the reserve shut down period. Further, these two parts exist in concept but their separate values are not known. The second approach assumes that the derated hours during demand are known but when the unit goes into the reserve shut down the identity of separate derated states is not maintained in data reporting.

Proposed Approach 1:

The proposed approach is first explained with the help of the model in Figure 2 and then generalized.

In this approach, it is assumed that

SH=Hours in the full capacity operating state + Derated Hours during the demand period.

1. First the time spent in states 5 to 8 should be determined, using the concept of equations 4-7. In these calculations, it is assumed that the times spent in combined states, for example, H_2 and H_6 are not individually known but that $(H_2 + H_6)$ is known. So the individual times are found using f factor just like in the $EFOR_d$ calculation. If the times in the two components of a derated state

(Reserve and Demand) are individually known then these can be used instead of apportioning the times from the combined state by the f factor.

2. The matrix N of number of interstate transitions, should be constructed by determining the number of times the unit moves between various capacity states.
3. To find the transition rates, use the times computed in step one in the denominator in equation 18.

This will be now illustrated using the example of unit 2 in the NYISO report, reproduced as Table 1.

Table 1

Event data and Resulting Unit Hours

Event Data									
Unit 1			**type**	**hrs**	**Unit 2**			**type**	**hrs**
01/01/2007 00:00			in RS	24	01/01/2007 00:00			in RS	744
01/02/2007 00:00			Unit start	720	02/01/2007 00:30			D1 100MW	672
02/01/2007 00:00			in RS	5808	03/01/2007 01:30			To full pwr	744
10/01/2007 00:00			Unit start	744	04/01/2007 12:00			in RS	2184
11/01/2007 00:00			Unit trip	720	07/01/2007 00:00			Unit start	744
12/01/2007 00:00			Unit start	744	08/01/2007 00:00			Trip U1	744
					09/01/2007 00:00			Unit start	720
				8760	10/01/2007 00:00			in RS	744
					11/01/2007 00:00			D1 100MW	720
					12/01/2007 00:00			in RS	744
SH	RSH	AH	EFOH	FOH	SH	RSH	AH	EFOH	FOH
2208.0	5832	8040.0	720	720	3600	4416	8016	1440	744
			NMC =	200				NMC =	200

The computed values of f factors from the appendix B [2] are

f_f = .70829

f_p = .44910

Using the concepts of equations 4-7, the time spent in various states are as follows

State 1: Cap=1.0

Time= SH - Derated hours x f_p = 3600 -1392 x .44910 =2975

State 2: Cap =0.5

Time= Derated hours x f_p = 1392 x .4491=625

State 3= Cap=0

Time = FOH x f_f = 744x .70829 = 527

So transition rates are

1 – 2 =2/2975= .00067227

1 – 3 = 1/2975 =00033613

2-1 = 2/625 = .0032

3-1 = 1/527 = .001898

Using these transition rates, state probabilities are,

P1 = 0 .721

P2 = 0.151

P3 = 0.128

And so,

EFORD = .151x.5+.128= .2035

This is about the same as calculated by NYISO formula.

Now the approach can be generalized as follows:

1. Let there be n capacity states of the unit, state 1 with capacity of 1 pu, state n with 0 pu and states 2 to n-1 as derated states.
2. Determine the matrix N representing number of interstate transitions and it should satisfy the property given by equation 18 very closely.
3. The time in state 1 is given by

   H_1 = SH-Total Derated Hours x f_p

   The time in the full outage state n is

   H_n = FOH x f_f

   The times in derated states 2 to n-1 are given by

H_i = (Hours in derated state i) x f_p

4. Find the transition rates using

$\lambda_{ij} = N_{ij} / H_i$

The probabilities of states can be determined from the transition rate matrix and the $EFOR_d$ can be calculated as,

$$EFOR_d = P_n + \sum_{i=2}^{n-1} r_i P_i \qquad (19)$$

Proposed Approach 2:

According to the NERC data collection,

SH= Hours in full operating state + Derated Hours. Here the derated hours represent the hours during demand but during the reserve shutdown, distinction between various derated states and full capacity is not reported. In this case the approach can be slightly modified as follows.

1. Let there be n capacity states of the unit, state 1 with capacity of 1 pu, state n with 0 pu and states 2 to n-1 as derated states.
2. Determine the matrix N representing number of interstate transitions and it should satisfy the property given by equation 18 very closely.
3. The time in state 1 is given by

   H_1 = SH-Total Derated Hours

   The time in the full outage state n is

   H_n = FOH x f_f

   The time in derated states 2 to n-1 are given by

   H_i = Hours in derated state i

4. Find the transition rates using

$\lambda_{ij} = N_{ij} / H_i$

The probabilities of states can be determined from the transition rate matrix and the $EFOR_d$ can be calculated as,

$$EFOR_d = P_n + \sum_{i=2}^{n-1} r_i f_p P_i \qquad (20)$$

Note: It should be observed that these approaches have the following effect. The time used in the denominator of the transition rates from a given state to lower capacity states is actually the service time in that state. For example for state 1, the time used is the time of service in the full capacity state. The time for the repair process is the repair time during the demand period. This will make the conditional repair times shorter than the full repair times or conditional repair rates higher. This is reasonable since only part of the repair may be done during the demand period and remaining repair may be accomplished during reserve shut down.

