Secondary System Voltage Drop Considerations

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Generally, most secondary systems are radial-designed except for specific service areas (downtown areas, business districts, and some military and hospital installations) where reliability considerations are far more important than cost and economic considerations. The secondary radial systems include distribution transformers, secondary main conductors, and service conductors. The secondary facilities can be overhead or underground. The secondary design (size of transformer, secondary conductor, and services) objective is to minimize costs while still meeting the Utility's standard guidelines.

The goal for each secondary design is to provide satisfactory performance typically with voltage-drops less than 3.33% or 4.0 Volts on 120 V Base at minimum costs. There is a variety of system designs for one distribution transformer; some serve only one customer having only one span of conductor, while others serve six to ten customers with multiple secondary connections. In practice, some voltage-drops maximums exceed design objectives (e.g., greater than 3.33% drop).

The following provides a methodology describing how to estimate the number of potential secondary connections that may have voltage drops greater than any design guideline (i.e., greater than 4.167% drop or 5 Volts). This information will help determine the impact of lowering the minimum allowed primary voltage from 120 V to 119 V. in the field.

The ANSI C84.1 defines the maximum and minimum voltage favorable zone "Range A" for service entrance voltage. In addition, the voltage level for a tolerable zone is provided. The favorable zone includes the majority of the existing operating voltages, and the voltages within this zone provide satisfactory operation of the customer's equipment.

US RUS (formally REA) Bulletin 169-4 interprets the ANSI C84.1 Standard as follows: "The electric system shall be so designed and operated that most service voltages are within the limits specified for Range A. The occurrence of service voltage outside of these limits is to be infrequent". The RUS Bulletin 169-4 provides voltage levels and limit values in accordance with ANSI C84.1 and are based on the regulator voltage band width not exceed two volts on a 120-volt base, voltage values used are at the center of the voltage regulator bandwidth (e.g. ±½ BW), and all voltage regulators have properly set and functioning line drop compensators. The RUS minimum normal operating primary voltage is 118 volts and the minimum service voltage is 114 Volts on a 120 V base. The distribution transformer (primary to service delivery connection to consumers' wiring (meter or entrance switch) is 3.33% or 4.0 Volts on 120V base.

Customer Coincident Loading - Considerations

Utility voltage guidelines are applied to a large range of customer connection possibilities. As more customers are served by one transformer, the individual customer maximum loading coincident with the system load becomes less. For example, see the load data example below.

		Typical 30 min annual maximum diversified demands* (kVA per customer)		
No of customers being served from one transformer	*CF*	Class 1	Class 2	Class 3
1	1.0000	18.0	10	2.5
2	0.7500	13.5	7.5	1.9
4	0.6250	11.3	6.3	1.6
12	0.5416	9.7	5.4	1.4

*Turan Goren, *Electric Power Distribution System Engineering*, Second Edition, New York, CRC Press, 2009

As the number of customers served by a transformer or secondary conductor increases, the effective load impact on capacity requirement is decreased. Ideally, the coincident factor (*CF*) is determined at each level of the distribution system and is a function of the total system coincidence and the number of similar loads. The average maximum diversified demand (AMDD) for any level is determined by multiplying the average maximum demand (AMD) for customers or components by *CF*. The coincident factor formulation used to determine the impact of customer or component loads on the next higher level in the distribution system where N is the number of parallel components given below. A typical formulation described by "IEEE Standard 141(TM)-1993, *IEEE Recommended Practice for Electric Power Distribution for Industrial Plants*, Red Book." to determine coincident factor *CF* as a function of the number of customers connected N is given by:

$$CF_N = CF_{TOTAL} \cdot \left[1 + \frac{1}{N}\right] \qquad \text{Eq 1}$$

Where, CF_{TOTAL} is the total system coincidence factor (e.g. 0.50)

The typical distribution secondary voltage drop is highest during customer peak loading periods. If distribution system modeling includes secondary modeling, the voltage drop is the absolute difference between voltage magnitude on the high side of the distribution transformer minus voltage at the lowest voltage customer. It is not the arithmetic sum of the transformer voltage drop and the secondary conductor voltage drop. The determination of voltage drop requires the use of coincident factors applied at each level of equipment.

Customers have peak demand at different times, and this is why capacity and voltage drops are calculated by taking coincidence factors into account. It is very unlikely that the transformer's customer coincident peak load will be sustained for 30 minutes or longer and occur at the same time as the minimum primary voltage (at peak load conditions). Coincident factors and typical customer load patterns can be obtained from residential load surveys.

