Alberta Electric System Operator

Loss Factor Methodologies Evaluation
Part 3 –Loss Factor Compression

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ALBERTA ELECTRIC SYSTEM OPERATOR

LOSS FACTOR METHODOLOGIES EVALUATION
PART 3 –LOSS FACTOR COMPRESSION

TABLE OF CONTENTS

Page

ALBERTA ELECTRIC SYSTEM OPERATOR

LOSS FACTOR METHODOLOGIES EVALUATION
PART 3 –LOSS FACTOR COMPRESSION

1 INTRODUCTION

This report discusses the results of full system testing of methodologies to compress normalized loss factors to the regulation limits of plus 2 and minus 1 times the average system loss factor

2 ALTERNATIVE COMPRESSION APPROACHES

2.1 Linear Compression

One methodology that is proposed to compress loss factors to the specified range is to apply a scaling factor to the loss factors of all generators to reduce the magnitude of the loss factors to the required limits. This process creates an energy balance error that must be compensated using a shift factor. Application of the shift factor may result in final loss factors outside the acceptable limits so the process may have to be repeated until an acceptable set of new loss factors are achieved.

This methodology is mathematically equivalent to rotating a vertical vector of loss factors (weighted by their volumes) around the average weighted loss factor for the system. The new loss factor becomes the vertical component of the rotated vector (divided by its weighting). Rotation continues until the largest positive new loss factor is less than twice the average system loss factor and the largest negative new loss factor is greater than the negative value of the average system loss factor.

Another mathematical equivalent of the linear compression approach is

1) Determine the average loss factor for the system
2) Select a scaling factor
3) For each generator, compute a compressed loss factor equal to the average system loss factor plus a new term equal to the scaling factor times the difference between the original loss factor and the average system loss factor

This linear compression algorithm is given by:

$$Lf_{average} = \frac{\Sigma Losses}{\Sigma Volumes} \qquad \text{Equation (1)}$$

$$Lf_{max} = 2 \cdot Lf_{average}$$ Equation (2)

$$Lf_{min} = -Lf_{average}$$ Equation (3)

$$K_{sf} = \mathrm{Max}\left(\mathrm{Min}\left(\frac{Lf_{max} - Lf_{average}}{\mathrm{Max}\left(Lf_{original_i}\right) - Lf_{average}}, \frac{Lf_{min} - Lf_{average}}{\mathrm{Min}\left(Lf_{original_i}\right) - Lf_{average}}, 1\right), 0\right)$$ Equation (4)

$$Lf_{compressed_i} = Lf_{average} + \left(Lf_{original_i} - Lf_{average}\right) \cdot K_{sf}$$ Equation (5)

In equation (1) above, "$\Sigma Losses$" is the total system energy losses to be assigned, and "$\Sigma Volumes$" is the sum of the volumes of all generators for which the losses are to be assigned.

The term "$\mathrm{Max}\left(Lf_{original_i}\right)$" represents the largest positive non-compressed loss factor of all generators.

The term "$\mathrm{Min}\left(Lf_{original_i}\right)$" represents the largest negative non-compressed loss factor of all generators.

In equation (4), the lower limit of "0" is to prevent a situation where to solve the loss factor constraints, it is necessary to reverse the sign of the loss factors. If "K_{sf}" becomes zero, all generators in the system would be assigned the same compressed loss factor.

In equation (4), the upper limit of "1" is to used prevent a scaling factor of greater than 1. I.e. if the largest uncompressed positive and negative loss factors are within the limits, no compression will be applied.

Equation (5) above can be re-arranged to:

$$Lf_{compressed_i} = \left(1 - K_{sf}\right) \cdot Lf_{average} + K_{sf} \cdot Lf_{original_i}$$ Equation (6)

or:

$$Lf_{compressed_i} = K_{sf} \cdot Lf_{original_i} + ShiftFactor$$ Equation (7)

where:

$$ShiftFactor = \left(1 - K_{sf}\right) \cdot Lf_{average}$$ Equation (8)

A MathCAD implementation of the linear compression Algorithm is given in Figure 1.

Application of this methodology to the 2005 'winter' normalized loss factors calculated using the current swing bus methodology is shown in Figure 2. In the figure, loss factors, sorted from highest to lowest, are plotted against the cumulated energy volumes of all generators with loss factors greater than or equal to the individual generator loss factor. The total area between the loss factor curve and the 'X' axis of the curve is equivalent to the total energy losses of the system. The lower set of curves (b) is a repeat of the upper set (a) with an extended vertical scale.

Two loss factors curves are shown on each graph, depicting the original loss factors, and the loss factors for each generator after compression.

The compression method exhibits several undesirable traits. The majority of the loss factors are compressed to close to the average system loss factor, reducing any locational-based incentives for those units. In addition, loss factors of generators with large negative loss factors (or credits) with the original set of loss factors are compressed to values that are greater than the minimum permitted loss factor. This could be argued to be 'over-penalizing' these generators.

The compression results in a significant shift in the responsibility for losses from those generators with original loss factors greater than the system average, to those generators with original loss factors less than the system average.

2.2 Exponential Correction

In this method, the correction that is applied to the individual generator loss factor is exponentially weighted based on the magnitude of the difference between the original loss factor and the average system loss factor. A MathCAD implementation of the algorithm used is shown in Figure 3. Loss factors greater than average have different weightings than loss factors less than the average. The term "Lf_i-Lf_{av}" is essentially a 'gross' correction that is applied to each loss factor. If the exponential weighting factor is unity, no correction is applied. This occurs if the maximum loss factor is less than the maximum permitted (α is set to zero) or the minimum loss factor is greater than the minimum permitted (β is set to zero).

Once loss factors are compressed, a shift factor is applied to correct the loss energy balance and linear compression is then applied to restore any new violations resulting from application of the shift factor to within the limits.

Application of this methodology is shown in Figure 4. While this methodology has less impact on generators with loss factors within the defined range, and the degree of 'over-penalizing' of generators with large negative loss factors is less than the linear compression methodology it has an undesirable, (almost unacceptable trait) it that after compression, the resultant loss factors are no-longer monotonically decreasing. This is evident in curve b of the figure in the high loss factor range where cumulated energy is less than about 1 GWh.

2.3 Exponential Compression

In this method the compressed loss factor is a simple exponential function of the original loss factor. A MathCAD implementation is shown in Figure 5, and the impact on loss factors is shown in Figure 6. With this algorithm it is necessary to adjust the constants k_1 and k_2 to insure compression of the large loss factors while limiting the impact on loss factors within range and maintaining monotonically decreasing loss factors.

