Development of Generator Transition Rate Matrices For MARS that are Consistent with the EFORd Reliability Index

Introduction

The GE MARS Program is based on a sequential Monte Carlo simulation which uses state transition rates, rather than state probabilities, to describe the random forced outages of the generating units. State probabilities give the probability of a unit being in a given capacity state at any particular time, and can be used if one assumes that the unit's capacity state for a given hour is independent of its state at any other hour. Sequential Monte Carlo simulation recognizes the fact that a unit's capacity state in a given hour is dependent on a given state in previous hours and influences its state in future hours. It thus requires additional information that is contained in the transition rate data.

The NYISO capacity market transacts in unforced capacity or UCAP. UCAP is determined by multiplying a generating resource's DMNC, or CRIS if less than DMNC, by its Equivalent Demand Forced Outage Rate (EFORd). EFORd is the industry standard index for determining generating unit performance in competitive markets. Because peaking units normally operate for relatively short periods of time, the basic two-state model was extended to a four-state representation in order to recognize this behavior. The Institute of Electrical and Electronic Engineers' (IEEE) four-state or EFORd model was developed in 1972 [1]. The EFORd is defined in the IEEE Standard 762 entitled: "IEEE Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity" [9]. The standard can be found on nerc.com at the following link:

http://www.nerc.com/docs/pc/gadstf/ieee762tf/762-2006.pdf.

Measures of generating unit performance have been defined, recorded, and utilized by the electric power industry for several decades. The North American Electric Reliability Corporation (NERC)'s Generator Availability Data System (GADS) is the process utilized in the power industry for reporting generator performance data. Generating resources subject to mandatory reliability standards are required to report GADS data as described in NERC's "Data Reporting Instructions" [2]. The reporting instructions can be found at the following link:

http://www.nerc.com/pa/RAPA/gads/Pages/Data%20Reporting%20Instructions.aspx.

It is important that there be consistency between the EFORd calculations utilized in the NYISO capacity markets and MARS transition rate matrices. In order for the MARS LOLE simulation to be consistent with the EFORd calculations, the transition rate matrix must maintain the conditional state probabilities used in the EFORd calculation. Two approaches were developed by Dr. Chanan Singh of Associated Power Analysts (APA) and provided in APA's report [3], which provides the basis for the methodology described in Appendix E. Approach 1 with some modification is the one selected for implementation with the GADS Open Source software.

Assumptions for the Methodology

The purpose of the methodology is to develop transition rates that yield EFORds of the units which are consistent with the formulae used by NYISO's capacity markets. The main difficulty in this process lies in the fact that programs like MARS assume that the units are running all the time and there are no mechanisms in these programs to start the units during the period of need and put them on reserve shutdown when not needed. However, EFORd is computed based on the derated and forced outage states given the period of demand.

The following points are working assumptions that underlie the development of the MARS transition rate methodology:

1. Embedded in the EFORd calculation are the following three steps:
    a. Finding times spent in various states during demand;
    b. Converting these times into conditional probabilities;
    c. Adjusting the times in derated states to equivalent times in the full forced outage state.
2. Under the present state of data collection, the accepted practice is to assume that the conditional probabilities calculated for EFORd procedure are the benchmark.
3. For the MARS calculations of LOLE to be consistent with the EFORd calculations, the transition rate matrix should maintain the conditional state probabilities used in the EFORd calculation.
4. MARS does not have mechanisms for starting units in response to demand or shutting down when not needed [4, 5]. Therefore, the program essentially assumes the units are running, in service, or in demand all the time.
5. To be consistent with the assumption of the units running all the time, models conditional on the demand should to be used.
6. The EFORd 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. The transition rate matrix should be constructed to maintain these conditional probabilities. The conditional approach used in the four-state model [1] that forms the basis of EFORd calculations was in fact proposed to deal with the assumption that units are running all the time.

Development of the Methodology

For ease of discussion, the methodology will be described using a unit with two derated states [10], which will later be extended to any number of derated states. The model in Figure E-1 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 shutdown and demand are shown separately at all capacity levels. The service hours SH are then the hours spent in states 5, 6 and 7.

