Busway distribution system-sizing & planning aspects for automotive weld shop

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Article Info

ABSTRACT

Resistance spot welding with its characteristic "dirty electrical load" is a distinctive engineering problem. The wide range of its industrial applications has made the subject an exciting research domain. Owing to the intermittence of a welding operation, random overlapping of welding pulses, its sensitivity to voltage variation, and application-specific quality control requirements, the electrical distribution system for welding loads need to be tied strongly with the process-related requirements. One of the most important applications of resistance welding is an automotive body shop, also called weld shop. This is where various units of a car body are welded together to form a shell that begins to look like a car. This paper focuses on explaining the nature of welding load and process requirements of a weld shop, leading towards the design and development of a Microsoft Excel based tool for optimal sizing of high current busway distribution system for resistance spot welding machines. This tool can be effectively used as a desktop application for efficient design development and comprehension of various design criteria. Besides, numerical based calculations have been provided with sound reasoning, progressively developing the proposed design criteria.

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NOMENCLATURE

I_w	Welding current	T	Integration period of welding operation
I_{th}	Thermal equivalent current	D	Duty cycle of welding operation
$I_{th\text{-}L}$	Thermal equivalent line current	L1/L2/L3	A single line in a three phase AC system
I_μ	Expected value of thermal equivalent current	L1-L2,	A line to line group in a there phase AC
I_c	Contingent value of thermal equivalent current	L2-L3, L3-L1	system
R_l	Resistance of a conductor/feeder per unit length (expressed in Ω/m)	n	Total number of welders connected to a group (L1-L2, L2-L3 etc.)
X_l	Inductive reactance of a conductor/feeder per unit length (expressed in Ω/m)	k	Number of welders welding simultaneously
L	Length of bus bar feeder	P_k	Probability of k welders out of "n" total welders, welding at a time
K	Load distribution factor of a bus bar feeder	P_b	Allowable proportion of bad welds
T_w	Duration of welding	W'	Number of welders for which voltage dips below the allowable limit

1. INTRODUCTION

Resistance spot welding is one of the most extensively employed methods of joining pressed metal sheets in the automotive industry [1]. The welding operation takes place in a weld shop or body shop. This is the very workshop in an automobile manufacturing plant, where a vehicle gets its shape [2]. There are around 3000 to 5000 spot welding joints in a typical vehicle [3], [4]. Whenever a new car model is to be launched, there required is a new body shop or complete revamping of the existing shop to cater to the new unique needs [5].

The fact that the resistance spot welding does not require any additional filler material for making the joint, makes it inexpensive and efficient [6], [7]. The process, however, is a multifaceted engineering problem and the comprehension of various process-related requirements is a prerequisite for effective planning of electrical supply and distribution architecture [8]. The welding operation is intermittent. It derives high current for durations as small as 1 to10% of the welding cycle [9], [10]. In the absence of interlocking of the welding machines, a lot of welding may take place simultaneously [11]. Not only the supply must be able to cater to the load requirement, but the distribution system must also be able to sustain that current. Yet the distribution system cannot be sized for that much high current.

However, considering manual actuations with random initiations, a very large percentage of simultaneous operations is hard to imagine, especially with many machines connected to a line. This instates the need for stochastic analysis of the welding operation, hinting towards the most probable scenario [12]. In addition to load intermittence and randomness of operation, the welding process is also vulnerable to voltage instability and supply quality deterioration. When sufficient power is not available for welding, bad or cold welds result, leading to reduced productivity and compromised profits. In order to quantify an acceptable amount of trouble, a limit is set to the number of spoilt welds called the allowable proportion of bad welds [12]-[14]. The prevalent use of high current busways in the automotive industry provides the flexibility of operation and ease of expandability [15], [16]. The resulting decentralized distribution system enables the utilization of the randomness of welding operation in design interest.

This research provides a systematic review on the nature of welding load and unique rudiments of automotive weld shop, streamlining the multifaceted design criteria for optimal sizing of distribution busway for automotive weld shop. The methodological numerical analysis presents a stepwise solution catering to each design criterion. Additionally, a Microsoft excel based design tool is developed easing the calculations elucidated. This paper targets to provide a one window solution to a novice designer of the busway distribution system for an automotive weld shop.