Secondary Voltage Drop Normal Distribution - Example

The determination of expected voltage drops for the secondary systems involves a variety of random variables (i.e., number of customer connected to one transformer, common service connections, maximum non diversified customer loads, coincidence probabilities, and physical design attributes.) These variables suggest a random distribution of coincidental secondary voltage drops. For example, given maximum voltage drop constraint of 5% or 6 Volts, the diversified average voltage drop across a large number of transformer populations may be only 2.5% while the maximum voltage drop observed may be greater than 5%.

The following is a real world example (from a 2011 EPRI Green Circuits Study in Jackson Michigan) of secondary voltage drops on one feeder for an actual utility illustrates the random nature of the secondary system voltage drops during peak load conditions. Load Flow simulations were performed and included the modeling of distribution transformers, secondary conductors, service conductors, and spot coincident customer loads. The example feeder served 727 customers with 418 distribution transformers/secondary systems. The load flow analysis included determination of voltage drops for each secondary system. Figure 1 shows the probability distribution for transformer/secondary voltage drops during peak conditions. The average secondary voltage drop at peak conditions is 1.9% (2.3V) with a Std. Dev. of 2.2%. There are 33 (7.9%) transformer/secondary systems that have voltage drops greater than 5.0% (6.0V). There are 42 (10.0%) transformers with voltage drops greater than 4.2% (5.0V) needed to maintain 114V ± ½ BW service voltage if the primary voltage is 119V ± ½ BW. The maximum voltage drop is 15.0% or 18.0V.

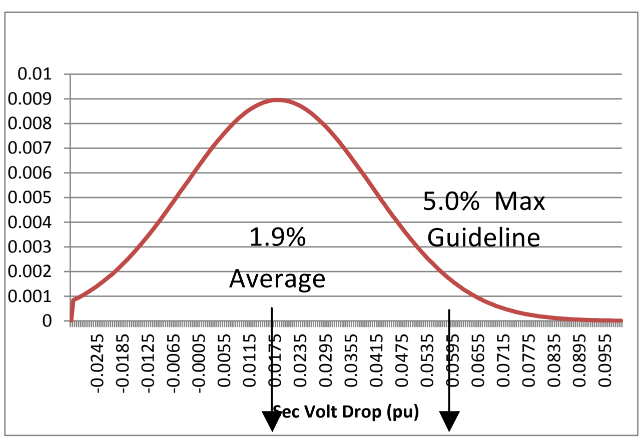

Figure 1 - Distribution transformer/secondary max voltage drops

The secondary systems are heavily loaded with an average distribution transformer utilization of 220% of rated kVA at peak load conditions. This example illustrates poorly managed, inefficient, and designed secondary systems.

In addition to evaluating maximum secondary voltage drops, the load flow assessment determined the secondary low voltages during peak load conditions. The minimum primary voltage is 119.8 Volts. There are 24 transformer/secondary installations that have customer service voltages less than 114V ± ½ BW at peak loading conditions. Figure 2 shows a scatter diagram that illustrates the number of transformer/secondary systems that are below 114V ± ½ BW. The average is service voltage is 118.8V. The minimum voltage is 103.0V during peak conditions. These customer low voltages are included as part of the 33 secondary systems having greater than 5% voltage drop at peak conditions.

