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Transformer Aging Due to High Penetrations of PV, EV Charging, and Energy Storage Applications

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***Abstract*—High penetrations of photovoltaic (PV) systems, energy storage (ES) applications, and electric vehicle (EV) charging may significantly affect the operational constraints of substation power transformers. In high penetrations these applications can flatten a transformer's daily load profile, which minimizes the cooling down period for the unit's paper insulation. Also, because these applications rely upon power electronics to interface with the electric grid, high penetrations can increase the volume of harmonic currents propagating through the distribution system, which can also impact transformer aging. Although the initial impact of PV and ES applications may reduce a unit's peak energy demand, long-term system planning and emergency operating conditions may require derating of existing capacity limits to prevent aging that impacts overall life expectancy. To identify transformer aging characteristics as a function of load profile and harmonic content, the authors developed a transformer transient model based upon the tested attributes of a 50MVA SPX Waukesha transformer and the modeling methods described in IEEE Std. C57.90 and IEEE Std. C57.110. Utilizing the model, the authors identified the relationship between aging, harmonic distortion, and load profile characteristics associated with high penetrations of PV, ES applications, and EV charging.**

***Keywords*- Energy storage, electric vehicle, harmonic distortion, photovoltaic, power transformer, THD**

I. Introduction

High penetrations of photovoltaic (PV) systems, energy storage (ES) devices, and electric vehicle (EV) charging can severely modify the characteristics (shape and harmonic content) of a power transformer's daily load profile, which has historically allowed for a cooling down period at some point during the day. The modified load profile can possibly lead to increased transformer losses and aging when compared to the operation of a power transformer on today's system. In the last 10 years the penetration rates of renewable energy interconnections have rapidly climbed in the US and in other parts of the world, suggesting a more flattened load profile may occur sometime in the near future [1] - [3].

Although the initial impact of renewable energy devices and ES applications may lower the peak energy demanded by power transformers, long-term system planning may require consideration of a reduced cooling period and a load possessing a high harmonic content when developing strategies for identifying normal operating conditions, emergency loading conditions, and transformer replacement options, which may consist of spreading the load of a failed unit amongst the remaining banks at a substation. As the energy demand approaches the pre-established capacity limit of a transformer, aging increases at an exponential rate [4]. For a flattened load profile, this excessive aging occurs for longer periods of time when compared to the traditional cyclic load profile. These extended heating periods can result in an operational life that is significantly less than the anticipated life.

Lowered implementation costs and zero fuel costs have made solar and wind generating facilities more competitive when competing for new system power capacity additions. In fact, since 2006 more than 30% of new power plant capacity in the US has come from wind or solar power [1]. The last two years have seen an increased number of small scale solar installations, suggesting more residential and commercial customers are participating in the renewable energy arena also. Although wind facilities are mostly installed on transmission systems, a good percentage of PV sources are connected to the distribution system where they can greatly affect a substation transformer's load profile between sunup and sundown [5], [6].

A transformer's nightly and early morning load profile characteristics may be changed by high penetrations of ES and early morning EV charging [7], [8], [9], [10]. Utility companies such as Pacific Gas and Electric (PG&E) have already begun implementing time-of-use programs to encourage owners to charge EVs during off-peak periods to prevent excessive increases in "peak" demand. High penetrations of ES applications, which can improve system instability that is created by high penetrations of PV, have the potential to reduce the evening peaking demand by discharging energy that was stored during the day. Combining these load demand effects with those produced by high penetrations of PV can result in daily load profiles that are flatter than those on today's system.

The heat generated from harmonic distortion may also add to the problems caused by the lack of cyclic cooling [11], [12]. Harmonic distortion is generated from electric devices that rely upon power electronics to convert power from AC to DC and DC to AC. These devices include laptops, LED lighting, electronic ballasts, TV's, and of course PV systems, ES applications, and EV charging systems [13]. Although penetration rates are currently low,

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some utility companies have measured harmonic distortion that exceeds the limitation of IEEE Std. 519-2014, which was developed to prevent electric device failure and excessive aging [13], [14]. This means increasing the penetration of wind generating facilities, large and small scale solar sources, ES applications, and EV charging systems will only increase the harmonic distortion on the distribution and transmission systems.

The remainder of this manuscript is split into two sections. Because the flattening of a transformer's load profile is dependent upon the penetration rate of PV systems, ES applications, and EV charging systems, Section II focuses on how these areas are changing across the world due to technology, lowered payback costs, and consumer awareness. The goal was to identify what influences are affecting penetration rates so that a future load profile representing high levels of PV, ES, and EV charging could be estimated.

Section III applies the load profiles developed in Section II to evaluate their effects on transformer aging. The transformer modeling techniques described in IEEE Std. C57.91-2011 and IEEE Std. C57.110-2008 were applied to a SPX Waukesha 50MVA, 115/13.5kV transformer to develop a test model. Because environmental conditions also contribute to the rate of internal heating of a transformer, the analysis utilized the average ambient temperatures in Denver, Colorado, which represents a mild climate in regards to extreme cold and hot temperatures in the US.