2. DISCUSSION

2.1. Nature of welding load

Use of single phase spot welding machines is prevalent in automotive industry. On a 400V network, these spot welding machines are supplied through two phases. Therefore these machines are often referred to as two phase machines [17]. These machines work on Joule effect. The energy required for welding is supplied by the energy expressed as heat upon circulation of high magnitude current though the metal parts to be joined. The work-pieces are held together under pressure, exerted by electrodes. The amount of heat available for welding depends on the resistance between the electrodes, and amplitude and duration of the current. The resistance at the junction of the metal pieces opposes the flow of current. The energy required to overcome the junction resistance is expressed as heat and raises the metal temperature. The metal melts and forms a welding nugget at the interface [18], [19].

2.2. Welding operation

The welding operation is a series of discrete time events. One complete welding cycle follows following sequence:

Squeeze Time → Weld Time → Hold Time → Off time

The welding process begins with the metal pieces being held together under the electrode force until the desired force is attained. This duration is called squeeze time. During this while, no welding current is applied. Once sufficient force is attained, the welding current is allowed to flow. The duration for which the welding current flows through the metal pieces, is called weld time. It is expressed in cycles of supply voltage. A welding duration, too long, causes expulsion of molten metal from the electrode surfaces. Conversely, a duration too short yields a cold weld. Weld time is followed by hold time, when the electrode force is continued to be applied on the work pieces, to allow the weld nugget to solidify before the electrodes are retracted. When the welding cycle is repetitive, an off time defines the duration between retraction of electrodes from one workpiece and their application on other. It is only the weld time, when the welding current is required. For rest of the duration, the supply needs to not to be committed [18], [20].

2.3. Concept of intermittence

To further clarify the nature of welding load, it is important to introduce here a term "duty cycle". Duty cycle is the ratio of the time for which a load is applied and the "Integration period" for the device, expressed in percentage. An integration period is the duration summing a load and a rest period. A comparison of currents at different duty cycles is given in Figure 1. Load at 5% duty cycle derives current for only 5% of the total integration period (20ms) however the load at 50% duty cycle conducts current for 10ms i.e. half the integration period. Duty cycle for welding operation ranges from 1 to 10%. In other words, the weld time accounts for only 1 to 10% of the welding operation.
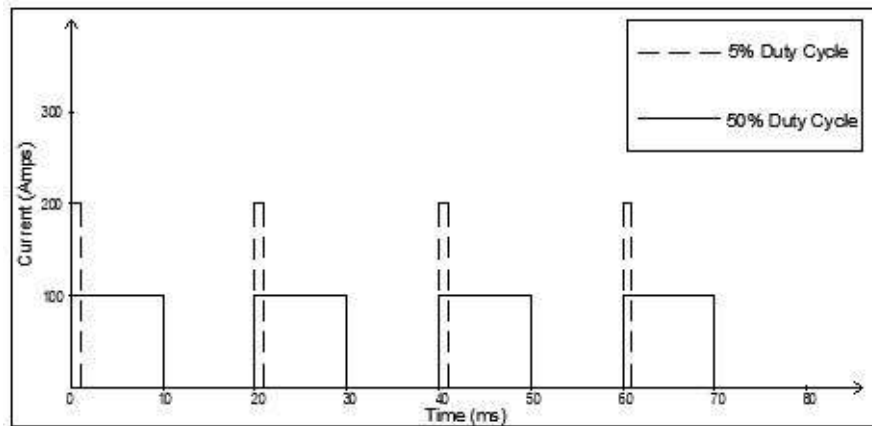

Figure 1. Depiction of 5% and 50% duty cycle

2.4. Thermal equivalence-the key to overloading without overheating

The electrical power supply and distribution systems are designed to carry the rated power continuously throughout their rated life. The fact that the welding load derives the welding current for a small period of time, instigates that a supply or distribution equipment can support more than its rated load without getting overheated.