The values of constants used for the compression shown in the figure are:

$k_1 := -.05$

$k_2 := .11$

With these constants, large loss factors are monotonically compressed, with reduced impact on loss factors within range and with the largest and smallest (most negative) loss factors compressed to the extremes directed by the board.

For this demonstration, the constants have been selected on a trial and error basis. It should be possible to establish a mathematical criterion for the selection of the constants for a production version of the algorithm.

2.4 Clipping Plus Linear Compression

In this algorithm, loss factors are limited to the maximum permitted values, a shift factor is applied to the set of loss factors not originally at the limit to balance the energy loss, and linear compression is applied to the reduced set of loss factors to restore loss factors (forced out of range by the shift factor) to the stated limits.

A MathCAD implementation of the clipping algorithm is shown in Figure 7. The impact on loss factors is shown in Figure 8.

The methodology has the advantage that:
- loss factors originally within the range are not significantly affected by the the compression.
- loss factors that were originally clipped are neither further credited nor penalized.

2.5 Recursive Clipping

This methodology involves a recursive application of loss factor clipping followed by shift factor correction to the remaining generators until the loss factors are all within limits and the energy loss balance is obtained.
A MathCAD implementation of the clipping algorithm is shown in Figure 9 and its impact on loss factors is shown in Figure 10.

The final loss factors are very close to the loss factors obtained with clipping followed by linear compression. The main difference is that no loss factors are changed from values outside the limits to new values within the limits. Again the impact on generators originally within the limits is small.

3 COMPARISON OF METHODOLOGIES

The five methodologies discussed above can be grouped into three categories namely linear compression, exponential compression and clipping. Within each category the impact of compression on losses is similar. The three categories are compared in Figure 11. In the upper figure, loss factors are plotted against the accumulated energy providing a visual assessment of the compression methodology on energy. In the lower figure, the loss factors are plotted against the generator number giving a visual assessment of the number of generators affected by the methodology.

Figure 12 shows the impact of compression methodology to the amount of losses allocated to each generator. Figure 13 shows the cumulated change in energy allocation of each methodology and is representative of the total swing in energy loss allocation resulting from each of the compression methodologies.

Linear compression not only involves the largest shift in energy allocation but also significantly affects the largest number of generators.

Exponential compression has less impact than linear compression in that fewer generators are significantly impacted and less shift in energy allocation is involved.

Clipping primarily affects only those few generators outside of the limits.

4 SENSITIVITY TO RANGE OF LOSS FACTORS

Preliminary investigations using the 50% area load adjustment methodology suggested in [1] indicate that the loss factors for almost all of the generators in the Alberta system will fall within the maximum permitted range of loss factors. Even though the majority of loss factors are presently within the range, changes to the transmission network and changes to system dispatch in the future may result in loss factors being slightly outside the specified range.

Each of the three categories of methodologies was tested for this sensitivity. All of the normalized loss factors calculated with the present swing bus methodology were arbitrarily reduced by a factor of two and an additional shift factor introduced to restore the energy loss balance. The comparisons are shown in Figure 14, Figure 15 and Figure 16.
This sensitivity study shows that with original loss factors that are outside but closer to the limits, the behaviour of the exponential compression methodology changes. Loss factors continue to decrease monotonically, i.e., the ranking of generators by loss factor does not

change. However, for some generators, the loss factor is increased, while for others, the loss factor is reduced. This is not unexpected as there is always a shift required to balance the energy loss equation. However, to reflect the objectives of the regulations, the general characteristics of the loss factor variation curves should at least be similar to those exhibited by linear compression methodology, which does reflect the stated objectives. Those generators receiving credits with linear compression should receive credits for all methodologies.

This is particularly evident in Figure 15 and Figure 16. Generators ranked from about 12 to 25 are penalized by the exponential compression method. With linear compression, however, their loss factors are improved. Similarly generators ranked above about 60 are credited with the exponential compression methodology and penalized with the linear compression method.

For the clipping methodologies, there will also be a few generators with loss factor changes that are in the opposite direction to that of the linear compression methodology. However, this would only apply to generators with loss factors that were originally close to zero.

5 RECOMMENDATIONS

The exponential correction algorithm is unattractive as it will over-compress loss factors at the extremities of loss factor range.

Exponential compression is unattractive since it requires a judicious selection of compression gains and could be a source for loss factor manipulation.

Linear compression is unattractive as resultant loss factors are extremely sensitive to small generators with large positive or negative loss factors. A small generator with a large loss factor will compress all loss factors to close to the system average loss factor. Locational based generating signals will be lost.

Both recursive clipping and clipping with linear compression have minimal impact on loss factors within limits for conditions with small generators outside of limits. If a situation does arise where a large generator with a large loss factor (positive or negative) exists, the algorithm with clipping and linear compression will have fewer units forced to limits by the requisite shift factor.

On this basis it is recommended that the 'clipping with linear compression algorithm' be used to compress loss factors. The methodology limits the magnitude of loss factors without significantly shifting the assignment of losses. For the expected situation where all loss factors are expected to be within limits, compression will not be required. However if a situation does arise where a small generator is added to the system at an unfavourable location or network configuration changes such that the loss factor of a small generator changes to a large positive or negative value, minimal shift in responsibility for losses occurs. If a similar situation arises but the generator capacity is large, a large shift in loss allocation is required, however, the loss factors of the other generators will retain their overall ranking.

6 REFERENCES

[1] Report ‘Loss Factor Methodologies Evaluation Part 1 - Determination of ‘Raw’ Loss Factors” prepared by Teshmont Consultants LP, Revised December 22, 2004.

