IMPACT OF EVOLVING LOAD PROFILES ON DISTRIBUTION SYSTEM ASSETS AND SYSTEM RELIABILITY ASSESSMENT

Jason TAYLOR
EPRI – USA
jtaylor@epri.com

Roger DUGAN
EPRI – USA
rdugan@epri.com

ABSTRACT

Many traditional planning models, methods, and metrics were derived based on traditional load profiles and assumed load growth characteristics. However, increasing levels of distributed energy resources and distribution system automation will intrinsically alter the nature distribution load profiles. As such, it is important to determine the ramifications of these changes to system assets and system reliability as well as the potential limitations and gaps associated with traditional planning tools used to evaluate and plan the system.

INTRODUCTION

Distributed energy resources (DER), advanced system operations, and changing customer behavior can have a marked impact on system load profiles. Many of the changes, such as shifting demand to off-peak periods, represent utility designed operations. Others, such as customer adoption of renewable resources, will intrinsically result in increased variability and uncertainty. New planning methods, models, and metrics will be needed to account for these changes as well as enable planners to evaluate potential resources and controls.

General descriptions for the load profile changes terminology used in this paper align with those often used in demand-side integration [1]. Many of these changes involve either reducing or leveling of the load profile, which is generally beneficial to power system operations. However, failure to account for the evolving load profile changes with increasing load growth can lead to inaccurate deferment calculations, stranded investments, or other unforeseen impacts. The influence of potential load profile changes on asset capacity and system reliability constraints are discussed in this paper along with limitations of traditional planning tools.

FIXED RATING ASSETS

In cases where asset capacity is defined by a fixed rating, the load profile's influence can be gauged simply in terms of changes in the peak demand. If the changes are independent of the load, due to PV generation for example, instantaneous values relating the concurrent behavior of the load and generation can be used to derive a closed form expression relating the maximum acceptable load growth and PV power output. This formulation is valuable as it permits direct calculation of capacity considering the non-coincident nature of the load profiles, while also reducing the computation burden.

Assuming the total demand at a given point in time, *t*, is defined as

$$D(t) = (1+\alpha) * L(t) - \beta * PV(t) \qquad (1)$$

Where:
$D(t)$ is the total demand at time *t*,
α represents load growth,
$L(t)$ is the existing load at time *t*,
$PV(t)$ is the initial PV output at time *t*, and
β represents changes to the assumed PV level.

Replacing $D(t)$ with the loading limit for the asset, *R*, equation (1) can be rewritten such that load growth that can be accommodated at each instance in time, α_t, can then be determined by:

$$\alpha_t = \frac{R+\beta*PV(t)-L(t)}{L(t)} \qquad (2)$$

The acceptable load growth with increasing PV levels, can then be simply determined by finding the minimum value of α_t across all instances in time.

Example values for α_t are plotted in Figure 3-12 using load and PV profiles representing a residential feeder located in the southern United States. Each line in the figure represents the maximum load growth which can be accommodated at a given hour as a function of increasing levels of PV. Given the alignment of the PV output with the profile for the base load, the PV's ability to reduce the peak demand diminishes as the peak is shifted later into the evening hours. Eventually, a point is reached where no additional capacity benefits can be gained with additional PV.

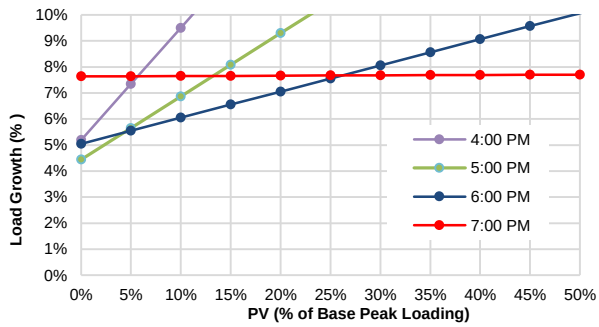


Figure 1. Acceptable Load Growth with Increasing Levels of PV

BEYOND NAMEPLATING RATINGS

In the case of transformers whose ratings are determined using thermal aging assessment methods, such as IEEE standard C57.91 [2], more complex evaluations must be performed considering the transformer's thermal characteristics, operating conditions, as well as the resulting load profiles. As the non-traditional load profile changes due no scale in the same manner as load growth, care must be taken when applying many of the tools used to determine beyond nameplate ratings. In many cases, the load profile changes must be manually created. Similarly, existing generation must be separated from the actual load when using measured load profiles in the calculations.