The research compared the differences in transformer aging rate (%) for load profiles of today to those exemplifying high penetrations of PV, ES, and EV charging. By varying the peak magnitude of the examined load profiles between and 0.90 – 1.10 per unit, both normal and emergency loading conditions were analyzed. Also, to identify the effects of harmonic distortion, the aging results were analyzed with varying total harmonic distortion levels.

II. Load Profile Evaluation

A load profile is defined as the daily load characteristics of electric demand as a function of time. It is quantified by the term "load factor" (*LF*), which is measured utilizing average demand (L_A) and peak demand (L_P) for a 24hr period, as illustrated in (1). A typical load factor on today's system will range between 0.50 – 0.75 and have the characteristics of those shown in Figure 1, which illustrates the load profile (load factor = 0.71) experienced by a 50MVA substation transformer located in Denver, Colorado in the month of August.

$$LF = \frac{L_A}{L_P} \tag{1}$$

It is obvious from Figure 1 that the transformer only delivers power near its capacity limit between the hours of 12:00PM and 6:00PM. Because of the transformer's insulation design, it will only experience significant aging when its demand approaches its rated capacity limit under environmental conditions comparable to its rated ambient temperature [11]. For a flattened load profile with a peak demand near the rated capacity, significant aging can occur continuously depending upon the environmental conditions.

In accordance with IEEE Std. C57.91, this paper refers to transformer aging as the mechanical degradation of a unit's paper insulation by means of thermal stress that is generated from the current flowing through the windings and leads [4]. Reducing the tensile and dielectric strengths of insulation reduces the materials ability to withstand short circuit stress and associated mechanical movement, which increases the possibility of failure during a downstream fault event. Although paper insulation degradation is also influenced by moisture and oxidation, the insulation degradation calculations described in IEEE Std. C57.91 only focus on the aging induced by heat since moisture and oxidation can be controlled by a transformer's oil preservation system. Therefore, the results of the aging calculations are conservative if transformer oil is not maintained.

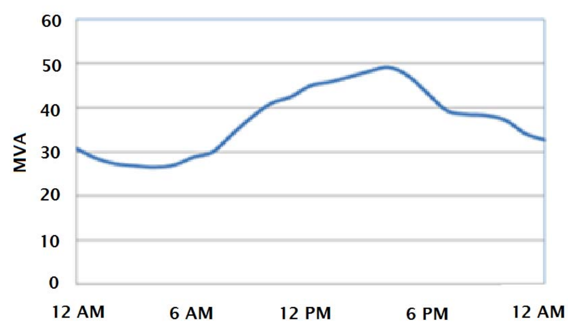

Figure 1: Load profile of 50MVA transformer in August.

A. *Impact of Photovoltaic Systems on Load Profiles*

The impact of PV on the daily load profile is greatly dependent upon the amount of solar energy generated throughout the day on panels connected to the distribution system. The penetration of PV has continued to grow in the last 5 years in both the utility and customer owned arenas [1]. Drivers behind the penetration growth include increased customer awareness regarding reduced carbon emissions and lowered payback costs, which in many cases are boosted by government subsidies.

Utility companies have historically (many still do) built new power plants to account for new capacity. Because economic growth was typically coupled with increased energy demand, the cost of building a new plant was simply spread amongst the old and new customers. The Wall Street Journal recently reported that economic growth has decoupled from energy demand [15]. In short, due to customer awareness of energy conservation, the economy can grow without the overall demand for energy growing.

Unfortunately, balancing authorities (Eastern Interconnection, Electric Reliability Council of Texas, and Western Interconnection) have reported a steady increasing trend for "peak" energy demand in the summer [1]. Because overall sales are somewhat stagnant, the cost of building a new power plant to support new "peaking" requirements may result in an increase in customer rates. When combined with the increased efficiency, zero fuel costs, and lowered installation costs, increasing PV penetration through incentives becomes very attractive. Encouraging utilities and customers to install more solar capacity is one way governments can ensure rates do not drastically increase as system capacity is added.

In 2015, the US reached 20 gigawatts of installed solar capacity, which was a significant increase from the 2013 capacity of 10 gigawatts [2]. In fact, through the first part of 2015, 40% of the newly installed capacity in the US was due to solar. Also, a total of 7.7 gigawatts were planned for total installation in 2015 [16]. As reported by GreenTech Media, most of this was projected to come from the residential market.

Between 2003 and 2013, the globally installed capacity of PV increased from 4 gigawatts to 138 gigawatts. Germany and Australia are the world leaders, although other countries such as Italy, Belgium and Japan have large penetrations [2]. Australia boasts the largest amount of residential PV systems [17]. Strangely, the country has a very low penetration of utility owned or large scale commercial sized systems.

As the penetration of small scale solar sources increases, the daily load profile experienced by power transformers will adjust based upon the available solar energy. Many researchers forecast that increased penetration levels will create a daily load profile with a "duck curve", as illustrated by the projections from the California Independent System Operator (CalISO) in Figure 2 [6]. Although this may be an exaggerated prediction, one cannot deny that middle of the day solar generation will influence transformer load profiles.