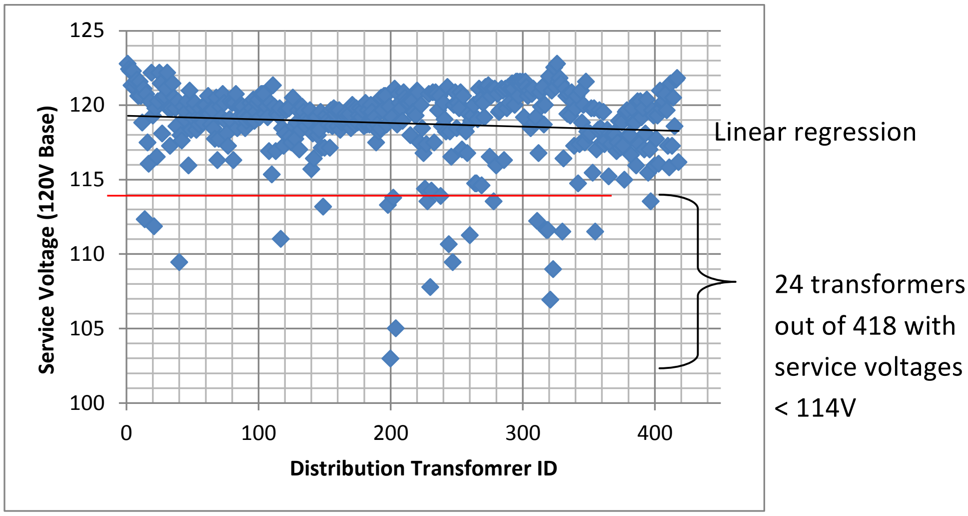

Figure 2 - Lowest service voltage for each distribution transformer/secondary

This real world example illustrates the random nature of secondary system voltage performance during peak load conditions.

Normal Distribution Probability Function – Basics

The Normal Distribution function is defined as

$$f(X) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left(\frac{x-\sigma}{\sigma}\right)^2}$$

Where,

σ = Std Dev and x = variable.

Given σ, the plot of $f(X)$ is a bell shaped curve similar to the curve shown in Figure 1. The total area under the curve represents 100% probability. The probability of an event occurring between X_1 and X_2 is the area under the Normal Distribution curve from X_1 and X_2 given σ. The values of X can be converted to a Z Score which is the number of σ separation from Mean $\overline{X}$. The Normal Distribution function is symmetrical allowing the calculation of probability by using the *Z* Score from Table 1. The probability for the positive half of the distribution function where $\overline{X}$ is zero is

0.50 or 50%. For example, the probability of having a value of $X < 1.88\ \sigma$ is 0.5000 + 0.4699 = 0.9699 or 97.0%. The probability of having $X > 1.88\ \sigma$ is therefore 3.0%.

Secondary Voltage Drop Normal Distribution –TPUD Wilson River Feeder 63 Example

Consider Wilson River feeder 63 with 1136 customers served from 246 transformers (4.6 customers per transformer) with an assumed 120 Volts ± ½ BW on the high-side of each distribution transformer. The Tillamook PUD distribution system is better designed, monitored, and maintained than the example given above. The TPUD maximum allowed maximum voltage drop design is 5.0% or **6.0 Volts**. It is also assumed that there are few customers with maximum secondary voltages drops greater than the 5.0%. Customers who exceed 5.0% secondary drop are assumed to have lower than median 114 Volts ± ½ BW at their service. This feeder example shows the probability of the number of customers (or transformers) that are likely to have voltage drops greater than 4.167% or **5.0 Volts** and service voltages less than 114 Volts ± ½ BW if the primary voltage is lowered by 1.2 Volt from 120V to 119V.

Although it is unlikely that there are any customers with greater than 5% voltage drop, it is assumed here that **2.0%** or 22.7 customers (4.9 transformers) have maximum voltages greater than the existing **5.0%** limit. The average maximum voltage drop is assumed to be **1.9%** based on the field experience in the example given above. The value of Z that yields 98.0% probability or 0.5000 + 0.4803 is Z=2.06. If $\overline{X}$ =1.9% and upper limit is X_1=5.0%, then $\sigma = (X_1 - \overline{X}) / Z$ = **1.505%**.

Given the assumptions above, if the design limit is reduced to 4.167 % or **5.0 Volts**, the probability of customers having maximum voltage drops greater than the 4.167% limit is determined with σ =1.505%, $\overline{X}$ =1.9%, and upper limit X_2=4.167%, then $Z = [(X_2 - \overline{X}) / \sigma]$ = 1.51. Entering this value into the Z Score Table yields a probability of 0.5000+0.4345 or 93.45% of customers with less than 4.167% voltage drop. The number of customers having greater than 4.167% voltage drop is 100% – 93.45% or **6.6%**. Therefore, the number of customers having greater than 4.167% voltage drop is 75.0 (or 16.3 transformers).

The true impact is <u>much less than 16.3</u> transformer secondary systems having a median service voltage less than 114V ± ½ BW because not all of the high-side transformer voltages are at 119 Volts. The number of transformers impacted can therefore be assumed to be 50% or approximately **8** transformers.

If and when it is determined that customer has lower than a median voltage of 114 Volts, the transformer taps can be changed, transformer can be replaced, a new transformer added. It is recommended that TPUD adopt 4.167% or lower as their maximum allowed secondary voltage drop.

