Subject: “Beware of Simplistic Voltage Drop Calculations”

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INTRODUCTION

Iterative voltage drop calculations are some of the most tedious and time consuming components of any electrical design process. This is especially true for large lighting installations such as those found in parks, parking lots, and street lighting. With the lighting industry trending toward LED use, it is becoming increasingly common to string large quantities of fixtures on a single circuit due to the decreased load per fixture. Now more than ever, detailed voltage drop calculations can avoid over engineering of lighting systems and substantially decrease project costs.

WHAT IS VOLTAGE DROP?

Ohm’s law states the relationship between voltage, current, and resistance. Given a constant current, voltage will drop a fixed amount when the current passes through a material with a fixed resistance. Generally the served loads, such as light fixtures, have far greater power consumption than the conductors serving them. However, given enough distance and enough current, the resistance found in conductors will cause the voltage to drop a significant amount over the length of the conductor.

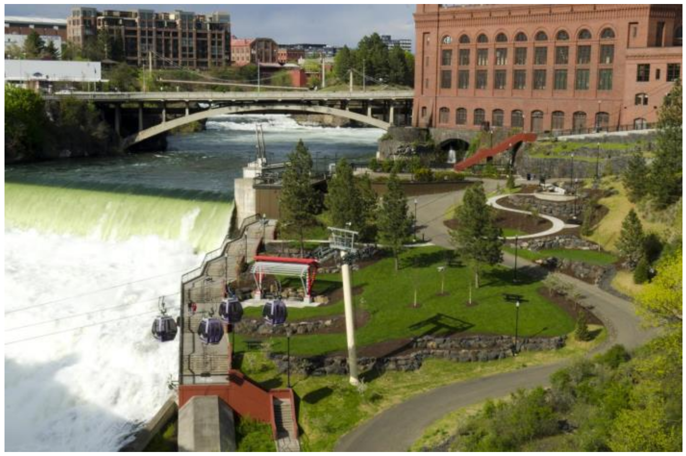
Conductor resistance is generally expressed as a fixed impedance for every unit of distance, e.g. impedance per foot. This data is published in NFPA 70, the National Electrical Code. Using the tables found there, a designer can calculate the total impedance over the length of a standard size conductor. Referencing an industry standard, such as IEEE std. 141-1993, will provide the necessary formulas and procedures for a proper voltage drop calculation over a segment of wire.

The actual mathematics of the voltage drop calculation are beyond the scope of this article, but it is important to keep in mind that the mathematics will reveal some complexities beyond ohm’s law. For example, the voltage drop will depend on the reactance of the conductor, the type of conduit surrounding the conductor, the power factor of the served load, as well as the temperature of the conductors during operation.

NFPA 70 does not address voltage drop recommendations directly. Instead, it includes informational notes that describe the recommended voltage drop limits for general installations. A maximum of 5% total drop including the source panel’s feeder, and no more than 3% for individual branch circuits is recommended. Although not a fire hazard, exceeding this amount will result in poor performance, and decreased equipment lifespan. If the resulting voltage is below a light fixture manufacturer’s published acceptable range, the light may fail to produce any light.

EXAMPLE OF A COMMON SITE LIGHTING PROJECT

The electrical construction industry has been leaning heavily toward the specification and use of LED-driven fixtures. This is especially so with projects such as parks, parking lots, and street lighting where the need for low maintenance and low energy consuming fixtures is high. As a result of the decreased watts per fixture, the typical branch circuit can now power a significant number of light fixtures and span great distances.



Parks such as Spokane Washington's recently renovated Huntington Park on the Spokane River, can even extend down hillsides with fixtures following winding paths away from a single source of electricity. In cases such as this one, voltage drop over the run can accumulate quickly.

Often times it becomes necessary to branch out from a single string of light fixtures. Taken from a recent street lighting project, the resulting one-line can resemble a tree shape such as the one in Figure 1. In this real world example, we will use the same one-line and use simplified parameters for the sake of argument. Let's assume the following about the project:

1. The average distance between fixtures is 50 feet
2. Each fixture is a pole mounted LED fixture that consumes 178VA
3. The power factor is 1.00
4. The feeder will utilize schedule 40 PVC
5. I^2R losses in the conductors are ignored
6. The available voltage at the source panel is 277VAC

Given the information above and the one-line in Figure 1, not all designers will approach sizing the required conductors in the same way. If the designer is still using traditional rules of thumb, the result could add significant cost to the project.