The hours spent in state i are denoted by $H_{i.}$ 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, the sum (H_6 + H_2) may be known, but not H_2 and H_6 individually. Consistent with the approach used for the EFORd calculation, the hours in the various derated states and down state during demand can be estimated as:

$H_6 = (H_6 + H_2)\, f_p$ (1)
$H_7 = (H_7 + H_3)\, f_p$ (2)
$H_8 = (H_8 + H_4)\, f_f$ (3)

Knowing the components of derated times during demand,

$H_5 = SH - H_6 - H_7$ (4)

The f factors used in these equations are defined in Appendix F of NERC's "Data Reporting Instructions" [2] along with the equations for their calculations. Of course, if the data kept allows the knowledge of H_6, H_7, and/or H_8 individually, then there is no need to use the f factors. From a conceptual perspective it can be stated that it should be possible to keep such data for derated states as they are similar to the full capacity state except with reduced capacity. However, for the forced outage state it may be hard to assign when the transition to reserve shut down happens. This is because when the unit is forced out, one can only calculate when the duty cycle would have ended.

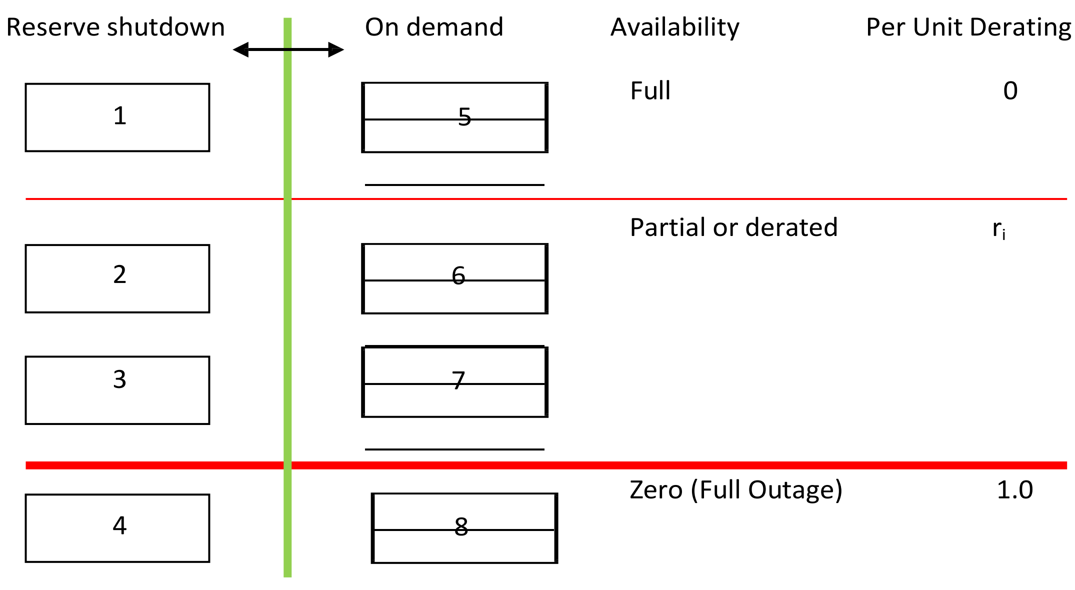

Figure E-1. States of a unit with two derated capacity levels

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

$P5d = H5 / Sum$ (5)
$P6d = H6 / Sum$ (6)
$P7d = H7 / Sum$ (7)
$P8d = H8 / Sum$ (8)

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 EFORd can be calculated from these probabilities as

$$EFORd = r_1 P_{6d} + r_2 P_{7d} + P_{8d} \qquad (9)$$

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 (5)-(8)) for the states of the system is the appropriate approach. However, MARS uses transition rates to generate the history of the states of the units and it does not have a mechanism to start and shut down units. Therefore, transition rates are needed such that the conditional probabilities of states remain the same as given by equations (5)-(8).