Method 1 Linear Compression plus shift factor

$$
Lf_1(Lf, E, k_{max}, k_{min}) := \left|
\begin{array}{l}
Losses \leftarrow Lf^T \cdot E \\
Lf_{av} \leftarrow \dfrac{Losses}{Sum(E)} \\
Lf_{max} \leftarrow k_{max} \cdot Lf_{av} \\
Lf_{min} \leftarrow k_{min} \cdot Lf_{av} \\
K_s \leftarrow \max\left(\min\left(\dfrac{Lf_{max} - Lf_{av}}{\max(Lf) - Lf_{av}}, \dfrac{Lf_{min} - Lf_{av}}{\min(Lf) - Lf_{av}}, 1\right), 0\right) \\
\text{for } \; i \in 0..\, rows(Lf) - 1 \\
\quad Lf_{1_i} \leftarrow Lf_{av} + \left(Lf_i - Lf_{av}\right) \cdot K_s \\
Lf_1
\end{array}
\right.
$$

Lf is a vector of uncompressed but normalized loss factors.
E is a corresponding vector of generator energy volumes.
k_{max} is a scalar that when multiplied by the average loss factor defines the maximum permitted loss factor
k_{min} is a scalar wthat when multiplied by the average loss factor defines the minimum permitted loss factor

Figure 1 MathCAD Implementation of Linear Compression Algorithm

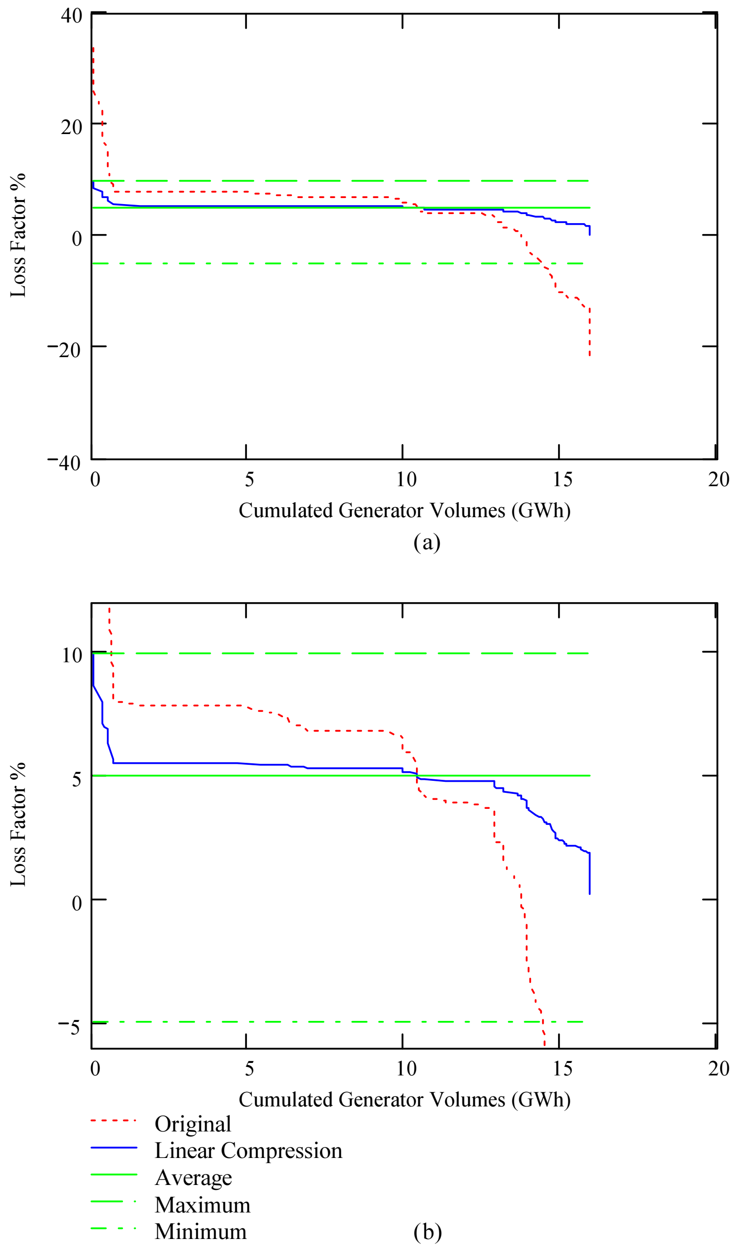


Figure 2 Impact of Linear Compression on Loss Factors

Method 2 correction to actual loss factor based on exponential weighting, plus linear compression after adjustment for energy

$$
Lf_2(Lf, E, k_{max}, k_{min}) := \left|
\begin{array}{l}
Losses \leftarrow (Lf)^T \cdot E \\
Lf_{av} \leftarrow \dfrac{Losses}{Sum(E)} \\
Lf_{max} \leftarrow k_{max} \cdot Lf_{av} \\
Lf_{min} \leftarrow k_{min} \cdot Lf_{av} \\
\alpha \leftarrow \left| \begin{array}{l} max_{lf} \leftarrow max(Lf) \\ 0 \text{ if } max_{lf} < Lf_{max} \\ \dfrac{\ln\left(\dfrac{Lf_{max} - Lf_{av}}{max_{lf} - Lf_{av}}\right)}{max_{lf} - Lf_{av}} \text{ otherwise} \end{array} \right. \\
\beta \leftarrow \left| \begin{array}{l} min_{lf} \leftarrow min(Lf) \\ 0 \text{ if } min_{lf} > Lf_{min} \\ \dfrac{\ln\left(\dfrac{Lf_{min} - Lf_{av}}{min_{lf} - Lf_{av}}\right)}{min_{lf} - Lf_{av}} \text{ otherwise} \end{array} \right. \\
\text{for } i \in 0..\, rows(Lf) - 1 \\
\quad Lf_{2a_i} \leftarrow Lf_{av} + e^{\left[\left| \begin{array}{l} \alpha \cdot (Lf_i - Lf_{av}) \text{ if } Lf_i > Lf_{av} \\ \beta \cdot (Lf_i - Lf_{av}) \text{ otherwise} \end{array} \right. \right]} \cdot (Lf_i - Lf_{av}) \\
Lf_2 \leftarrow Lf_{2a} + \dfrac{\left(Losses - Lf_{2a}{}^T \cdot E\right)}{Sum(E)} \\
Lf_2 \leftarrow Lf_1(Lf_2, E, k_{max}, k_{min})
\end{array}
\right.
$$

Lf is a vector of uncompressed but normalized loss factors.
E is a corresponding vector of generator energy volumes.
k_{max} is a scalar that when multiplied by the average loss factor defines the maximum permitted loss factor
k_{min} is a scalar wthat when multiplied by the average loss factor defines the minimum permitted loss factor