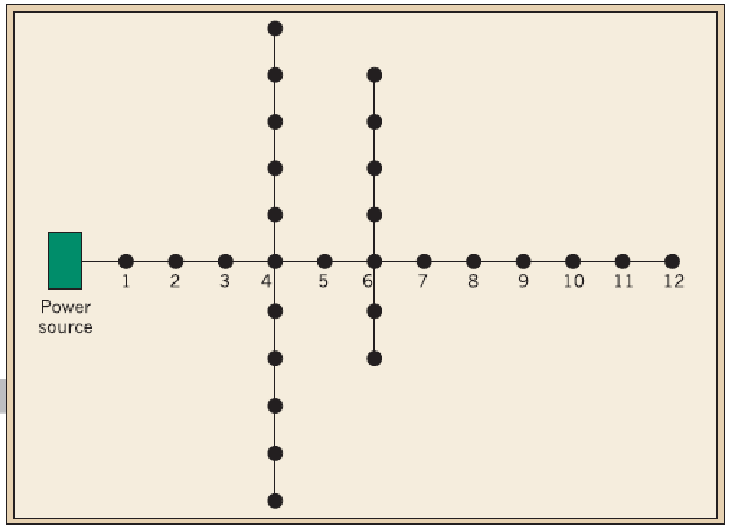


Fig. 1. Shown is a simplified one-line diagram of light pole connections in a Spokane, Wash., park.

SIMPLE VOLTAGE DROP CALCULATIONS

There are numerous tools available to today's engineers to aid in voltage drop calculations. Guides to detailed hand calculations and online calculators are readily available for little or no cost. Southwire, for example, offers a reliable voltage drop calculator available online as well as in a mobile app for Android and Apple's iOS platforms.

Many of these tools are based on IEEE std. 141-1993. In chapter 3.11 entitled "Calculations for Voltage Drop", voltage drop calculations and formulas are outlined with great detail and is an excellent read for any electrical designer. This standard, however, does not address voltage drop over long strings of loads. It is written primarily for a situation where a single load is energized at the end of a long feeder.

As a result, some of the rules of thumb that employ this approach are often used for lighting installations. The above one line could then be modeled as shown in Figure 2. For example, in order to quickly size the required conductor in the example below, a designer might perform the following calculation:

1. Determine the total load on the circuit.
2. Determine the branch with the longest distance from the source.
3. Determine the design characteristics of the installation (such as those in Table 1).
4. Using the findings from the above steps, determine the required conductor size.

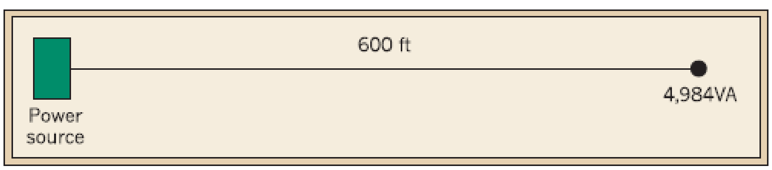


Fig. 2. Here, the one-line diagram from Fig. 1 is being modeled as a single-point load.

Suppose the installation has the parameters as shown in Table 1. This exercise will yield a result of two 4 AWG conductors and a 4 AWG ground in a 1" schedule 40 PVC conduit. Note that the equipment grounding conductor increases along with the phase conductors per NEC 250.122(B). With a calculated voltage drop of approximately 2.3%, this installation will be code compliant, meet desired design requirements, and adhere to IEEE std. 141-1993's requirements for proper voltage drop calculations.

Phase	Single
Conductor	Copper
Conduit	SCH 40 PVC
Voltage	277
Max voltage drop	3%
Length of run	600 ft
Total load	4,984VA

Table 1. Design characteristics of conductor run serving the park luminaires.

This calculation can be performed in less than an hour and does not require expensive software in order to yield an acceptable result. There are, however, numerous flaws with this approach, and more sophisticated approaches to this calculation will save the owner of this installation a substantial amount of money during construction.

SIZING WITH PRECISION – THE "NODAL" MODEL

The above method was sufficiently accurate in situations where few fixtures are placed on a single circuit. As the number of fixtures on the circuit increases, the result of such a simplistic calculation deviates increasingly from reality. This is primarily due to the fact that the load on a segment increases as you approach the source, a factor ignored by this model. The first segment out to the first fixture carries substantially more load than the segment near the end of the string.

In order to properly model the example above, the designer must treat each load as a "node" and run a voltage drop calculation for each segment between nodes. Where a node has multiple branches, the longest branch should be selected first, and that node should be treated as a single node with the sum of all the loads on the unused branches. This can be seen in Figure 3. The longest string, ending with load 12, was selected, and all the loads at nodes 4 and 6 were consolidated into single large loads.

In Figure 3, the string of lights can be separated into 11 segments. This will require 11 voltage drop calculations. The starting voltage for each segment will be the end voltage of the previous voltage drop calculation. Table 2 summarizes the cumulative loads found in each segment and the resulting voltage drop.