Power quality and system stability concerns may limit the amount of "useful" solar generation during the day. One solution to improve operational concerns due to high penetrations of PV is to install sufficient amounts of ES devices (utility and customer owned) throughout the distribution system.

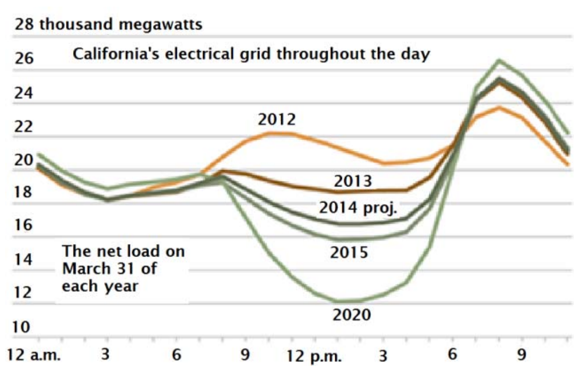

Figure 2: CalISO's projections of load profile augmentations due to increased PV capacity [6].

B. *Impact of Energy Storage Devices on Load Profiles*

In 2013, the Department of Energy (DOE) and Electric Power Research Institute (EPRI) identified ES applications as one of the most important features of the grid of the future [18]. ES applications include pumped storage, lead-acid batteries, sodium sulfur batteries, lithium-ion batteries, and flow batteries, all of which have advantages and disadvantages when it comes to storing and releasing energy.

In fact, due to lowered costs and customer awareness, many in Australia believe ES systems will become "the norm" in the country by 2018 [3]. The payback cost of installing energy storage systems in the country is averaging between 6 - 15 years, depending upon system and electric rates [19]. However, even with payback rates decreasing, the industry still faces obstacles such as monetary compensation schemes, cost competiveness, validated performance of specific systems, and the full acceptance from utilities [19].

One of the obstacles to widespread implementation has been the multi-level control and regulation of energy generation and delivery, which typically consists of national agencies, state commissions, and sometimes independent system operators. However, in the last several years, these same agencies have begun initiating policies to increase ES implementation, which suggests higher penetrations of energy storage devices are on their way [19], [20].

The DOE classifies ES applications into five categories; (1) bulk energy services, (2) ancillary services, (3) distribution infrastructure deferral, (4) transmission infrastructure deferral, and (5) customer energy management services. From the perspective of power transformer operation and aging, the most impactful services are bulk energy services (electric energy time shift, supply capacity) and transmission infrastructure deferral (peak decreasing).

Electric energy time-shift consists of charging an ES system when energy rates are reduced because of low marginal costs, and then discharging them when energy rates are higher. This feature is very attractive to owners of PV systems, since it allows them to store excess energy that was generated during the day. Minimizing the real-time use of solar power can maintain system stability in areas where PV penetrations are high. Large solar integrated systems, such as San Diego Gas & Electric's 6MW facility in Borrego Springs, Ca, will assist in reducing the "duck curve" as illustrated in Figure 3, which further flattens transformer load profiles [21]. Even if a residential customer does not own a PV system, ownership of an ES system could allow them to peak shave if variable energy rates apply in their area.

Connecting large amounts of ES capacity on distribution systems assists in the capital deferral of transmission projects. With 70% of transmission lines and transformers being in service longer than 25 years, moving the energy source to the distribution system reduces the energy supplied by transmission equipment, which essentially prolongs the life of said equipment [2].

Both capital deferment and bulk energy supply applications have the same effect on the load profile experienced by substation transformers; they reduce the peak demand of the load profile. Depending upon time-of-use rates, the early morning characteristics of the load profile may increase due to battery charging. Both of these augmentations, if due to high penetrations, will flatten the transformer load profile as illustrated in Figure 3.

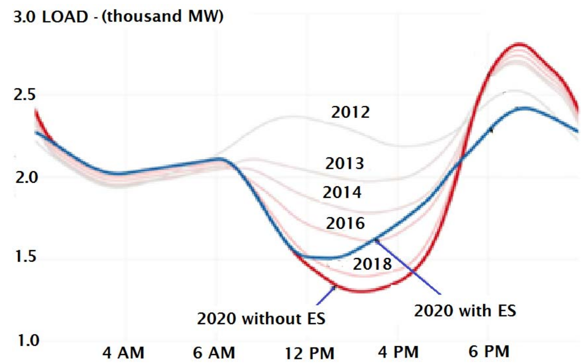

Figure 3: Projections on how ES can affect the daily load profile [21].

C. *Impact of Electric Vehicle Charging on Load Profiles*

Demand side management is defined as the modification of consumer demand for energy through financial incentives. By augmenting or shifting customers' energy demand, utility companies are able to minimize the operation of peaking generator units, defer capital investments in generation, and/or balance system load with generation. Through the use of smart receptacles, direct online appliance connections, or direct customer interaction, household loads are operated based upon time-of-use rates established by the utility company. Moving further into the 21st century, the "household" duty that utilities may benefit the most from load shifting with time-of-use rates is electric vehicle charging.