Table 1 - Normal Distribution Z Score

Probability Area from central to Z Score (Z = # of Std. Dev. mean)										
Z	**0.00**	**0.01**	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**
0.0	0.0000	0.0040	0.0080	0.0120	0.0160	0.0199	0.0239	0.0279	0.0319	0.0359
0.1	0.0398	0.0438	0.0478	0.0517	0.0557	0.0596	0.0636	0.0675	0.0714	0.0753
0.2	0.0793	0.0832	0.0871	0.0910	0.0948	0.0987	0.1026	0.1064	0.1103	0.1141
0.3	0.1179	0.1217	0.1255	0.1293	0.1331	0.1368	0.1406	0.1443	0.1480	0.1517
0.4	0.1554	0.1591	0.1628	0.1664	0.1700	0.1736	0.1772	0.1808	0.1844	0.1879
0.5	0.1915	0.1950	0.1985	0.2019	0.2054	0.2088	0.2123	0.2157	0.2190	0.2224
0.6	0.2257	0.2291	0.2324	0.2357	0.2389	0.2422	0.2454	0.2486	0.2517	0.2549
0.7	0.2580	0.2611	0.2642	0.2673	0.2704	0.2734	0.2764	0.2794	0.2823	0.2852
0.8	0.2881	0.2910	0.2939	0.2967	0.2995	0.3023	0.3051	0.3078	0.3106	0.3133
0.9	0.3159	0.3186	0.3212	0.3238	0.3264	0.3289	0.3315	0.3340	0.3365	0.3389
1.0	0.3413	0.3438	0.3461	0.3485	0.3508	0.3531	0.3554	0.3577	0.3599	0.3621
1.1	0.3643	0.3665	0.3686	0.3708	0.3729	0.3749	0.3770	0.3790	0.3810	0.3830
1.2	0.3849	0.3869	0.3888	0.3907	0.3925	0.3944	0.3962	0.3980	0.3997	0.4015
1.3	0.4032	0.4049	0.4066	0.4082	0.4099	0.4115	0.4131	0.4147	0.4162	0.4177
1.4	0.4192	0.4207	0.4222	0.4236	0.4251	0.4265	0.4279	0.4292	0.4306	0.4319
1.5	0.4332	0.4345	0.4357	0.4370	0.4382	0.4394	0.4406	0.4418	0.4429	0.4441
1.6	0.4452	0.4463	0.4474	0.4484	0.4495	0.4505	0.4515	0.4525	0.4535	0.4545
1.7	0.4554	0.4564	0.4573	0.4582	0.4591	0.4599	0.4608	0.4616	0.4625	0.4633
1.8	0.4641	0.4649	0.4656	0.4664	0.4671	0.4678	0.4686	0.4693	0.4699	0.4706
1.9	0.4713	0.4719	0.4726	0.4732	0.4738	0.4744	0.4750	0.4756	0.4761	0.4767
2.0	0.4772	0.4778	0.4783	0.4788	0.4793	0.4798	0.4803	0.4808	0.4812	0.4817
2.1	0.4821	0.4826	0.4830	0.4834	0.4838	0.4842	0.4846	0.4850	0.4854	0.4857
2.2	0.4861	0.4864	0.4868	0.4871	0.4875	0.4878	0.4881	0.4884	0.4887	0.4890
2.3	0.4893	0.4896	0.4898	0.4901	0.4904	0.4906	0.4909	0.4911	0.4913	0.4916
2.4	0.4918	0.4920	0.4922	0.4925	0.4927	0.4929	0.4931	0.4932	0.4934	0.4936
2.5	0.4938	0.4940	0.4941	0.4943	0.4945	0.4946	0.4948	0.4949	0.4951	0.4952
2.6	0.4953	0.4955	0.4956	0.4957	0.4959	0.4960	0.4961	0.4962	0.4963	0.4964
2.7	0.4965	0.4966	0.4967	0.4968	0.4969	0.4970	0.4971	0.4972	0.4973	0.4974
2.8	0.4974	0.4975	0.4976	0.4977	0.4977	0.4978	0.4979	0.4979	0.4980	0.4981
2.9	0.4981	0.4982	0.4982	0.4983	0.4984	0.4984	0.4985	0.4985	0.4986	0.4986
3.0	0.4987	0.4987	0.4987	0.4988	0.4988	0.4989	0.4989	0.4989	0.4990	0.4990