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). It should be noted that the probability based indices like LOLE and EUE may not be affected by the choice of the solution for transition rates, but any frequency based index will be affected by the choice of transition rates.

Let's define an (n x n) 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

$$\lambda_{ij} = N_{ij} / H_i \qquad (10)$$

Where H_i is the time spent in state i.

Now the matrix N needs to satisfy the following property:

$$\sum_{j, j\neq i} N_{ij} = \sum_{i, i\neq i} N_{ij} \qquad (11)$$

This equation ensures that the frequency of entering a state is the same as the frequency of exiting from the state [6-8]. Since in practice, the data may not be collected over a 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.

MARS Transition Rate Methodology

The approach of the methodology can be generalized as follows. It is assumed that SH=Hours in the full capacity operating state + Derated Hours during the demand period.

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 (11) 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

In these calculations, it is assumed that the times spent in a combined derated state (Reserve and Demand) are not individually known but their total (Reserve + Demand) is known. So, the individual times are found using the f_p factor just like in the EFORd calculation. If the times in the two components of a derated state (Reserve or Demand) are individually known, then they can be used instead of apportioning the times from the combined state by the f_p factor. **It should be noted that the times in the derated states can be individually known from the GADS data collected by the NYISO, which eliminates the need for the f_p factor in the NYISO implementation.**

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 EFORd can be calculated as

$$\text{EFORd} = P_n + \sum_{i=2}^{n-1} r_i P_i \qquad (12)$$

Implementation and Validation of the MARS Transition Rate Methodology

In order to generate the metrics needed to populate the transition rate matrices for the generating units modeled in MARS, the above methodology was coded into the GADS Open Source software package but modified as described above. The GADS Open Source (GADS OS) is the software utilized by the NYISO to analyze generator performance data. It is used to calculate the generator performance indexes used in determining a generator's UCAP value and, now, for developing the transition rates that are used in the MARS model. GADS OS allows electric generating companies to collect and report validated GADS performance data and event data. GADS OS can be found at this link:

http://gadsopensource.com/

GADS OS, written by industry veteran Ron Fluegge, consists of two open source applications—GADS OS Data Entry and GADS OS Analysis & Reporting to analyze the GADS data. Besides the use of this software for submittal of GADS data to NERC and the NYISO, the software is also used for submittal of data to the ISO New England, PJM, and the MISO.

Measures of generating unit performance—such as Availability Factor (AF), Equivalent Availability Factor (EAF), Forced Outage Rate (FOR), Equivalent Forced Outage Rate (EFOR), and Starting Reliability—have been defined, recorded, and utilized by the electric power industry for several decades. Analysis & Reporting not only calculates these important standard measures, but also includes measures such as the Equivalent Demand Forced Outage Rate (EFORd) used in UCAP/ICAP calculations that have been developed to respond to the deregulated capacity and energy markets.

GADS OS is already in use at a wide range of generating companies from single-plant sites to larger generating companies with hundreds of generating units. The latest count shows that the GADS OS code base is being used to collect and analyze data on more than 200 companies and 3,800 generating units both domestically and internationally.

In order to correctly calculate the transition rates of a unit using its historic events-data, its state durations need to be in a strictly seamless sequence without any overlapping. There will be little difficulty in calculations if the raw data events are in an ideal sequence, i.e., the beginning time of any event is equal to or later than the ending time of its previous event. However, it was found that in the raw data there are quite a few records indicating existence of overlapping events. In addition, some records even show discrepancies in the sequence of events, e.g., an event started and ended before the beginning time of its previous event. All these discrepancies in raw data will frustrate the standard programming algorithms and can cause erroneous calculation results.

As a result, two pretreatment procedures were developed before the raw events data can be used for calculating transition rates. When events in mistaken sequence are found, their places in the overall event sequence list will be reordered by the Pretreatment Procedure 1—Handling Mistaken Sequence of Events. Unless all mistaken sequence records of a unit are corrected, the next Pretreatment Procedure 2—Handling Overlapping Events should not begin.

In order to benchmark statistics in the performance data, Pretreatment Procedure 2 is based on the following classification of event priority levels.