Uncontrolled EV charging may lead to significant increases in peak demand as the penetration rates of such vehicles continues to grow. Currently, customers are utilizing level 1 and level 2 chargers, which require 120V and 240V sources respectively. A Level 1 charger, which is the most commonly utilized type, can require 11 hours of charging while having a peak demand of 1.4kW [22]. If faster charging is required, customers can utilize a level 2 charger that requires between 1 – 6 hours of charging with a peak demand of 8kW [22]. If left uncontrolled, the most likely time to charge would coincide with the evening peaking period, which already requires the utilization of peaking generating units.

Utilities such as PG&E have already begun adopting time-of-use programs to encourage consumers to charge vehicles during off peak periods [23]. As penetration rates increase, more utilities may be forced to implement similar demand side management programs. In fact, EPRI predicts that even at low growth rates, only 56% of passenger vehicles in 2050 will rely strictly on gasoline [24].

Controlling EV charging with time-of-use rates will flatten transformer load profiles even more. Although time shifting prevents the peak energy demand from increasing, its largest influence is the demand increase during the middle of the night. Typically, the energy demand is low during these hours, which coincides with PG&E's "off peak" period. Moving EV charging to these times results in an upward shift of the load profile.

Transformer load profiles may also be affected by Vehicle-to-Grid (V2G) electric automobiles. As with battery storage systems, V2G vehicles can discharge energy into the electric grid on command [19]. The effect on the typical load profile is the same as peak-shaving ES applications, which further flattens the load profile.

D. *Aggregate Load Profiles*

The combined effects of high penetrations of PV systems, ES applications, and EV charging systems will change the typical load profile experienced by substation transformers. As illustrated in Figure 4, the resulting load profile exhibits a more flattened characteristic with a load factor equal to or greater than 0.90, which is much higher than today's typical maximum value of 0.75. The impact on transformer aging is heavily dependent upon the magnitude of the demand, the transformer's cooling system, transformer construction, and ambient temperature. The relationship between these factors and transformer aging are analyzed extensively in Section III.

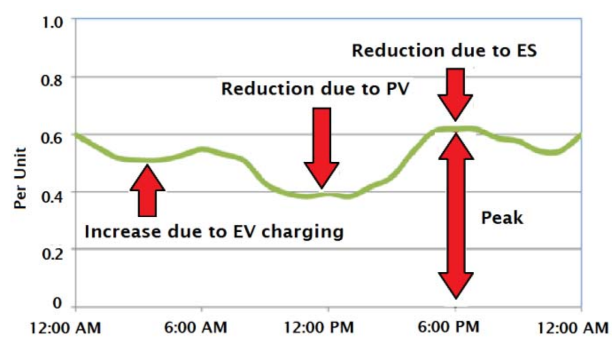

Figure 4: Transformer load profile that represents high penetrations of PV systems, ES applications, and EV charging systems.

III. Transformer Aging Analysis

A. *Impact of Photovoltaic Systems on Load Profiles*

A transformer model based upon the IEEE Std. C57.91-2011 transient model was evaluated to assess how paper insulation aging is affected by flattened load profiles that possess high harmonic distortion. Varying load profiles and levels of harmonic content were applied to the model to evaluate the corresponding aging.

The IEEE Std. C57.91-2011 transient model calculates the loss of life in 30-second increments utilizing demand, ambient temperature, cooling system, winding properties, altitude, tap position, tank configuration, rated losses and oil properties [4]. Because the research goal was to identify how a flattened load profile with a high harmonic content affects transformer aging, derating factors such as altitude adjustment and tap position were ignored so that a true measurement of the load profile effects could be identified. Unfortunately, the IEEE Std. C57.91-2011 model does not account for harmonic distortion, which is known to create additional internal heating. To account for harmonics, the transformer modeling methods described in IEEE Std. C57.110-2008 were applied to the IEEE Std. 57.91-2011 transient model [25].

IEEE Std. 57.91-2011 categorizes transformer losses into three categories: 1. No-load losses (excitation losses) 2. Load losses (impedance losses) 3. Total losses (sum of no-load losses and load losses). Load losses are comprised of I^2R losses and "stray losses", which are determined by subtracting I^2R losses from the measured load losses during testing. Stray losses are comprised of winding losses (conductor strand eddy current losses and circulating current between strands) and component losses (core, core clamps, magnetic shields, and tank).

Testing has proven that winding losses (*Pec*) tend to be proportional to the square of the load current and approximately proportional to the square of the frequency. In short, the heat generated in the windings by harmonic currents will increase at a rate that is the square of the harmonic frequency. This is one of the reasons harmonics can rapidly age transformers.