Electrical energy convertible to thermal energy is given by:

$$E = I^2 Rt \tag{1}$$

With constant opposition, higher the magnitude of current or longer the duration of conduction, higher will be the electrical energy lost as heat. It is this heating of the equipment that limits its operation at loads higher than its rating. Equalizing the heat produced by a current "I" passing for "t" seconds with another current "I'" passing for "t'" seconds.

$$I' = I\sqrt{\frac{t}{t'}} = I\sqrt{\frac{D}{D'}} \tag{2}$$

Equation 2 tells that a current of a high magnitude of 1000A flowing intermittently with a duty cycle of 5% is thermally equivalent to ≈224A flowing continuously. The distribution system equipment, need not to be sized at 1000A. A continuous current rating of around 224A should suffice. Equation 2 expressed in terms of welding parameters gives the thermal equivalent current corresponding to any welding current [8], [9], [13], [21]:

$$I_{th} = I_w\sqrt{\frac{T_W}{T}} = I_w\sqrt{D} \tag{3}$$

2.5. Voltage Drop

Concerning the design of welding networks, another consideration is to handle the voltage dips due to random overlapping of welding pulses. In most applications, the voltage drop is limited to 10% of the supply voltage. 10% drop doesn't seem much of a hassle, however, as the power line voltage drops by 10%, the available electrical energy convertible to thermal energy, required for welding, decreases by 19%. Unavailability of sufficient energy for welding results in poor quality welds.

For a group of welders connected to the same bus bar, the cause of bad weld at a welding gun is not only the voltage drop due to the welder itself but also due to the other welders welding at the same time [11]. The voltage drop limit is application-specific. 10% limit for voltage drop is a generalized criterion for welding of mild steel. For other materials like aluminum for which the effect of variations in heat may be more severe, the allowable voltage drop may be less than 10% [9].

2.6. Quality of weld

The quality of a weld can be expressed in three ways:
− Physical or geometrical features like cracks and porosity.
− Strength or performance.
− Process characteristics e.g. visible expulsion of molten metal from electrode surface [8].

Due to a variety of reasons, some welds do not pass the quality test and are called "bad or cold weld". Following are some reasons for bad welds:
− Defects in material.
− Wear and tear of electrode tips.
− Insufficient supply voltage.

The importance of a stable and sufficient supply voltage has already been established in previous section, however, not all drops in voltage are due to the welding current. Following are some non-welding reasons of voltage drop:
− Other loads connected to same source.
− Excessive length of feeder from the transformer.
− Fault in any feeder or elsewhere in the network.
− Poor voltage quality from utility.
− Other industrial consumers on same network.

For the purpose of regulating the quality of welds, both welding and non-welding reasons for bad welds need to be controlled [9].

2.7. Allowable proportion bad welds

As established, the number of spoilt welds is not equal to the number of welds for which the voltage drops below the assigned limit. Therefore, the allowable proportion of welds for which the voltage drop is allowed to drop below the assigned limit must be less than the actual permissible limit of bad welds. The limit is decided in consultation with the plant engineers and expressed in percentages. It is user's prerogative to decide, based on the length and cost of the rectification process, the number of bad welds permissible. A limit of 1% means that it is acceptable if one out of a hundred welds is of poor quality [9]. As follows logically, there required is a way to calculate the odds of supply voltage dropping below the allowable limit. If the possibility of such occurrence turns out to be less than the allowed limit of bad welds, then the design turns out to be acceptable.

2.8. Welding operation as a bernoulli trial

The welding process by nature of operation is a stochastic problem. The probability of any number of welders welding at an instant can be expressed as a binomial distribution [10]. A Binomial distribution depicts that the outcome of a trial can only assume one of two independent values under assumptions, listed below:
− There's only one outcome for each trial.
− Each trial has same probability of success.
− Each trial is independent of previous trials.

Binomial distribution can also be regarded as the sum of a series of multiple independent and identically distributed Bernoulli trials. A Bernoulli trial is an experiment which is random and could generate only one of the two possible outcomes: success or failure. In other words, the Bernoulli distribution is a special case of the binomial distribution where the number of trials n = 1 [22].

For welding operation there are only two possible states; welding and rest, both the states are independent of each other and mutually exclusive i.e. either a welder welds or welds not, there's no third possibility and no chance of overlap of the two states. Consequently, the evaluation of welding operation at any instant is a Bernoulli trial. The probability of success i.e. welding for every instant is same and equal to duty cycle of the operation. The outcome of one trial doesn't in any way have an effect on other trials. Then, P_k i.e. probability of k welders out of "n" total welders, welding at a time is given by following relation [10]:

$$Pk = \binom{n}{k} D^k (1 - D)^{n-k} \tag{4}$$

3. NUMERICAL ANALYSIS

Based on Bernoulli equation, consider an example of 20 welding machines connected to a group (L1-L2/L2-L3/L3-L1), welding intermittently for two different processes with different duty cycles; 6% and 10%. Following results can be obtained in Figure 2.
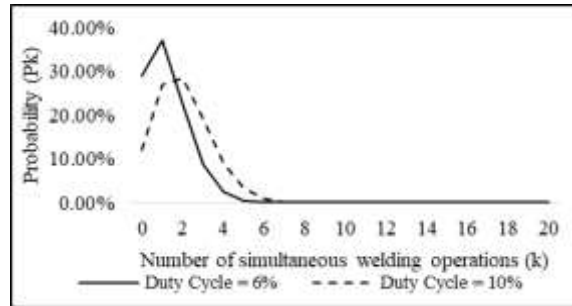