Sensitivity evaluations using IEEE C57.91 calculations are presented in this section assuming different types of load profile changes. While a deterministic approach is taken in the sensitivity evaluations, probabilistic methods may be necessary to fully evaluate the potential impacts and benefits of many load profile changes on transformer life expectancy, see for example [3]. Additionally, these evaluations are divided between designed operations and variable resources, given the differing nature of the planning challenges. However, capacity planning techniques, such as those presented in [4], which are capable of accounting for the myriad of load profile changes and uncertainties will be need in planning future distribution systems.

Designed Operations

Figures 2 and 3 illustrate changes to the calculated top-oil temperature and loss of insulation life for an example transformer under various load profile changes. Examination of the changes in this manner permits the potential deferment benefits to be calculated and subsequently compared against implementation and operational costs.

Considering the load profile as a design objective, the potential also exists to identify the optimal resource design criteria. For example, the two peak clipping operations are shown in Figures 2 and 3. The first assumes a firm limit where the energy required to perform this operation will increases exponentially with increases in the load growth. The second type of peak clipping represents a case where a fixed amount of generation is installed on the system. In this example, the non-firm scenario only achieves half the additional deferment, compared to the firm limit, but does so with a third of the energy requirement. Thus, a point will likely exist where the cost of implementing this operation outweighs the potential deferment benefits. System planners will need tools to help determine appropriate designs and control schemes along with their performance over changing system conditions.

All of the considered changes act to flatten the load profile, which generally shifts the limiting criteria from the top-oil temperature to thermal aging. If a fixed rating is used in conjunction with the peak clipping operation, significant thermal aging may occur even though the transformer rating and monitored temperatures are never violated. This eludes to the fact that many traditional capacity metrics may not fully encapsulate the system response associated with potential load profile changes. Potential solutions may be to calculate the peak demand that would have occurred without peak clipping or application of a dynamic rating criteria.

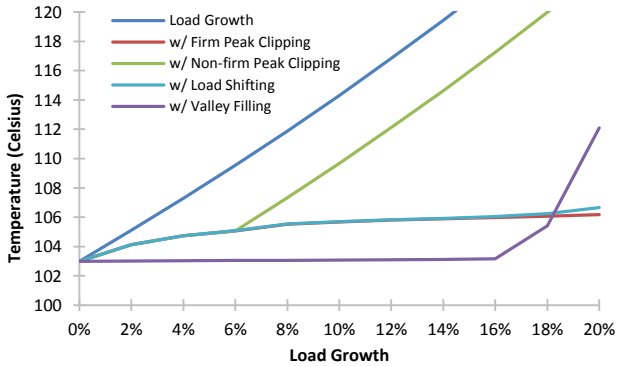


Figure 2. Maximum Top-Oil Temperature with Load Growth

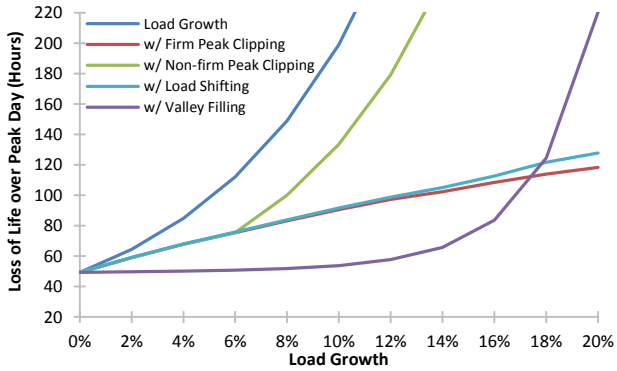


Figure 3. Transformer Thermal Aging with Load Growth

Variable Sources

Profile changes associated with variable and uncertain resources, such as photovoltaics (PV), also pose a challenge to traditional planning methods. Modeled transformer loss-of-life sensitivities to varying levels of PV and load growth are plotted in Figure 4. In these evaluations, the PV is assumed to provide full output during the 24-hour period. Additionally, the level of PV is the ratio of the maximum PV output and the transformer nameplate rating. Similar capacity benefits from PV have been examined in [5] – [6], but these examination treat the amount of installed PV is treated as known value.