Priority Level	Event Types	Event Code in GADS
1st	Forced Outage, Startup Failure	U1, U2, U3, SF
2nd	Reserve Shutdown	RS
3rd	Planned Outage and its Extension, Maintenance Outage and its Extension	PO, PE, MO, ME
4th	Forced Derating (lower net available capacity)	D1, D2, D3
5th	Forced Derating (higher net available capacity)	D1, D2, D3
6th	Planned Derating and its Extension, Maintenance Derating and its Extension	PD, DP, D4, DM
7th	Noncurtailing Event	NC
8th	Full capacity (gaps between adjacent events)	--

The different types of events in the same priority level are observed not to be overlapping data records. For any two adjacent overlapping events from different priority levels, four rules for appropriate handling are summarized as follows.

(1) If the lower priority event started before the beginning time of the higher priority event, and the lower priority event ended before or at the same time as the ending time of the higher priority event, adjust the ending time of the lower priority event benchmarking the beginning time of the higher priority event.

(2) If the lower priority event started before the beginning time of the higher priority event, and the lower priority event ended after the ending time of the higher priority event, replace the original lower priority event by two new separate events. For the first new event, inherit the beginning time of the original lower priority event as its beginning time, and adopt the beginning time of the higher priority event as its ending time. For the second new event, inherit the ending time of the original lower priority event as its ending time, and adopt the ending time of the higher priority event as its beginning time.

(3) If the lower priority event started at the same time as or after the beginning time of the higher priority event, and the lower priority event ended before or at the same time as the ending time of the higher priority event, invalidate the lower priority event for transition rate calculation.

(4) If the lower priority event started at the same time as or after the beginning time of the higher priority event, and the lower priority event ended after the ending time of the higher priority event, adjust the beginning time of the lower priority event benchmarking the ending time of the higher priority event.

After Pretreatment Procedure 2, an additional rule is also applied to eliminate possible human errors for raw data gaps. This is the Rule of Seamlessness: If the time gap between any two adjacent events is no greater than 1 minute, it will be ignored and the two events are considered as neighboring events. Otherwise, the time gap will be regarded as an event of full-capacity state existing between the two adjacent events.

It is important to note that all the derating states remaining in the sequential event list after above raw data pretreatment procedures are already separated from reserve shutdown states. Hence, these remaining derating states are actually in demand. When counting the total durations of these derating states for calculating transition rates, the f_p factor is no longer necessary. However, the f_f factor is still needed since there is no good way to distinguish in-demand or not- in-demand states when a unit is actually in a forced outage status.

The use of the APA methodology as coded in the GADS OS software with data pretreatment resulted in small differences (less than 0.6% of the total NYCA resources or approximately 225 MW) between the Market calculated EFORds and the GADS OS generated EFORds as implemented in GADS OS [12]. Most of these differences are accounted for in the data used for the calculation (event data versus performance data) and the differing formulae themselves (fp in the market calculation versus direct determination of EFDHs in computing transition rates). The small difference between the total UCAP determined by the NYISO Market EFORd formula and the GADS OS transition rate calculation demonstrates that the methodology for populating generator transition rate matrices for MARS that are consistent with the EFORd reliability index has been successfully implemented.

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. North American Electric Reliability Corporation, “Generating Availability Data System: Data Reporting Instructions”, North American Electric Reliability Corporation (NERC), January 2013.
3. Installed Capacity Subcommittee, “New York control Area Installed Capacity Requirements for the period May 2013 to April 2014: Appendix E—Development of Generator Transition Rate Matrices for MARS That Are consistent with the EFORd Reliability Index”, New York State Reliability Council, LLC, Technical Report, December 7, 2012.
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
11. C. Singh, Course Notes: Electrical Power System Reliability, Available on URL: http://www.ee.tamu.edu/People/bios/singh/index.htm
12. New York Independent System Operator (NYISO), “Status of EFORd Methodology Review”, New York State Reliability Council (NYSRC) Installed Capacity Subcommittee (ICS) white paper, NYSRC ICS Meeting #149, June 2013.