Figure 2. Probability of simultaneous welding operations as given by Bernoulli's equation

It can be observed from Figure 2 that simultaneity curve follows binomial distribution. When the duty cycle of an operation increases, there is more possibility of simultaneous operations. For any practical value of duty cycle, there is absolutely minimal chance of all the welders welding together. For 6% duty cycle there's a fair chance (66%) that none or only 1 welder would weld at a time. For 10% duty cycle such a possibility is still appreciable (39%).

3.1. Thermal equivalency for a group of welders

Considering following abstract problem, as shown in Table 1.

Table 1. Abstract problem's system specifications for numerical analysis

Number of welders per group	20
kVA demand of individual welder	150kVA
Duty Cycle of Operation	6%
System Voltage	400V

The RMS demand current can be calculated as follows:

$$emand\ current\ = \frac{kVA\ Demand}{\sqrt{3}*System\ Voltage} \tag{5}$$

For the mentioned parameters, the RMS demand current is 216A. Had the concept of intermittence not been developed, the straightforward calculation would have resulted in following ampacity requirement for distribution network:

$$Required\ Ampacity\ =\ 216*20 = 4320A \tag{6}$$

3.1.1. Optimistic case: no overlapping

When only one welder welds at a time there's no overlapping of welding durations. Any new welder starts welding only when no other welder is welding. Figure 3 depicts that the conducting time is "n" times the welding time. In (3) can be reworded as (7) [10]:

$$I_{th}\ =\ I_W\ \sqrt{(nD)} \tag{7}$$

For the considered example, the optimistic value of thermal equivalent current (I_{th}) turns out to be 237A.

3.1.2. Pessimistic Case: All Machines Weld Simultaneously

When all of the welders weld at the same time, there's absolute overlapping of welding durations. Figure 4 depicts the overlapping welding peaks. The thermal effect due to "n" welders is "n" times that of a single welder, given by [10],

$$I_{th}\ =\ nI_W\ \sqrt{D} \tag{8}$$

The pessimistic value of thermal equivalent current for the example in discussion calculates to be 1058A.
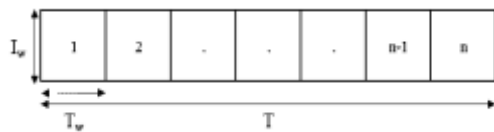
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Figure 3. Optimistic case of weld durations overlap i.e. no overlapping
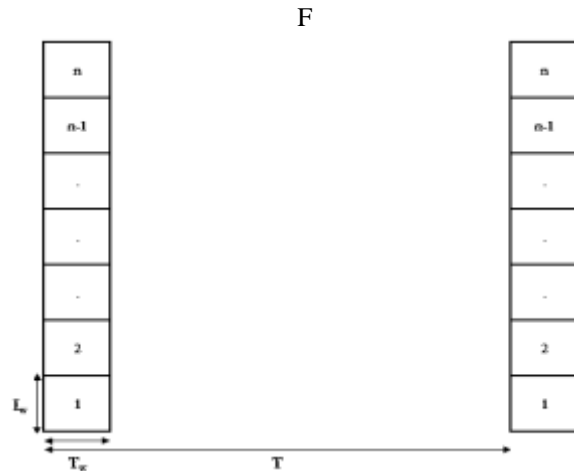
Figure 4. Pessimistic case of weld durations overlap i.e. absolute overlapping

Discussed calculations limit the value of thermal equivalent current for a group of 20 welders, welding at 6% duty cycle, within the range $237A < I_{th} < 1058A$.