Calculation Examples of Approach 2

Two examples are used here to illustrate this approach, one from the NYISO report [2] and the other from the ConEdison report [3].

NYISO Example

Again we use the example of unit 2 in NYISO report[2] but assume that the derated hours are on demand only.

$f_f = .70829$

$f_p = .44910$

Using the concepts of equations 4-7, the time spent in various states will be as follows,

State 1: Cap=1.0

Time= SH - Derated hours = 3600 -1392 =2208

State 2: Cap =0.5

Time= Derated hours = 1392

State 3= Cap=0

Time = FOH x f_f = 744x .70829 = 527

So transition rates are

1 – 2 =2/2208= .0009058

1 – 3 = 1/3600 =.0004529

2-1 = 2/1392 = .00143678

3-1 = 1/527 = .00189753

Using these transition rates, state probabilities are,

P1 = 0 .53501

P2 = 0 .33729

P3 = 0 .12770

And so using equation 20,

$EFOR_d$ = .33729x.5x.44910+.12770= .2034

which is exactly the same as using NYISO formula.

Example from the ConEd report (excel workbook)

The following data in tables 2 and 3 is provided by the ConEd for their model shown in Fig 1.

Table 2
Residence Hours before Moving to Next States:

S	**0**	**1-3**	**2**	**4**	**5**	**P(S)**	**Total**
0		299455	5310405	424365	473534	0.74276	6507759
1-3	603052	0	58319	51060	45186	0.08647	757617
2	900239	105696		64893	76186	0.13091	1147014
4	115657	13227	38514		4310	0.01960	171708
5	126631	10241	40628			0.02026	177500

Table 3

Frequency Moving from One State to the Next State:

S	**0**	**1-3**	**2**	**4**	**5**	
0		317	5327	495	497	
1-3	643	0	123	113	118	
2	4605	551		357	365	
4	637	73	222		32	
5	751	56	205			

The f factors are

f_f = .3561

f_p = .1869

For creating the model conditional on demand, the following states are identified

State in the conditional model	**Original state in Figure 1**
State 1 : Cap = 1.0 pu	State 2 in Fig 1
State 2 : Cap = 0.8 pu	State 4 in Fig 1
State 3: Cap = 0.65 pu	State 5 in Fig 1
State 4: Cap = 0 pu	State 3 in Fig 1.

The matrix N of transition frequencies and state times for the conditional model can be created as shown in Table 4. The number of transitions from the new state 1 to other new states represents the transitions from the old states 2 and 0 to the respective states. Similarly number of transitions from new state 4 to other new states represents the transitions from old states 1 and 3 to the respective states. The column sum in the N matrix gives the frequency of entering the state and the row sum gives the frequency of exiting from the state. In table 4, the frequency balance is very closely maintained. The time spent in the new state 1 is the time in old state 2 and the time in new state 4 is the time in old state 3.

So for new states

H_1 = Time in old State 2

= 1147014

H_2 = Time in old state 4

= 171708

H_3= Time in old state 5

=177500

H_4 = (Time in old state 1-3) x f_f

=757617x.3561

= 269787

Table 4: Transition frequency matrix N and state times H_i for the conditional model

State	1	2	3	4	Row Sum	H_i	P_i
1	0	852	862	868	2582	1147014	0.649495
2	859	0	32	73	964	171708	0.097229
3	956	0	0	56	1012	177500	0.100509
4	766	113	118	0	997	269787	0.152766
Column Sum	2581	965	1012	997		1766009	

The transition rates can now be calculated using

$\lambda_{ij} = N_{ij} / H_i$

and are shown in table 5

Table 5: Transition rate matrix and state probabilities:

State	1	2	3	4	P_i
1	-0.002251	.000743	.000752	.000757	0.6494
2	.0005003	-.005614	.000186	.000425	.0973
3	.005386	0	-.005701	.000315	.1005
4	.002839	.000419	.000437	-.003696	.1528

It can be seen that the state probabilities obtained in Table 5 using the transition rate matrix are the same as those obtained in Table 4 using the fraction of time spent in the state.