Figure 3 MathCAD Implementation of Exponential Correction Algorithm

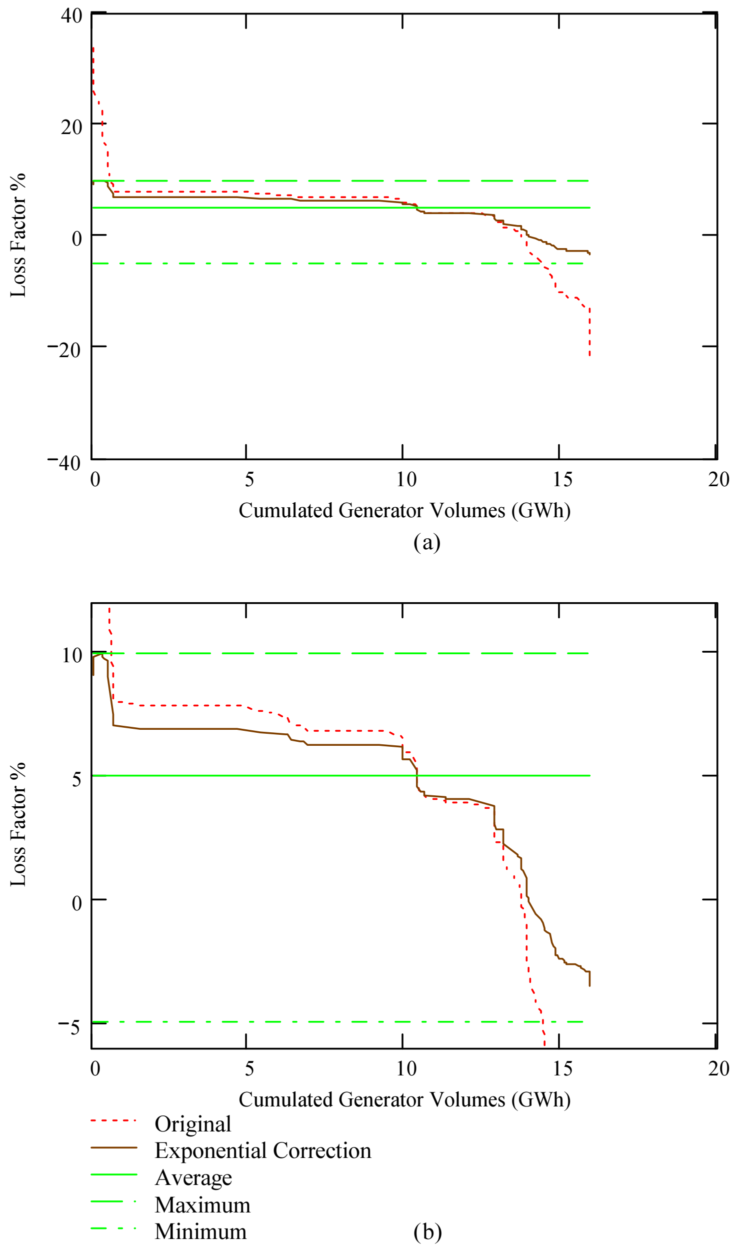


Figure 4 Impact of Exponential Correction Algorithm on Loss Factors

Method 3 Exponential Weighting Plus Linear Compression

$$
\begin{aligned}
Lf_3(Lf, E, k_{max}, k_{min}, k_1, k_2) := \; & Losses \leftarrow (Lf)^T \cdot E \\
& Lf_{av} \leftarrow \frac{Losses}{Sum(E)} \\
& Lf_{max} \leftarrow k_{max} \cdot Lf_{av} \\
& Lf_{min} \leftarrow k_{min} \cdot Lf_{av} \\
& \alpha \leftarrow \left| \begin{array}{l} max_{lf} \leftarrow max(Lf) \\ 0 \;\text{ if }\; max_{lf} < Lf_{max} \\ \dfrac{\ln\left(1 + \dfrac{Lf_{max} - Lf_{av}}{k_1}\right)}{max_{lf} - Lf_{av}} \;\text{ otherwise} \end{array} \right. \\
& \beta \leftarrow \left| \begin{array}{l} min_{lf} \leftarrow min(Lf) \\ 0 \;\text{ if }\; min_{lf} > Lf_{min} \\ \dfrac{\ln\left(1 + \dfrac{Lf_{min} - Lf_{av}}{k_2}\right)}{min(Lf) - Lf_{av}} \;\text{ otherwise} \end{array} \right. \\
& \text{for } i \in 0 .. rows(Lf) - 1 \\
& \quad Lf_{3a_i} \leftarrow Lf_{av} + \left[\left| \begin{array}{ll} k_1 \cdot \left[e^{\left[\alpha \cdot (Lf_i - Lf_{av})\right]} - 1 \right] & \text{if } Lf_i > Lf_{av} \\ k_2 \cdot \left[e^{\left[\beta \cdot (Lf_i - Lf_{av})\right]} - 1 \right] & \text{otherwise} \end{array} \right. \right] \\
& Lf_3 \leftarrow Lf_{3a} \\
& Lf_3
\end{aligned}
$$

Lf is a vector of uncompressed but normalized loss factors.
E is a corresponding vector of generator energy volumes.
k_{max} is a scalar that when multiplied by the average loss factor defines the maximum permitted loss factor
k_{min} is a scalar wthat when multiplied by the average loss factor defines the minimum permitted loss factor
k_1 is a factor applied to the exponent of loss factors greater than the average
k_2 is a factor applied to the exponent of loss factors less than the average