3.1.3. Expected value of thermal equivalent current

For a binomial distribution the expected value is defined as the weighted average of all possible outcomes. The weight assigned to any outcome is equal to its probability of occurrence. In essence, expected value of any distribution or set of random variables is the most expected value of the average or mean of the outcomes if the trial is repeated infinite times. It is used as a means of taking unbiased decisions based on available information [23]. Expected value for a binomial distribution is given by:

$$\mu = np \tag{9}$$

For 20 welders welding at 6% duty cycle the expected number of welders welding at any instant of time equals 1.2. Although 1.2 number of welders cannot be given a practical thought, however, it can indicate the value of thermal equivalent current one should expect for a feeder feeding 20 welders. The expected value of thermal equivalent current can be equated as:

$$I_{\mu} = I_{W}\mu \tag{10}$$

The above relation yields a thermal equivalency of 259A; a more thoughtful and reasonable concord compared to two extremes; 237A & 1058A.

3.1.4. Standard deviation as a contingency margin

Though the expected value of a set of data gives a fair idea about it, the consideration of a contingency factor is appreciable for most practical problems. For this, it's prudent to determine standard deviation of the binomial distribution. The standard deviation tells, how much the members of a data set differ from its expected value. In other words, it measures the dispersion of values of a data set around the mean. For a binomial distribution it is given by [22], [23]:

$$\sigma = \sqrt{np(1-p)} \tag{11}$$

For the considered example the standard deviation computes to 1.06. With the standard deviation at hand, the "classical interval" of "one standard deviation plus the expected value" can be considered a fair estimation [24]. It is very probable that any value randomly occurring will lie within the range $\mu-\sigma < \mu < \mu+\sigma$. For this, the expected value and standard deviation are geometrically added yielding a more contingent value of number of simultaneous welding operations.

$$C = \sqrt{(\mu^2 + \sigma^2)} \tag{12}$$

Similarly, a more contingent value of thermal equivalent current for a group of welders can be expressed as:

$$I_c = I_W C \tag{13}$$

With C=1.6 for the considered case, the conservative value of thermal equivalent current for a group of 20 welders welding at 6% duty cycle comes out to be 345A.

3.1.5. Ceiling the no. of simultaneous welding operations

It can be argued that the contingent value of number of simultaneous welding operations determined in the above section is not a whole number. Although it is just a multiplier for the thermal equivalent current, but the motivation towards the determination of an optimal value of thermal equivalent current is also to be able to predict the number of simultaneous welding operations at any instant. Thus, as a resort, the constant multiplier can be mathematically ceiled to give it a practical shape.

In addition, it can be a reasonable upsize, considering that the electrical distribution system is not usually designed at its exhausting capacity. Some breathing space is always allowed as a safety consideration. Based on this, the number of simultaneous welding operations at any instant is given by:

$$k = Ceil(C) \tag{14}$$

Hence the optimal value of thermal equivalent current:

$$I_{th} = I_W k \tag{15}$$

For 20 welders welding at 6% duty cycle, 432A is the most optimal value of the thermal equivalent current. This value corresponds to 2 numbers of simultaneous welding operations. Above determined currents are line to line currents for each group (L1-L2, L2-L3 or L3-L1), for feeder sizing however it is essential to evaluate the current to which each line is subjected to. Following relation converts line to line or group currents to line currents.

3.1.6. Summary of thermal equivalent current calculation for a group of welders

To conclude, Table 2 presents all the different angles to look at the problem of 20 welders welding at 6% duty cycle with no interlocking and random initiation times. Table 2 also compares the feeder sizes as per standard ratings for various currents calculated above. It can be observed that the optimal value of thermal equivalent current lies between the determined extremes and is more inclined towards the minimum where major proportion of the simultaneity curve lies. The determined value of number of simultaneous operations "2", covers 88.5% of the simultaneity curve (Figure 2). In essence, any distribution system designed for 2 nos. simultaneous welding operations, will effectively carry the load for 88.5% instances.

Table 2. Summary of thermal equivalent current calculation for a group of welders

Description	Line to Line Current	Line Current	Feeder size
Peak welding current (without thermal equivalency)	4320A	7482A	2 Nos. 4000A
Pessimistic value of thermal equivalent current	1058A	1832A	2000A
Optimistic value of thermal equivalent current	237A	410A	500A
Expected value of thermal equivalent current	259A	448A	500A
Contingent value of thermal equivalent current	346A	600A	630A
Optimal value of thermal equivalent current	432A	748A	800A

3.2. Voltage drop analysis

Determination of voltage drop is specific to the method of power distribution. For a cable, for instance, the method of installation is of prime importance. The same cable laid in a trench will have reduced ampacity in comparison to when it is laid in a cable tray. On the other hand, for bus bar trunking system, the load distribution strategy takes over other factors. Of prime importance, therefore, is to establish the method of power distribution.