Because other stray losses are manifested within the core, clamps, and other structural components, the losses will not increase at a rate equivalent to winding losses. IEEE Std. C57.110-2008 recommends a conservative exponent factor of 0.8 instead of the square of the harmonic frequency (h). Therefore, to account for harmonics in the IEEE Std. C57.91-2011 transformer model, a harmonic loss factor (F_{HL}) and a harmonic loss factor for other stray losses (F_{HL-STR}) were applied to winding losses and other stray losses within the model. Equations (2) and (3) illustrate each of the loss factors, which also rely upon the *rms* harmonic current (I_h) and *rms* load currents (I_1).

$$F_{HL-STR} = \sum_{h=1}^{h=h_{max}} \frac{\left[\frac{I_h}{I_1}\right]^2 h^{0.8}}{\left[\frac{I_h}{I_1}\right]^2} \tag{2}$$

$$F_{HL} = \sum_{h=1}^{h=h_{max}} \frac{\left[\frac{I_h}{I_1}\right]^2 h^{2}}{\left[\frac{I_h}{I_1}\right]^2} \tag{3}$$

B. Evaluated Load Profiles

Four load profiles were utilized to assess transformer aging. Load Profiles A and B, which are illustrated in Figure 5, represent typical load profiles experienced by substation transformers today. Profile A possessed a load factor of 0.65, while Profile B possessed a load factor of 0.64. With a peak load demand of 0.90 per unit, Profile A represents the load profile for an adequately sized transformer based upon demand. Hence, the benchmark for assessing normal operating conditions is Profile A with a current total harmonic distortion (THD_I) = 0.0%. Profile B with a peak demand of 1.10 per unit and a THD_I = 0.0% was utilized as the benchmark for emergency operating conditions. Transformer aging due to the other profiles were compared to these benchmark results.

As evident from Figure 6, Profile C represents an almost completely flattened load profile due to high penetrations of PV, ES applications and EV off-peak charging. Profile D, which is illustrated in Figure 7, is identical to Profile C with the exception that it accounts for periods when solar generation is minimized due to weather conditions. The peak value of each profile was varied between 0.60 - 1.10 per unit of the transformer's rated capacity (50MVA) to simulate load growth or the implementation of N-1 scenarios. The load factors for Profiles C and D were 0.835 and 0.911. When varying the peak demand of a profile, all hourly demand values were increased equally so that the load factor was maintained. The THD_I of each profile was also varied between 0 - 30% in order to identify how harmonic distortion affects transformer aging.

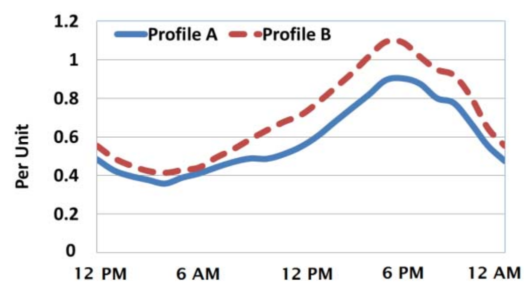

Figure 5: Load Profiles A (benchmark- normal operating conditions) and Profile B (benchmark – emergency operating conditions.

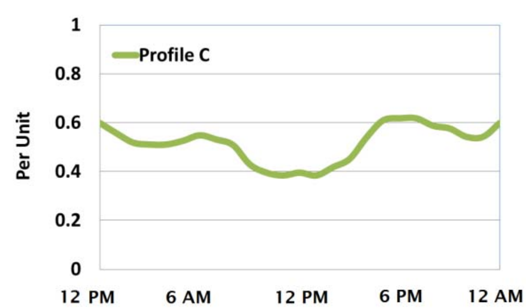

Figure 6: Load Profile C, which illustrates the effects of high penetrations of PV systems, ES applications, and EV charging.

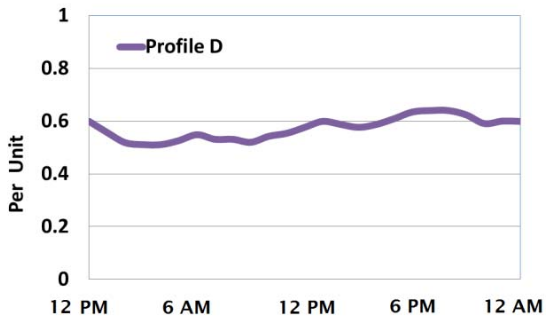

Figure 7: Load Profile D, which illustrates the effects of high penetrations of PV, ES applications and EV charging.

C. *Ambient Temperatures*

Since transformer aging is heavily dependent upon ambient temperature, the loss of life calculations utilized the average hourly ambient temperatures for Denver, Colorado, which was selected because of its mild ambient temperature when compared to locations with extreme cold or hot temperatures. Historical ambient temperature data was retrieved from wunderground.com. For assessment of emergency conditions, the average hourly temperatures for each month of 2014 were utilized. Since most "normal operation" transformer aging occurs in the summer, the average ambient temperatures for August were utilized for this analysis. Because transformer aging that occurs during emergency conditions is a result of exceeding the normal operating conditions capacity limit, this type of aging can occur during any month. Therefore, for the emergency condition analysis, the average monthly ambient temperature of each month of 2014 was utilized.