Figure 5 MathCAD Implementation of Exponential Compression Algorithm

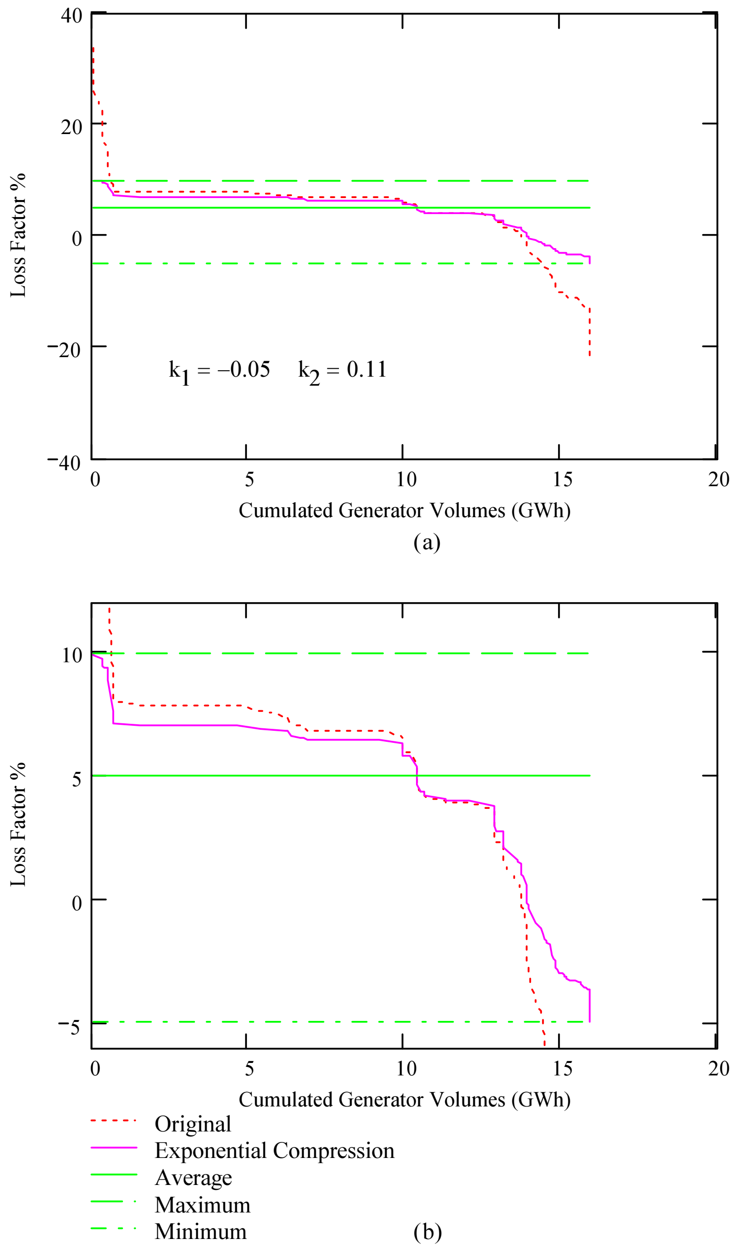


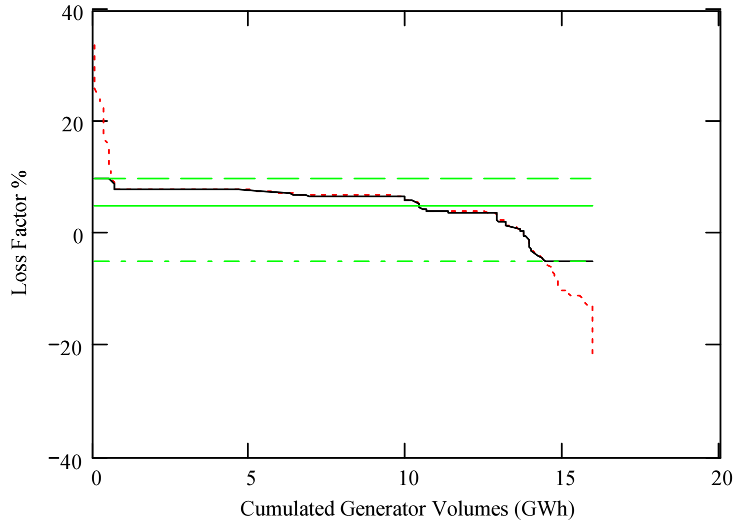
Figure 6 Impact of Exponential Compression Algorithm on Loss Factors

Method 4 Clipping Plus Linear Compression

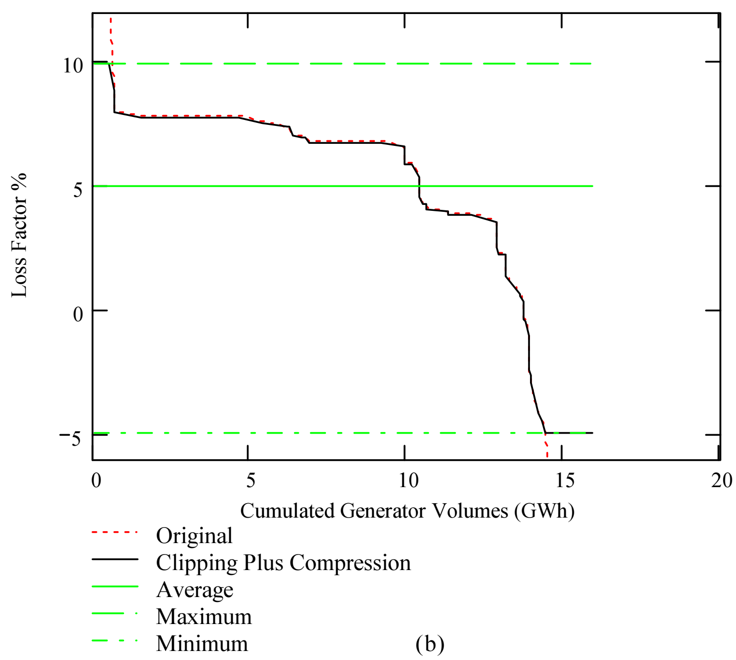
$$
\begin{aligned}
Lf_4(Lf, E, k_{max}, k_{min}) := \; & \text{Losses} \leftarrow ((Lf))^T \cdot E \\
& Lf_{av} \leftarrow \frac{\text{Losses}}{\text{Sum}(E)} \\
& Lf_{max} \leftarrow k_{max} \cdot Lf_{av} \\
& Lf_{min} \leftarrow k_{min} \cdot Lf_{av} \\
& lf \leftarrow \; \left| \begin{array}{l} j \leftarrow -1 \\ \text{for } i \in 0..(\text{rows}(Lf) - 1) \\ \quad \left| \begin{array}{l} lf_i \leftarrow Lf_{max} \;\text{ if } Lf_i > Lf_{max} \\ lf_i \leftarrow Lf_{min} \;\text{ if } Lf_i < Lf_{max} \\ \text{if } (Lf_i \ge Lf_{min}) \wedge (Lf_i \le Lf_{max}) \\ \quad \left| \begin{array}{l} lf_i \leftarrow Lf_i \\ j \leftarrow j + 1 \\ iref_j \leftarrow i \\ lftemp_j \leftarrow Lf_i \\ Etemp_j \leftarrow E_i \end{array} \right. \end{array} \right. \\ lf \end{array} \right. \\
& sf \leftarrow \frac{\text{Losses} - lf^T \cdot E}{\text{Sum}(Etemp)} \;\text{ if } j > 0 \\
& lftemp \leftarrow lftemp + sf \\
& lftemp2 \leftarrow Lf_1(lftemp, Etemp, k_{max}, k_{min}) \\
& \text{for } k \in 0..j \qquad \text{if } j \ge 0 \\
& \quad lf_{(iref_k)} \leftarrow lftemp2_k \\
& lf
\end{aligned}
$$

Lf is a vector of uncompressed but normalized loss factors.
E is a corresponding vector of generator energy volumes.
k_{max} is a scalar that when multiplied by the average loss factor defines the maximum permitted loss factor
k_{min} is a scalar wthat when multiplied by the average loss factor defines the minimum permitted loss factor