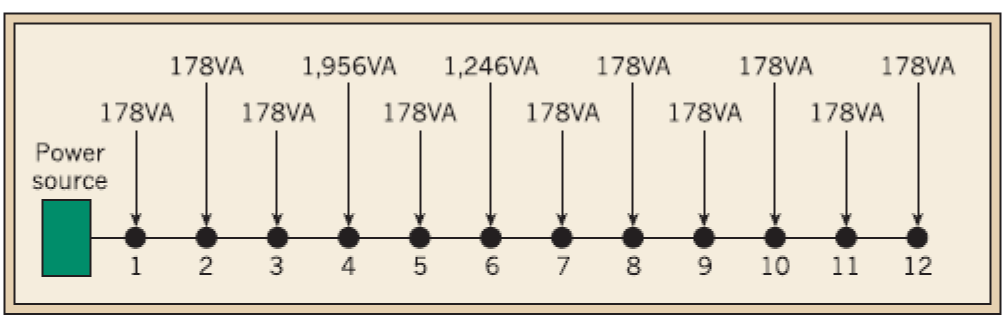


Fig. 3. This one-line diagram models the lighting load on the circuit using a "node" approach.

The simplest approach to sizing the wiring at this point is the guess-and-check method. Assume a conductor size, run through the voltage drop calculations, adjust the wire size as necessary, and repeat. The overall voltage drop for the feeder will be the total of all voltage drops calculated. It can be assumed that the consolidated unused branches, such as the branches on nodes 4 and 6, will have a voltage less than the calculated voltage drop due to the decreased distance and load.

Some designers choose to build complicated spreadsheets that can perform these multiple iterations quickly. Regardless of the method, it becomes clear early in the process that this will require substantially more effort than the simple method outlined in the previous section. However, we will see that it is well worth the effort spent.

Using this approach will yield a result of two 8 AWG conductors and an 8 AWG ground in a 3/4" Schedule 40 PVC conduit. Again, with a calculated voltage drop of approximately 2.79%, the design achieved the same design goals and code requirements as the previously described method.

From	To	Load (VA)	Segment Voltage Drop	Cumulative Voltage Drop	V_{START}	V_{END}
Source	Node 1	4,982	0.5%	0.5%	277.0	275.6
Node 1	Node 2	4,804	0.5%	1.0%	275.6	274.2
Node 2	Node 3	4,626	0.5%	1.5%	274.2	272.9
Node 3	Node 4	4,448	0.5%	1.9%	272.9	271.7
Node 4	Node 5	2,492	0.3%	2.2%	271.7	271.0
Node 5	Node 6	2,314	0.2%	2.4%	271.0	270.3
Node 6	Node 7	1,068	0.1%	2.5%	270.3	270.0
Node 7	Node 8	890	0.1%	2.6%	270.0	269.8
Node 8	Node 9	712	0.1%	2.7%	269.8	269.6
Node 9	Node 10	534	0.1%	2.7%	269.6	269.4
Node 10	Node 11	356	0.0%	2.8%	269.4	269.3
Node 11	Node 12	178	0.0%	2.8%	269.3	269.3

Table 2. Here's a summary of the cumulative voltage drop calculations for each segment of the lighting system shown in Fig. 3.

STEPPED CONDUCTOR SIZES

The previous two approaches make the assumption that a single conductor size will be used for the entire installation. To take the nodal method even further, a designer may wish to size each segment separately in order to achieve even greater cost savings to the project. However, it is important to keep in mind that for some projects, requiring many different wire sizes may cost more than choosing two or three. For example, in smaller installations it may be less cost effective for a contractor to bring many wire sizes on site each with a minimum ordering quantity that ismuch greater than the required length.

Therefore, a reasonable balance must be found. Using our example from above, consider finding what appears to be the “trunk” of the system. This will be the area where the majority of the current will be carried. The most effective place to have an altered conductor size will be in this area. Leaving that conductor large and decreasing the conductor size in the less heavily loaded branches will allow for the most effective gains. Node 6 is the last node with branches and could represent the end of the “trunk”. For example, 8 AWG wire could remain in segments 1 through 6, and 10 AWG wire could be used for all the remaining branches. The resulting voltage drop over the branch circuit will approach 2.98% but still remain within recommended design limits and code requirements.

COST BENEFIT

The cost benefit of this detailed approach outweighs the cost of the designer's time by a significant margin. Estimating the cost of each installation provides some surprising results. Note that cost estimates were performed using the recent published conductor pricing, conduit and labor pricing from the latest edition of RS Means, industry standard contractor overhead and profit, and a 10% margin of error.

Using the simple method of sizing conductors, Method 1, the installation would cost approximately $24,088. Using Method 2, the "nodal" model, and utilizing a single conductor size, the installation would cost approximately $17,353. Using Method 3, the "nodal" model with a stepped conductor sizing scheme, the cost of the installation would be $13,424. The percent of cost savings compared to Method 1 is summarized in Table 3.

	Cost of Installation	Cost Savings	Percent Savings	Design Time (hr)	Design Cost ($98/hr)
Method 1	$24,088	0	-	1	$98
Method 2	$17,353	$6,735	28%	8	$784
Method 3	$13,424	$10,664	44%	10	$980

Table 3. Here is a cost summary of the three different design approaches outlined in this article.

As we can see from these findings, the cost of the additional design effort is well worth the savings between methods 1 and 3. In a large park or street lighting project, where branches of these type can be found numerous times throughout the design, the savings to the project add up quickly.