D. *Transformer Aging Analysis – Normal Operations*

Normal operation is defined as the system condition where a transformer serves a demand that is below its rated capacity. Identifying the required MVA rating of a power transformer is mostly based upon normal operating conditions. For the purpose of the aging analysis, the peak value of Profiles C and D were kept below 0.90 per unit.

As predicted in the Introduction, the results revealed that transformer aging and losses are minimized for Profiles C and D during low demand levels. However, as the energy demand grew, the aging associated with both profiles exceeded those from Profile A, the normal operating condition benchmark. At 60% and 75% peak loading, Profiles C and D resulted in aging that was 60 - 70% below the benchmark profile. However, at a 90% peak demand for both profiles, the aging for Profiles C and D were significantly higher than Profile A, regardless of the level of harmonic distortion. As illustrated in Figure 8 at Point 1 and Point 2, with a 90% peak and THD_I of 10% (typical on today's system) Profiles C and D result in daily aging that is 1.91 and 2.97 times "greater" than the aging experienced with Profile A with a THD_I of 0.0%. These results suggest that capacity derating will be required to maintain the same expected life under these conditions.

For Profiles C and D to expend the same amount of aging as Profile A, regardless of harmonic content, they would have to be limited to peak demands of 82% and 86%, which would be an "estimated" derating factor of 4.5% and 8.9%. For comparisons, the typical derating in Colorado due to altitude is 3.8% - 11.6% (5,280ft – 10,000ft) [4]. These derating estimates held true for current harmonic distortion levels between 0 – 30%. Due to the nonlinear effects of harmonic distortion, it is unknown how much the derating estimates will fluctuate beyond harmonic distortion levels greater than 30%.

Regardless of profile, aging due to harmonics distortion was evident. At low peak demand levels (60 – 75%), aging only varied between 0 – 14% for a THD_I range of 0 – 30%. Because transformer aging is minimal when peak demand is low, the transformer aging factor only varied between 0.0 – 0.05 when compared to the benchmark. However, at higher peaks (90%) the nonlinear increase due to distortion becomes obvious, which is illustrated in Figure 8. For a THD_I range between 0 – 20% at a peak demand equaling 0.90, the aging for Profiles C and D increases between 23 – 25%. When compared to the benchmark, the aging factor for this level of THD_I and peak demand results in aging factors (multiples) of 2.04 and 3.21 for Profiles C and D. When THD_I increased to 30% at a 0.90 per unit peak, the nonlinear characteristics of harmonic distortion are evident as aging factors for Profiles C and D increase to 2.93 and 4.92. These results suggest harmonic distortion must be considered when derating substation power transformers if THD_I is greater than 10%.

Identifying derating requirements should be based upon 1) preventing the peak demand from reaching damaging conditions and 2) minimizing the accrued annual aging. Transformer damage includes extreme aging of the paper insulation and bubble formation within the mineral oil, which lowers its dielectric strength. The lowered ambient temperatures in the winter and fall help to minimize aging. In fact, the aging that occurs in these periods may be negligible when compared to the aging that occurs in the summer. Therefore, it is quite possible a transformer can experience loading above its nameplate rating for a given period, but still operate sufficiently for its full expected life because of the little amount of life that is expended during off peak periods.

Existing methods for derating substation power transformers that account for seasonal and daily on and off peak periods can be utilized for derating under these flattened load demand and harmonic conditions. The key to performing these assessments is to ensure that the load profile and heat generated from harmonics is included the analysis. If derating procedures are based upon IEEE Std. C57.91-2011, then the harmonic method described in IEEE Std. C57.110-2008 can be utilized to estimate the harmonic effects, as were done in the calculations performed in this document.

E. *Transformer Aging Analysis – Emergency Operations*

Due to unexpected system failures, power transformers are sometimes required to serve loads that are in excess of

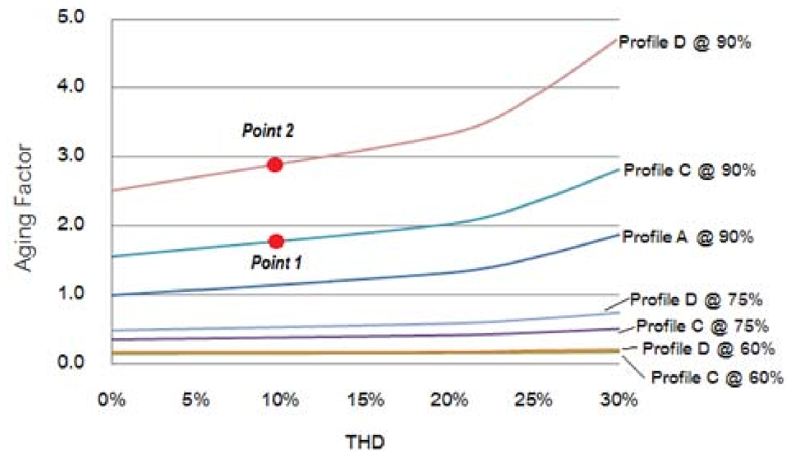

Figure 8: A comparison of transformer aging for future load profiles and the typical load profile experienced by transformers today in the month of August.

their normal operating capacity limit. System failures can include distribution feeder failures, substation bus equipment failures, and transformer failures. Many times the need to serve customers far outweighs the desire to prevent increased aging of the transformer. For these cases, emergency condition capacity limitations are established. For the transformer analysis, Profiles C and D were compared to Profile B, which was considered the benchmark for this evaluation because of its resemblance to emergency loading condition on today's transformers.