As shown, PV can provide additional capacity benefits and at a higher degree compared to cases where a fixed rating is applied. This is to be expected as the PV not only acts to initially reduce the peak but also reduces the loss, and thus

the heat injected into the windings, during the daylight hours. However as thermal insulation loss-of-life is non-linear and the PV output does not fully align with the assumed residential load profile, incremental deferment benefits with increasing levels of PV are again diminishing in nature. Load profiles with higher demands during daylight hours, such as commercial and industrial load shapes, might see greater deferment benefits.

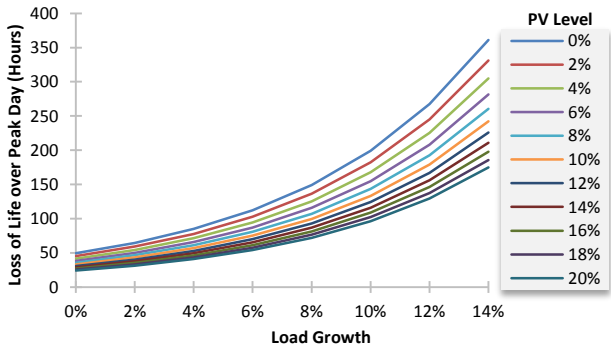


Figure 4. Transformer Thermal Aging with Load Growth and PV

Associated risks given the uncertainties with the PV can be evaluated deterministically using the sensitivity results shown in Figure 4. Using the 0% PV line as a reference, the distance between this line and any other along the x-axis represents the potential risk of underutilized deferment benefits. In contrast, the distance between this line and another along the y-axis represents the maximum thermal aging risk if no PV output was realized. Thus, planning uncertainties can be reduced if the existing PV on a feeder is known and used to evaluate potential deferments; however, potential deferment benefits may go unrealized. Nonetheless, more accurate assessments of the risks require more detailed probabilistic assessments and models.

The impact of PV on the transformers capacity can also be expressed directly in terms on the impact to the calculated thermal ratings with the changing load profile. Figure 5 shows the calculated thermal rating limit with as a function of the PV level. Note that the change in the thermal rating limit is parabolic in nature and would eventually begin to decrease as losses increase with reverse power flows. The figure also shows the change in the energy being transferred across the transformer. This is shown to illustrate that traditional valuation of capacity simply in terms of the peak demand on the asset does not accurately represent the utilization of the asset. While a similar conclusion may be gleamed from changes to the load factor metric, care must be taken when using the metric if the PV results in reversal of the power flows during this period.

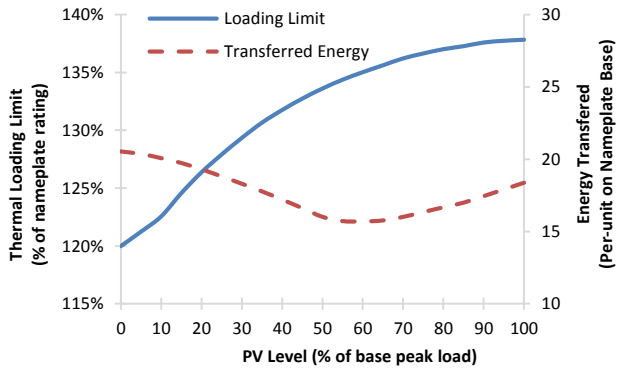


Figure 5. Thermal Loading Limit and Total Energy Delivered during 24-Hour Period

RELIABILITY

Load profile changes also influence system capacity reserved for reconfiguration during contingency events. A risk assessment metric termed Energy Exceeding Normal (EEN), presented in [7], [8], and [9], is used to compare the influence of load profile changes on reliability. The EEN concept is proposed as a risk, or regret, function as a means to determine the relative impact on reliability of different load shape-altering phenomena that occur on the distribution system. This metric is used as standard reliability indices, such as SAIFI and SAIDI, are generally much too coarse to quantify impacts on reliability due to relatively small capacity changes brought on by widely dispersed DER.