Also using equation 20,

$EFOR_d = P_4 + P_2 \, x f_p \, x r_2 + P_3 \, x f_p \, x r_3$

$=.1528+.0973\times.1869\times(1-.8)+.1005\times.1869\times(1-.65)$

$= .1630$

Using NYISO formula,

FOH = 757617

EFOH= 171708x.2+177500x.35+757617

=854083.6

$EFOR_d$ =(757617x.3561+.1869x(854083.6-757617))/(1496222+757617x.3561)

=.1630

So the $EFOR_d$ calculated from the transition rate matrix and the NYISO formula are the same.

Concluding remarks:

10. Embedded in the $EFOR_d$ calculation are the following three steps:

    - Finding times spent in various states during demand

    - Converting these times into conditional probabilities

    - Adjusting the times in derated states to equivalent times in the full forced outage state

11. Under the present state of data collection, it is appropriate to assume that the conditional probabilities calculated for $EFOR_d$ procedure are the bench mark. This is not because $EFOR_d$ calculation is the 'absolute truth' but because that is the practice.

12. For the LOLE calculations using MARS or a similar program to be consistent with the $EFOR_d$ calculations, transition rate matrix should maintain the conditional state probabilities used in the $EFOR_d$ calculation.

13. It should be kept in mind that MARS and similar programs do not have mechanisms for starting units in response to demand or shutting down when not needed. Therefore, these programs essentially assume the units running or in service or in demand all the time.

14. To be consistent with this assumption of the units running all the time, models conditional on the demand should to be used.

15. The $EFOR_d$ calculation formula is based on the conditional probabilities of the states and these conditional probabilities should be assumed as a good estimates of the performance. So the transition rate matrix should be constructed to maintain these conditional probabilities. The conditional approach used in the 4-state model that forms the basis of $EFOR_d$ calculations was in fact proposed to deal with the assumption of units running all the time.

16. The NYISO true-up approach may give correct $EFOR_d$, but it does not allow the conditional probabilities of the individual states to stay consistent with those required for $EFOR_d$ and assumed as benchmark. Therefore, while it may give correct EFORD, the LOLE calculation using MARS may be distorted. The amount of distortion will depend on the system characteristics and will vary from one study to the other.

17. The ConEd approach assumes a reserve shut down state which is assumed to be full capacity but without any exposure to failure. To correctly use this model, the program needs to have unit start and shut down capability. As explained in the text, just assigning full capacity to the reserve state will over estimate the unit availability when used in MARS or similar programs.

18. Two approaches have been proposed in this report to generate the transition rate matrix that will yield conditional probabilities of individual states to be consistent with the $EFOR_d$ formula. Further they have been illustrated using examples from the NYISO and ConEd reports. The underlying philosophy of these approaches is the same but they differ on the nature of data availability for the derated states. Since in these approaches, the conditional probabilities stay consistent with the conditional approach used for $EFOR_d$ these approaches are suitable for use with MARS.

References:

1. IEEE Committee, “A four state model for estimation of outage risk for units in peaking service”, IEEE Task Group on Model for Peaking Units of the Application of Probability Methods Subcommittee, IEEE Transactions, PAS-91 (1972), pp. 618-27.
2. Adjustment of Event-Generated EFORs to Mach EFORds in Resource Adequacy Studies, ISO New York, Nov 2,2010.
3. Chi-Hung Kelvin Chu, Carlos Villalba, Developing generating Unit State Transition Rates from Historical Events, ConEdison, Inc.
4. A.D. Patton, C. Singh, M. Sahinoglu, Operating Considerations in Generation Reliability Modeling - An Analytical Approach, IEEE Transactions, PAS-100, May 1981.
5. A.D. Patton, C. Singh, et al, Modeling of Unit Operating Considerations in Generating Capacity Reliability Evaluation, Vol. 1: Mathematical Models, Computing Methods, and Results, Electric Power Research Institute Report EPRI EL-2519, Vol. 1, Project 1534-1, July 1982.
6. C. Singh, Reliability Calculations of Large Systems, Proceedings 1975 Reliability and Maintainability Symposium, 1975.

7. C. Singh & R. Billinton, Frequency and Duration Concepts in System Reliability Evaluation, IEEE Transactions on Reliability, vol R-24, Bo 1,April 1975.
8. A.D. Patton, C. Singh, et al, Reliability Modeling of Interconnected Systems Recognizing Operating Considerations, EPRI Report EL-4603, Vol. 1, Project RP 1534-2, Dec. 1985.
9. IEEE Std 762, IEEE Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity, 2008
10. M. P. Bhavaraju,J.A. Hynds, G.A. Nunan,"A method for estimating equivalent forced outage rates of multistae peaking units", IEEE Transactions on Power Apparatus and Systems, vol PAS-97,No. 6, Nov/Dec 1978

C. Singh, Course Notes: Electrical Power System Reliability, Available on URL: http://www.ee.tamu.edu/People/bios/singh/index.htm