The results revealed most of the aging that occurs during emergency conditions will be caused by harmonic distortion and not by the flattened load profile. With a THD_I between 0 - 10%, the aging for Profiles C and D were almost identical to Profile B (benchmark) without harmonic distortion. However, the nonlinear relationship between aging and harmonics is evident as THD_I increases beyond 10%. In fact, during the summer months, the aging that occurs due to Profile C with a current distortion of 30% is more than triple the aging that occurs without harmonics, as illustrated in Figure 9. These results suggest it is possible that existing emergency condition ratings can be maintained if harmonic distortion during peaking periods is kept below 10%. Considering that THD_I values near 10% have already been measured at utilities, harmonic mitigation steps should be taken to minimize derating requirements as the penetration of renewable energy sources and ES applications increase.

IV. CONCLUSION

As we move further into the 21st century, the increased implementation of photovoltaic systems, energy storage applications, and electric vehicle charging may significantly

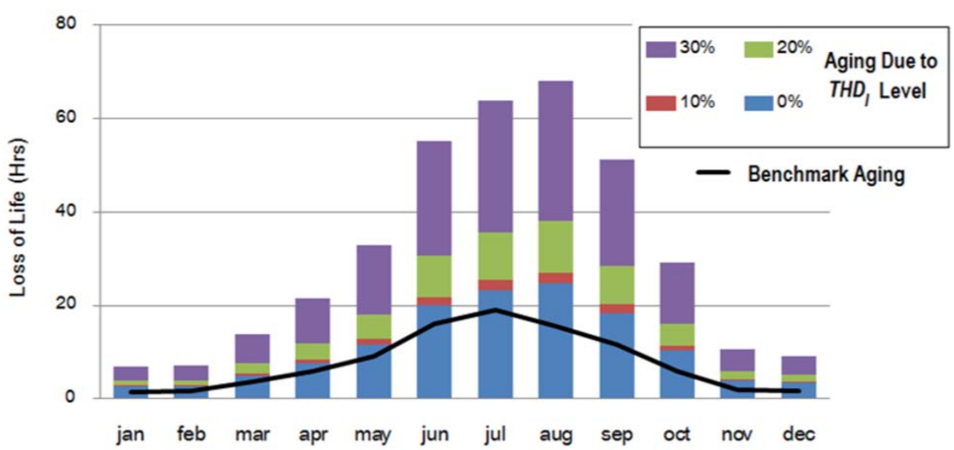

Figure 9: Transformer aging as a function of THD_I and monthly climate changes for Profile C.

change how utilities identify the peak capacity of their substation power transformers. High penetrations of these programs and devices can lead to a flattened load profile with a high harmonic content, which can lead to increased aging.

Analysis of the effects of harmonic distortion upon transformer aging suggests that THD_I levels above 10% will drastically increase the aging during emergency operating conditions. During normal operating conditions, the aging is driven more by the almost constant energy demand. For this flattened load profile condition, the analysis revealed that a 10% capacity derating may be required to maintain the expected life of the unit. The constant energy demand also influences the amount of load losses that are expended, whose daily accumulation can increase by 1.5 when compared to those expended today for a load profile with an identical peak demand. Understanding how these system changes are influenced by the penetration of PV system, ES applications, and EV charging can help utility companies identify transformer capacity limitations during emergency and normal operating conditions, to identify harmonic distortion mitigation procedures to prevent equipment failures, to forecast carbon emission impacts, and/or to identify IEEE Std. 519-2014 violations.

V. References

[1] Ferrell, John, "Beyond utility 2.0: part 2 "the present", [online]. Available: https://ilsr.org/beyondutility-2-0-part-2-the-present

[2] Electric Power Research Institute, 2014, "The integrated grid: Realizing the full value of central and distributed energy resources" [online] Available: http://energy.gov/sites/prod/files/2015/03/f20/EPRI%20Integrated%20Grid021014.pdf

[3] Macdonald-Smith, A., 2015, "Energy storage tipped to drive revolution in power grids," [online] Available: http://www.smh.com.au/business/energy/energy-storage-tipped-to-drive-revolution-in-power-grids20151005-gk1ypb.html

[4] IEEE C57.91-2011, "IEEE Guide for Loading Mineral-oil Immersed Transformers."