For automotive industry the use of high current bus bar trunking systems have far and wide taken over the cable distribution systems with main and sub-distribution networks. The use of tap-off circuit breakers directly installed on the bus bar trunking allows decentralized power distribution. It reduces the space utilization by substituting the floor or wall-mounted switchgear while additionally providing more flexibility in operation. With the use of bus bars, the facility's expandability and refurbishment remain to the creativity of the electrical designer. With smaller cost and more ease of installation and maintenance, the bus bar distribution takes the unprecedented lead in the car manufacturing industry [12], [15], [16].

3.2.1. Voltage drop in a bus bar trunking system

Voltage drop for a three phase balanced system is given by:

$$\Delta V = \sqrt{3}.I.L.(R_L.cos\emptyset + X_L.sin\emptyset) \tag{17}$$

It follows directly from (17) that the farther the load from the sending end, the higher the voltage drop supposed to be. In (17), however suffices for only a bulk load at the end of a feeder's length. If there are multiple taps offs along the length of the feeder, which makes the case for bus bar distribution's suitability, there required is a modification.

It can be deduced intuitively, that a bulk load at the farthest end of a distribution network will cause more voltage to drop along the line in comparison to a gradually tapped off load along the length of the distribution network. Figure 5 presents various load distribution cases for evaluation of a compensating factor for the voltage drop
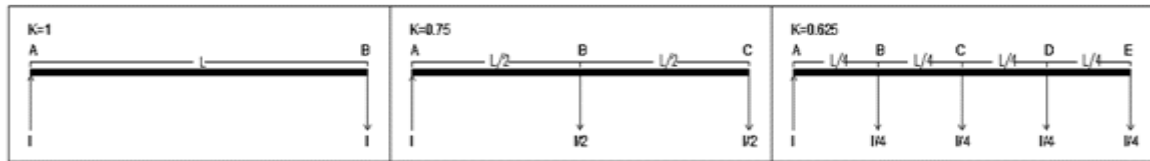

Figure 5. Load distribution cases for bus bar trunking system

Neglecting reactance of the conductor and considering resistive load for the purpose of simplicity, the voltage drop for the cases illustrated in Figure 5 can be expressed as given in Table 3.

Table 3. Voltage drop in various load distribution cases for bus bar trunking system

Case I: Load at end of the feeder	$\Delta V_I = \sqrt{3}.I.L.R_L$
Case II: Load distributed symmetrically across two equally loaded tap offs	$\Delta V_{II} = \sqrt{3}.(I.\frac{L}{2}.R_L + \frac{I}{2}.\frac{L}{2}.R_L)$
Case III: Load distributed symmetrically across four equally loaded tap offs	$\Delta V_{III} = \sqrt{3}.(I.\frac{L}{4}.R_L + \frac{3I}{4}.\frac{L}{4}.R_L + \frac{I}{2}.\frac{L}{4}.R_L + \frac{I}{4}.\frac{L}{4}.R_L)$

Generalizing expressions for above cases, for "n" number of tap offs:

$$\Delta V_n = \sqrt{3}.(I.\frac{L}{n}.R_L + \frac{(n-1)I}{n}.\frac{L}{n}.R_L + \frac{(n-2)I}{n}.\frac{L}{n}.R_L \ldots + \frac{I}{n}.\frac{L}{n}.R_L) \tag{18}$$

$$\Delta V_n = \Delta V(\frac{1}{n} + \frac{n-1}{n} + \frac{n-2}{n} + \frac{n-n+1}{n}) \tag{19}$$

Summing $(\frac{1}{n} + \frac{n-1}{n} + \frac{n-2}{n} + \frac{n-n+1}{n})$ as an arithmetic series:

$$\Delta V_n = \frac{n+1}{2n} . \Delta V \tag{20}$$

Represented by "K", $\frac{n+1}{2n}$ is designated as load distribution factor. Incorporating load distribution factor, in (17) can be rewritten as (21) [16]:

$$\Delta V = K.\sqrt{3}.I.L.(R_L.cos\emptyset + X_L.sin\emptyset) \tag{21}$$

3.2.2. Voltage drop calculation for the case of 20 welders

Revisiting the case of 20 welders connected to a group, welding at 6% duty cycle. It has been established as part of thermal current calculation that a feeder with an ampacity of 800A shall suffice for the said distribution. Further, in (14) establishes 2 number of simultaneous operations. It should be noted that for 2 simultaneous operations per group, there shall be 4 simultaneous welding peaks for each phase. Figure 6 details the same.
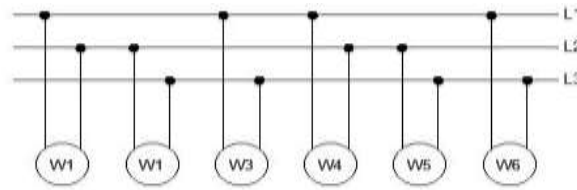
Figure 6. Depiction of two phase welding load on three phase network

Assuming that the loads simultaneously operating shall be symmetrically distributed along the length of the feeder, the load distribution factor can be calculated as 0.625. Factors R_L and X_L can be obtained for the selected bus bar from the manufacturer's datasheet. Following is a brief summary of some typical bus bar sizes and the respective resistance and reactance values, for two bus bar manufacturers, as shown in Table 4.

Table 4. Impedance reference values, for two bus bar manufacturers [25], [26]

Feeder Rating		Impedance Reference Values (mΩ/m)			
		Siemens		Schneider	
		R_L	X_L	R_L	X_L
250A		0.375	0.128	0.39	0.16
400A	BD2A	0.215	0.122	I-Line	0.21	0.14
630A		0.134	0.065		0.13	0.07
800A		0.098	0.057		0.09	0.06
1000A		0.066	0.057		0.06	0.06

Values for both the manufacturers are largely identical, and as a simpler resolve, worse of the two may be considered for calculation. Power factor for resistance spot welders is usually between 30% and 50% [10]. Considering 50% power factor and an arbitrary feeder length of 50m the voltage drop turns out to be:

$$\Delta V = 0.625. \sqrt{3} . 4 . 375 . 50. (0.098 . 0.5 + 0.057 . 0.866) = 7.98 = 2\% \tag{22}$$

It should be noted that the current used for calculation is the number of simultaneous operations times' peak welding current instead of the calculated thermal equivalent current of 748A. It must be acknowledged that the thermal equivalent current is not a physical entity and shall not be measurable, although it can be calculated through energy analysis. The voltage dropped along the feeder impedance will be due to the current flowing at an instant which in this case is the peak current for 4 welders. At 2% comes out to be the voltage drop for the bus bar feeding the welding load, however there can be an elaborate system at the back end of the welding bus bar. The total voltage drop that needs to be contained within the welding limits, need to be evaluated by detailed system analysis and added to this calculated value.

3.3. Evaluation of quality of weld

Calculation of voltage drop and the same being within allowable limit for say 10%, does not suffice the welding quality criteria. The voltage drop limit is to be seen in conjunction with the allowable proportion of bad welds. Let the example of 20 welders allow one in 10,000 bad welds i.e. P_b = 0.01%. Which means that once in 10,000 welding operations the voltage is allowed to drop below 10%. As explained earlier this limit is subjective of the welding application and must be decided by operations team at site. The cost of rectification and the process cessation in due course need to be taken in account. Since voltage drop calculation method is already established in previous section, if worked out in reverse sequence, the number of welders for which the voltage drops below 10% can also be determined. Consequently the probability of that many welders welding at a time can be determined using (4). If the calculated probability turns out to be smaller than the allowable proportion of bad welds, the system can be seen as optimally designed.

In order to work out reverse solution, it is significant to identify the factors in voltage drop calculation that shall change as the number of simultaneous operations changes. In (21) it can be observed that factors except K & I are independent of number of welders and form the designed system's property. If W' be the number of welders for which the voltage drop valuates the voltage drop limit, K' and I' represent the load distribution factor and peak welding current corresponding W' welders respectively, following relation can be written:

$$\Delta V' = \frac{\Delta V}{K.I} . K'.I' \tag{23}$$

Re-writing at (23) in terms of number of welders:

$$W' = \frac{\Delta V' . K . W}{\Delta V . K'} \tag{24}$$

Since the number of welders W' is not known, it is not possible to calculate the load distribution factor, however it can be thoughtfully generalized. In order to derive any valuable conclusion regarding the value of K', it is prudent to have some values at hand. Figure 7 shows the load distribution factor for up to 100 equally loaded and symmetrically distributed tap offs.
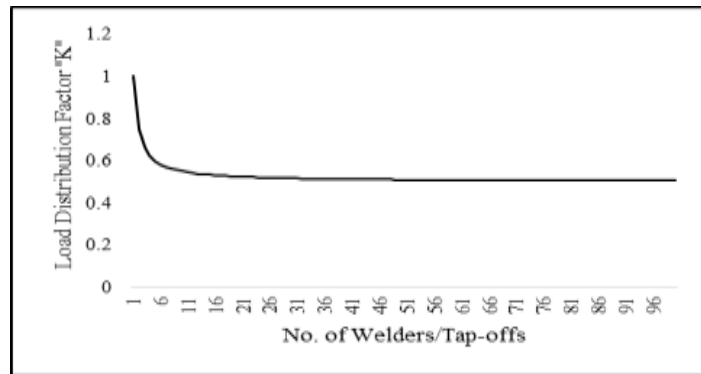

Figure 7. Load distribution factor "K" vs no. of welders/tap-offs

From Figure 7, it's indubitable that the load distribution factor approaches a value of 0.5. Further Table 5 establish that a value less than 0.5 is inevitable in a practical scenario.

Table 5. Load distribution factor for very high number of tap-offs

Number of tap offs	Load distribution factor "K"
500	0.501
1000	0.5005

It should also be understandable that higher the selected value of K', smaller will be the number of simultaneous welders. A value of 0.55 stands an apt choice after multiple iterative calculations. For 1 to 8 number of tap-offs, however a load distribution factor of 0.55 will give a value higher than actual, which is why an iterative voltage drop calculation is necessary if the calculated number of welders lie in the range 1-8.

Having determined K', we evaluate ΔV'. As earlier discussed, let 10% be the limit of voltage drop corresponding to the allowable proportion of bad welds. Let the voltage drop in upstream network be 2%. Therefore 8% of 400V (reference voltage) shall be used in calculation. The calculation follows as (25):

$$W' = \frac{32 . 0.625 . 4}{7.98 . 0.55} \tag{25}$$

W'= 18.22 ≈ 18 welders

Since 18 does not lie between 1 and 8, there's no need to re-calculate voltage drop using 18 no. of welders. Next to the calculation of number of welders for which voltage drops below the limit of 10%, is the evaluation of the probability of this many welders welding at a time. Employing Bernoulli's equation to determine the simultaneous welding probability of 18 out of 40 welders connected to a line (L1/L2/L3).

$$P_{18} = \binom{40}{18}(0.06)^{18}(1 - 0.06)^{40-18} \tag{26}$$

$$P_{18} = 2.95 \, x \, 10^{-10}$$

Since P18<Pb, the criteria of voltage drop and weld quality are duly met. It can be concluded that the 800A rated distribution bus bar is an optimal selection for the discussed system.

4.   RESULTS AND DISCUSSION

An outcome of this research and thorough numerical-based exemplification of various design requirements is an effective and user-centric Microsoft excel based design tool. This tool allows a designer to input project-specific information and yields all the parameters of designers' interest, in essence, the number of welders most probable to be welding simultaneously, the thermal equivalent line to line current, thermal equivalent line current, voltage drop, and the probability of the voltage dipping below the allowable limit.

Figure 8 is an illustrative example of the design tool's framework and functionalities. Presented is the face of the tool that accepts the user's inputs and summaries the calculation results. Besides, detailed step-wise calculations are also provided in subsequent tabs to help a designer understand the physical implications of each step of design.

Figure 8. Illustrative example of design tool's framework

5.   CONCLUSION

Designing a weld shop is a challenging sport. The supply and distribution system schemes cannot be in line with conventional designs. A system designed without consideration of the peculiarities of the welding operation and weld shop quality control requirements, shall not be an optimal design. Such a design shall not necessarily cease to function, but it shall cost hefts in terms of initial investment, operation, maintenance, and occupancy of undeserved pricey space. The course of the discussion of this paper, well established the need for process-dependent electrical distribution system designing for automotive weld shop. An 800A busway proved to be sufficient for a ten times higher connected welding load. Additionally, a handy design tool has been developed to supplement the fast progressing industry's needs. Moreover, for a distinctive problem like this, effort may be invested in developing a means to look into the system with a wider perspective. Such a means could be best supplemented in form of a software or an interactive simulation.

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