Figure 7 MathCAD Implementation of Clipping With Linear Compression Algorithm



(a)



(b)

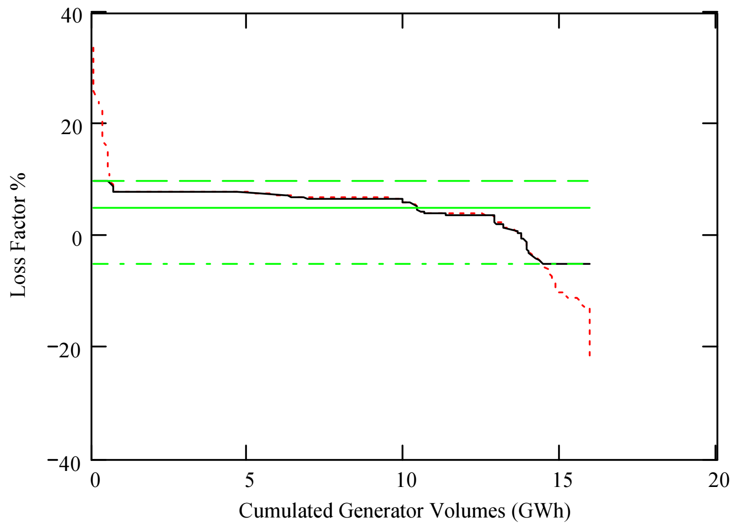
Figure 8 Impact of Clipping With Linear Compression Algorithm on Loss Factors

Method 5 Recursive clipping plus shift factor

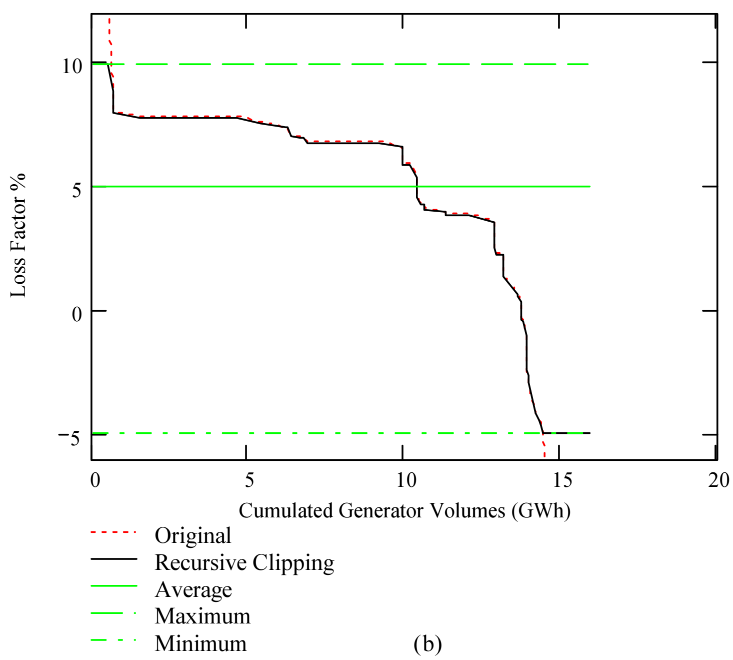
$$
Lf_5(Lf, E, k_{max}, k_{min}) := \left|
\begin{array}{l}
count\_max \leftarrow 50 \\
toler \leftarrow .00001\% \\
Losses \leftarrow Lf^{T} \cdot E \\
Lf_{av} \leftarrow \dfrac{Losses}{Sum(E)} \\
Lf_{max} \leftarrow k_{max} \cdot Lf_{av} \\
Lf_{min} \leftarrow k_{min} \cdot Lf_{av} \\
i_{max} \leftarrow (rows(Lf) - 1) \\
lf \leftarrow Lf \\
count \leftarrow 0 \\
\delta \leftarrow max(Lf) > (Lf_{max} + toler) \vee min(Lf) < (Lf_{min} - toler\,\%) \\
\text{while } count < count\_max \wedge \delta \\
\quad \left|
\begin{array}{l}
lf \leftarrow \text{for } i \in 0 .. i_{max} \\
\qquad \left| \begin{array}{l} lf_i \leftarrow max(min(lf_i, Lf_{max}), Lf_{min}) \\ lf \end{array} \right. \\
SumE \leftarrow \left| \begin{array}{l} SumE \leftarrow 0 \\ \text{for } i \in 0 .. i_{max} \\ \quad SumE \leftarrow SumE + E_i \;\text{ if }\; lf_i < Lf_{max} \wedge lf_i > Lf_{min} \end{array} \right. \\
sf \leftarrow \dfrac{Losses - lf^{T} \cdot E}{SumE} \\
lf \leftarrow \left| \begin{array}{l} \text{for } i \in 0 .. i_{max} \\ \quad lf_i \leftarrow lf_i + sf \;\text{ if }\; lf_i < Lf_{max} \wedge lf_i > Lf_{min} \\ lf \end{array} \right. \\
\delta \leftarrow \left| \begin{array}{l} \delta \leftarrow max(lf) > (Lf_{max} + toler) \vee min(lf) < (Lf_{min} - toler\,\%) \\ \delta \leftarrow \delta \wedge sf \geq 0 \end{array} \right. \\
count \leftarrow count + 1
\end{array}
\right. \\
lf
\end{array}
\right.
$$

Lf is a vector of uncompressed but normalized loss factors.
E is a corresponding vector of generator energy volumes.
k_{max} is a scalar that when multiplied by the average loss factor defines the maximum permitted loss factor
k_{min} is a scalar wthat when multiplied by the average loss factor defines the minimum permitted loss factor

Figure 9 MathCAD Implementation of Recursive Clipping Algorithm



(a)



(b)