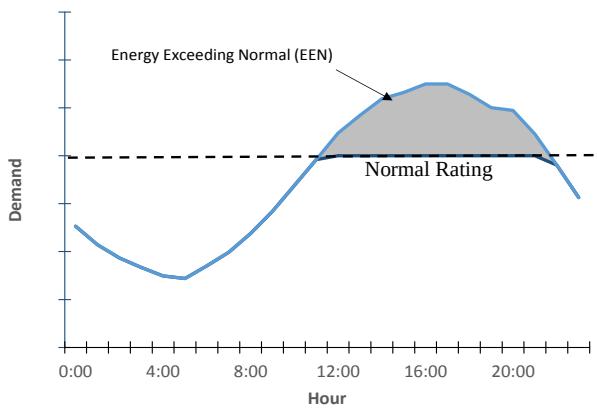


Figure 6. Illustration of the Energy Exceeding Normal (EEN) Concept

EEN is the energy at risk of becoming unserved if a key element in the system fails and there is insufficient capacity to serve the load. As illustrated in Figure 6, EEN is calculated as the total energy that exceeds the defined Normal capacity rating. The Normal rating has various definitions in the power industry. For this analysis, it is ideally the kW maximum load that can be served in a defined planning area while maintaining the capability to serve all the load despite a major power delivery device failure.

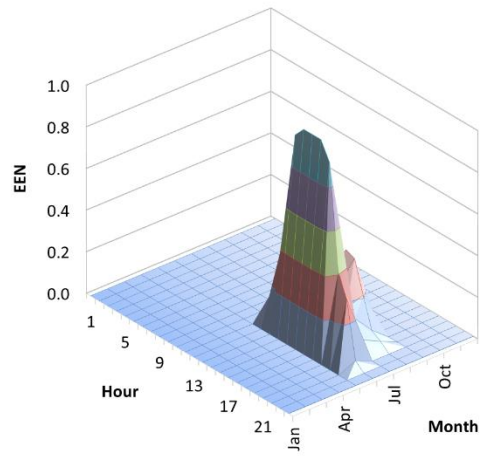
The critical failure might be a substation transformer, circuit breaker, or a cable that would require load to be transferred to an alternate source. Some users of this technique establish the rating as the amount of load that can be transferred with 1 or 2 automatic or remotely-controlled switch operations. Loading above this value would require some customers to become unserved.

Typically, EEN is calculated using either a daily or annual simulation of the load profile.

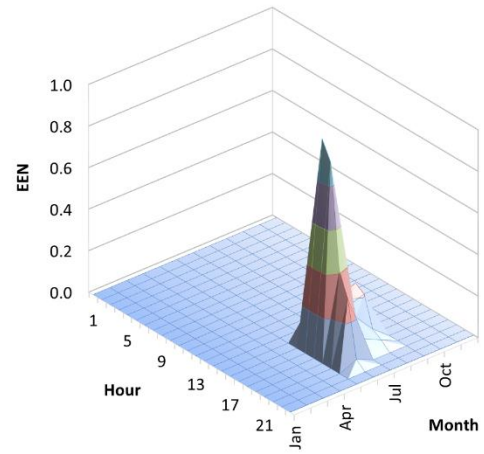
Frequently, backup capacity is reserved in one or more feeders to serve the entire load of an adjacent feeder. This capacity is often given as a percentage of the maximum asset loading. For example, any time the load exceeds 50% of the maximum capacity there is a risk that an outage cannot be covered by simple reconfiguration. The 50% capacity requirement can be overly conservative in some cases and probabilistic assessment techniques, such as [10], have been developed to determine optimal asset utilization while achieving reliability targets. While these methods account for system configuration and load profiles, they do not necessarily accurately represent DER operations and characteristics.

The ability of the PV to reduce EEN is illustrated in Figure 7. The summer peaking load profile is clearly visibility in Figure 7(a) with the EEN contained within July through August and spanning early afternoon to late evening. The PV output, as seen in the Figure 7(b), is can potentially reduce the EEN during many of these hours, thus offering potential security benefits, assuming the PV is not isolated following the contingency event. However given the timing of the PV output, it cannot completely mitigate the EEN.