[5] California ISO, 2010, "Integration of Renewable Resources: Operational Requirements and Generation Fleet," [online] Available: https://www.caiso.com/Documents/IntegrationRenewableResourcesOperationalRequirementsandGenerationFleetCapabilityAt20PercRPS.pdf

[6] California ISO, 2014, "What the duck curve tells us about managing a green grid," [online]. Available: https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

[7] Singh, M., Kumar, P., Kar, I., "A multi charging station for electric vehicles and its utilization for load management and the grid support," IEEE Transactions on Smart Grid, vol. 4, issue 2, pp. 1026-1037, May 2013.

[8] Zhanbo, X., Xiaohong, G., Qing-Shan, J., Jiang, W. Dai, W., Siyun, C., "Performance analysis and comparison on energy storage devices for smart building energy management," IEEE Transactions on Smart Grid, vol. 3, issue 4, pp. 2136-2147, Dec. 2012.

[9] Xiao, L., Ka Wing, C., "Real-time scheduling of electric vehicles charging in low-voltage residential distribution systems to minimize losses and improve voltage profile," IET Generation, Transmission, and Distribution, vol. 8, issue 3, pp. 516-529, Mar. 2014.

[10] Sexauer, J. M., McBee, K.D., Bloch, K. A., "Applications of probability model to analyze the effects of electric vehicle chargers on distribution transformers," IEEE Transactions on Power Systems, vol. 28, issue 2, May 2013.

[11] McBee, K. D., Simões, M. G., "General smart meter guidelines to accurately assess the aging of distribution transformers," IEEE Transaction on Smart Grid, vol. 5, issue 6, Nov. 2014.

[12] Munir, S., Yun Wei Li, "Residential distribution system harmonic compensation using PV interfacing inverter," IEEE Transactions on Smart Grid, vol. 4, issue 2, May 2013.

[13] McBee, K. D., Simões, M. G., "Evaluating the long-term impact of continuously increasing harmonic demand on feeder-level voltage distortion," IEEE Transactions on Industry Application, Vol. 50, Issue 3, May 2014.

[14] IEEE 519 "Recommended Practices and Requirements for Harmonic Control in Electric Power Systems," IEEE, New York, 1992.

[15] Smith, R., "Electric utilities get no jolt from gadgets, improving economy," Wall Street Journal, July. 2014 [online] Available: https://drive.google.com/file/d/0B8Hmrr6Ve2pvaWk3VGhPZXZSMFk/view

[16] Munsell, M., 2015, "Installing 1,393MW of PV in Q2 2015, US solar market surpasses 20GW," [online] Available: http://www.greentechmedia.com/articles/read/installing-1393-mw-of-pv-in-q2-2015-us-solarmarket-surpasses-20-gw

[17] Gifford, J., 2015, "Australia leads world in residential solar penetration," [online] Available: http://www.pv-magazine.com/news/details/beitrag/australia-leads-world-in-residential-solarpenetration_100021291/#

[18] Department of Energy, "Grid Energy Storage," [online] Available:http://energy.gov/sites/prod/files/2014/09/f18/Grid%20Energy%20Storage%20December%202013.pdf

[19] Bloomberg New Energy Finance, 2014, "BNEF's Goldie-Scot on electric cars driving energy storage investor return," [online] Available: http://about.bnef.com/video/bnefs-goldie-scot-electric-cars-drivingenergy-storage-investor-returns/

[20] St. John, J, 2015, "The reality of energy storage policy is different from what solar-storage vendors expect," [online] Available: http://www.greentechmedia.com/articles/read/Energy-Storage-Policy-RealityVersus-Solar-Storage-Vendor-Expectations

[21] Munson, K., 2015, "Integrated energy storage: an answer to addressing the Duck Curve," [online] Available: http://www.renewableenergyworld.com/articles/2015/04/integrated-energy-storage-ananswer-to-addressing-the-duck-curve.html

[22] Energy Star, 2013, "Energy Star market and industry scoping report electric vehicle supply equipment (EVSE)" [online] Available: https://www.energystar.gov/ia/products/downloads/Electric_Vehicle_Scoping_Report.pdf

[23] Electric Power Research Institute, 2007, "Environmental assessment of plug-in hybrid electric vehicles" [online] Available: http://mydocs.epri.com/docs/CorporateDocuments/SectorPages/Portfolio/PDM/PHEV-ExecSum-vol1.pdf

[24] Crow, M., Crow, M., 2014, "Economic scheduling of residential plug-in (hybrid) electric vehicle (PHEV) charging," [online] Available: http://www.mdpi.com/1996-1073/7/4/1876/htm

[25] IEEE C57.110-2008, "IEEE Recommendation Practice for Establishing Liquid-Filled and Dry-Type and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents."

VI. Biography

Kerry D. McBee received his Ph.D. from Colorado School of Mines, Golden, Colorado, in 2014, which is where he also received his B.S. in 1999. He received his M.S. in Electric Power Engineering in 2000 from Rensselaer Polytechnic Institute, Troy, New York. He is an Assistant Professor with California State University, Fresno, where he is establishing research and education activities in the development of smart grid functionality/implementation, power quality and forensic engineering. During his engineering career he has been affiliated with NEI Power Engineers, Xcel Energy and Tesla Power Engineers, LLC.