Figure 10 Impact of Recursive Clipping Algorithm on Loss Factors

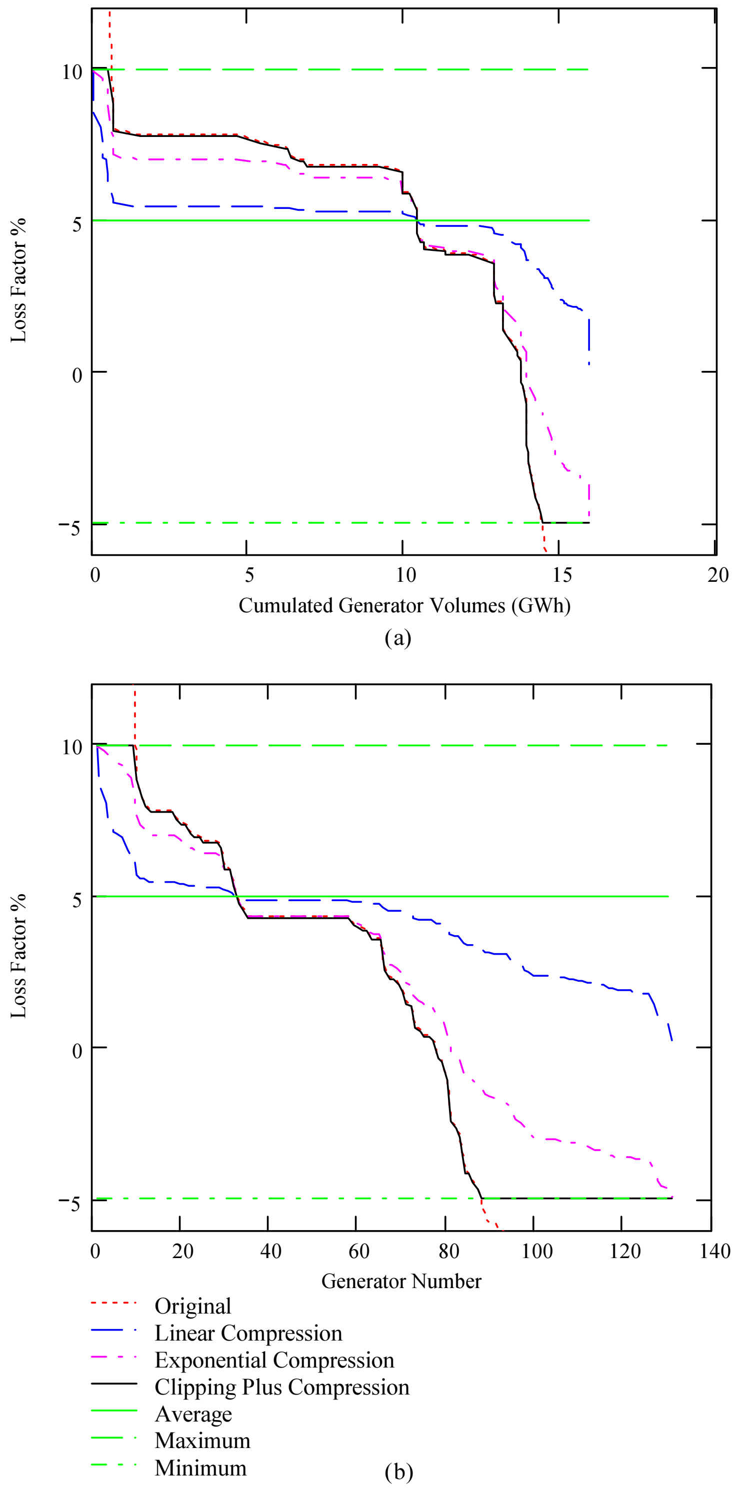


Figure 11 Comparison of Impact on Loss Factors

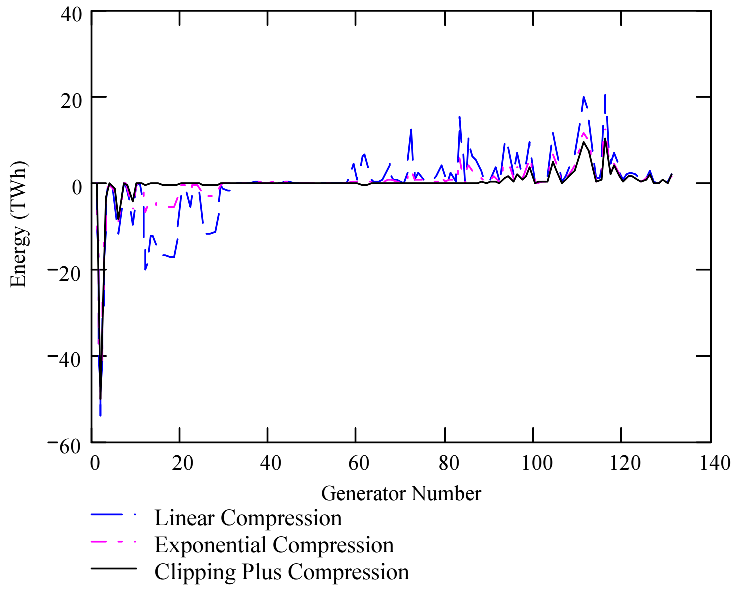


Figure 12 Changes in Individual Generator Loss Allocation

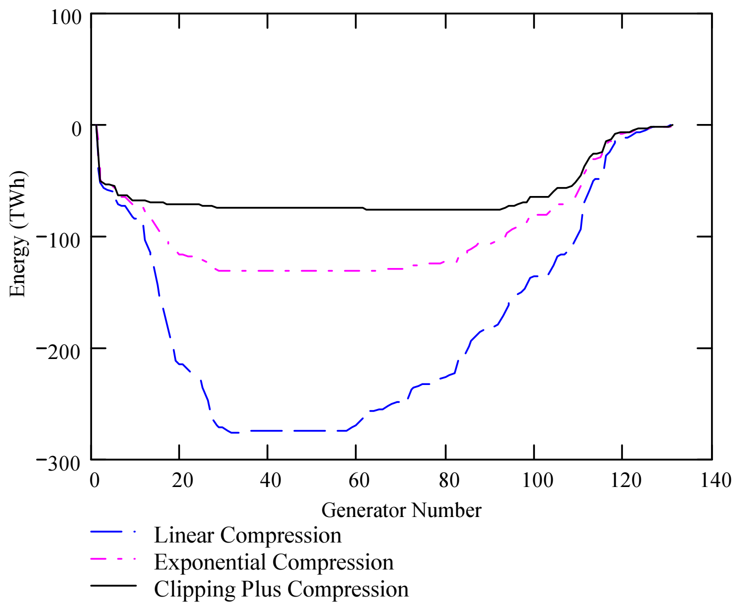


Figure 13 Cummulative Change in Generator Loss Allocation

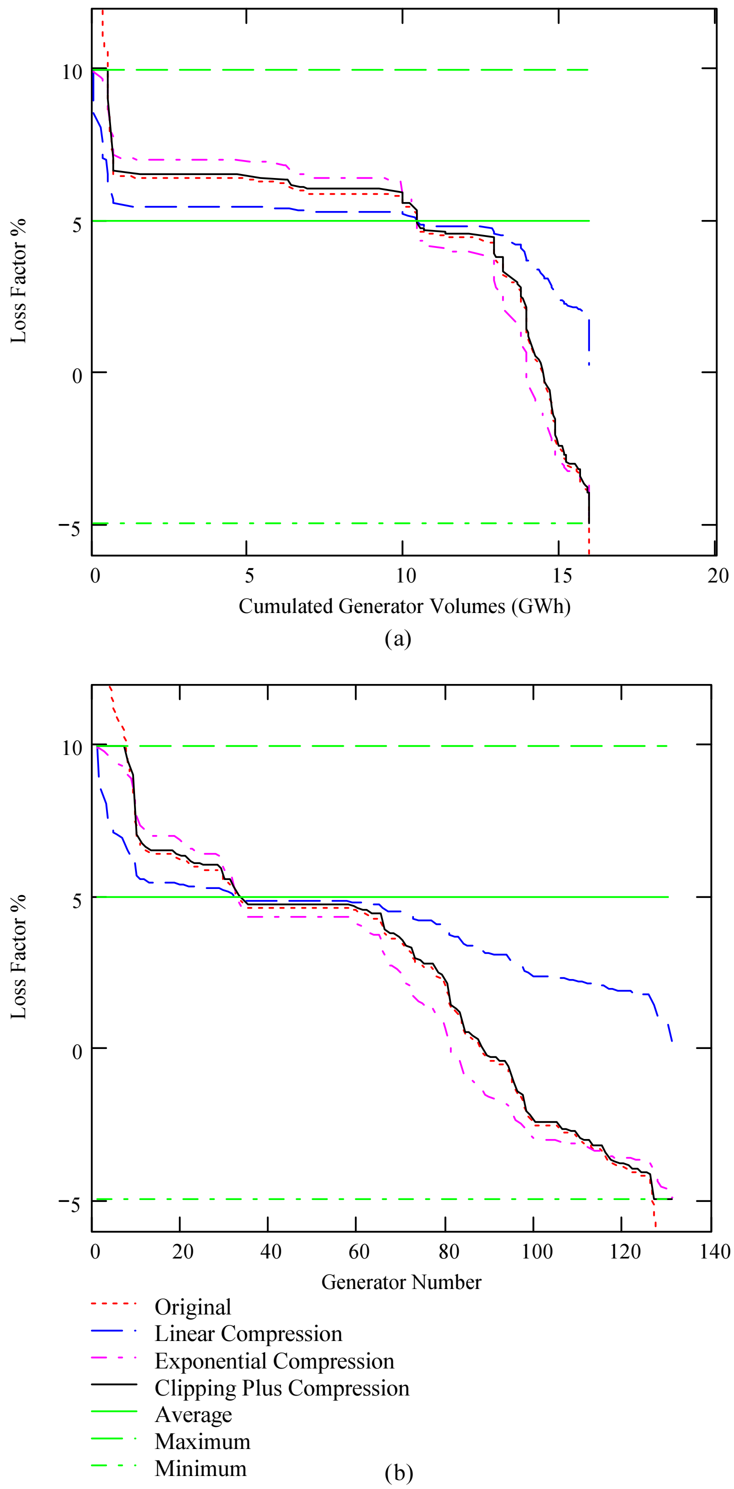