The total yearly EEN is plotted in Figure 8 for increasing load growth with and without the PV generation. In this example, the PV is scaled to provide a maximum output of 20% of normal rating and this level is fixed as load growth is increased. As with the thermal capacity evaluations, potential upgrade deferment can be gauged by the additional load growth which can be accommodated. However, in this case the defining criteria is the equivalent risk expressed in terms of the EEN. In other words, the reliability benefits provided by the PV may be used to defer system upgrades. The incremental capacity benefits is simply the additional load growth that can be accommodated before same degree as risk is again achieved



(a)



(b)

Figure 7. Annual Energy Exceeding Normal Shape with 0% PV (a) and 50% PV (b)

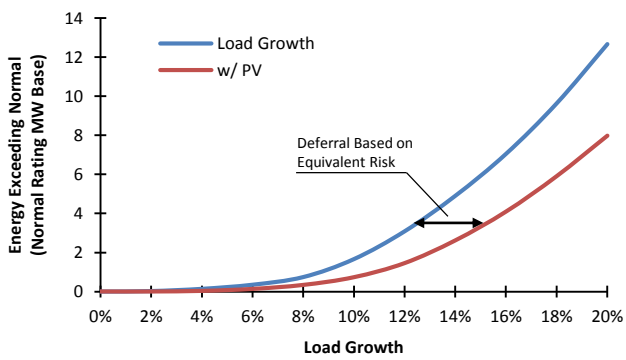


Figure 8. Energy Exceeding Normal for increasing Load Growth with and without PV Generation (at 20% of Normal Rating)

The incremental capacity for this example case is the horizontal difference between the curves in Figure 9. [10]The first thing to note is the PV does not provide any capacity benefits until the normal rating is exceeded.

Hence in this case, the incremental capacity is zero when the load growth is zero. As the load increases, however, the PV is initially able to lower the peak demand below the normal rating threshold until the load growth reaches about 2.0%. As shown, this reduction results in the largest incremental increase to capacity for the example case. As the load continues to increase, the demand during non-daylight hours increases sharply thereby reducing the incremental capacity benefits. At around 8% load growth, the load profile increases sufficient enough during dallying hours, that the incremental capacity benefits again starts to increase.

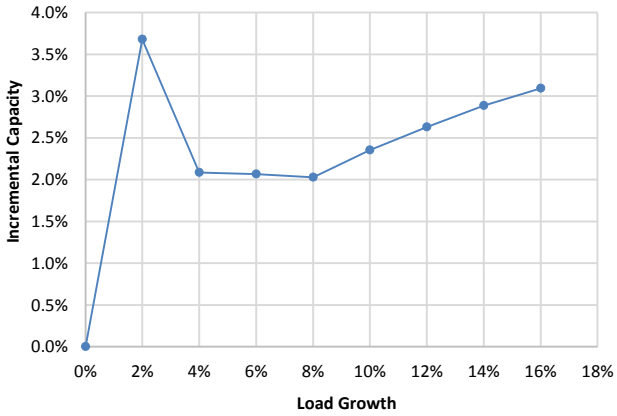


Figure 9. Incremental Capacity with PV vs. Load Growth

CONCLUSIONS

Nontraditional load profile changes potentially offer both thermal and reliability capacity benefits but can pose a challenge to current planning tools designed to support traditional methods. The examples presented here clearly demonstrate the value of being able to perform sequential-time simulations to better capture the impact of variable generation.

While many distribution planners are reluctant to attribute any capacity value to variable generation such as solar PV, the methods described do show a realistic capacity value. Of course, the value depends on the nature of the constraint and the time of day it occurs. There is generally more value when there is a longer thermal time constant for the power delivery system asset under consideration so that it can withstand overloads for a longer time until generation recovers and can offset loading. This is often the case for transformers. If the time constant is short, as it is with lines and cables, less credit can be given.

If the overload occurs at a time when the resource is unavailable, no capacity credit can be offered. This occurs when there is high load at night for heating or for charging EVs and the generation resource is PV. It can also occur at mid-day for wind generation when there may be a lull in the wind pattern.

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