Figure 14 Comparison of Impact on Loss Factors
Sensitivity to Smaller Magnitude Initial Loss Factors

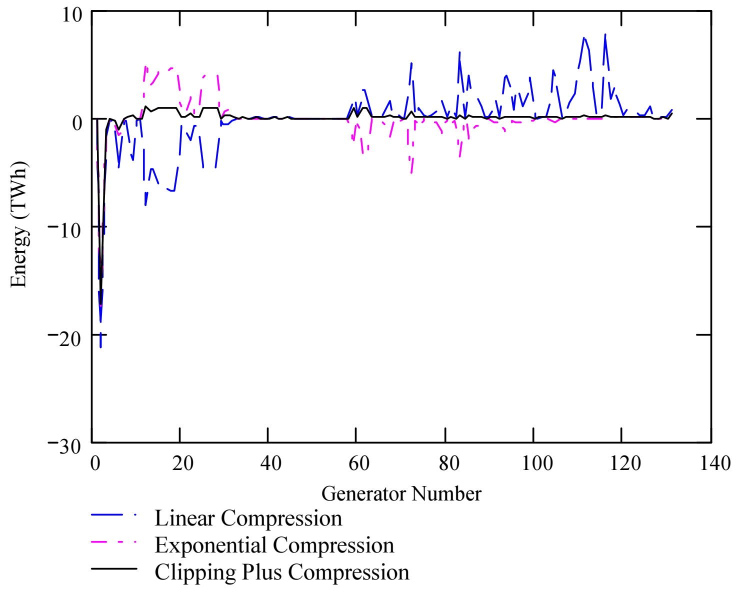


Figure 15 Changes in Individual Generator Loss Allocation Sensitivity to Smaller Magnitude Initial Loss Factors

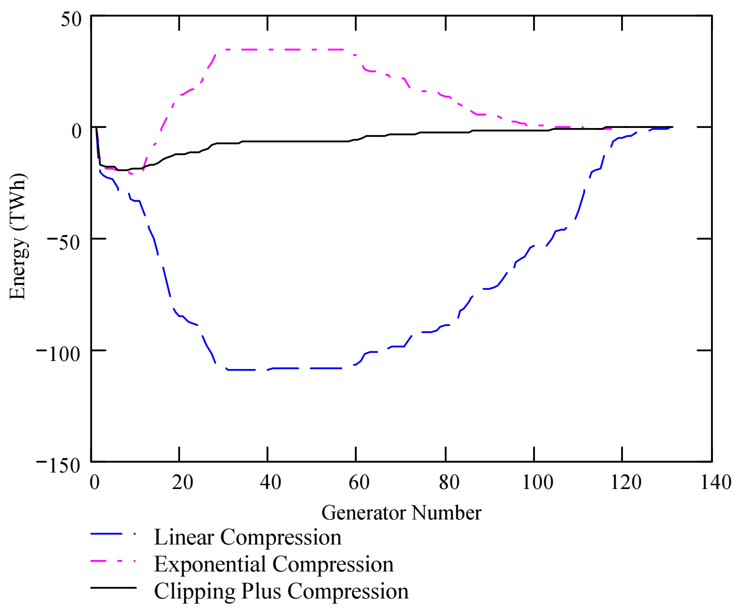


Figure 16 Cummulative Change in Generator Loss Allocation Sensitivity to Smaller Magnitude Initial Loss Factors