Stopping the Short-circuit Fault Spreading in DC Distribution Systems

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1 Introduction

Figure 1 shows a classic DC distribution system with three "branches" connecting several loads to the uninterruptible power supply system. Several loads can be connected to each branch, provided that each load has its own (separate) fuse installed.
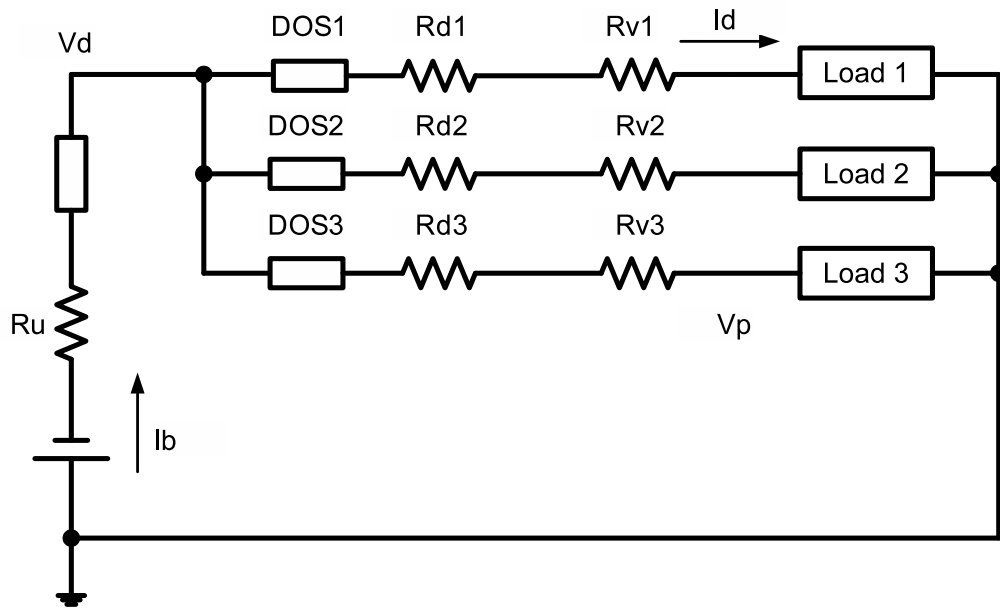
Fig.1. DC distribution in the system with uninterruptible power supply

For classic DC distribution Rd = 0

For High-Ohmic DC distribution Rd is calculated

As shown in Fig. 1, if a short circuit occurs on the consumer R1, the current through that branch is limited only by the resistance of the distribution line and the internal resistance of the battery.

The internal resistance of the battery is not constant, it depends to a significant extent on the state of charge of the battery, its capacity, the temperature of the environment and other parameters. The state of charge of the battery has the greatest influence. The internal resistance is the lowest when the battery is full. It can be assumed that the short circuit current of a new, fully charged battery in Amps is up to 100 times higher than the declared battery capacity in Ah. For example, if a 100 Ah battery is used to calculate the internal resistance, the short circuit current can be taken to be around 10,000A. It means that for a 48V battery, the internal resistance is 4.8mΩ. Ohm's law is applied to calculate the internal resistance of batteries connected in parallel. The internal resistance increases non-linearly when the discharge current rises above the value of the discharge current in the ten-hour discharge mode. Depending on the type of battery and the state of charge, the internal resistance can increase several rows of magnitude. That is why ten times the minimum value is usually taken for calculation, i.e. for our example 10 x 4.8mΩ = 48mΩ. For optimal design of DC distribution systems, engineer's experience and a good insight into the type and condition of the batteries both play an important role.

The type of battery is also important, i.e. the battery overdischarge voltage threshold. For lead-acid batteries it is usually assumed that battery discharge is allowed down to 1.7V per cell. If the battery voltage falls below the minimum value, overdischarge protection is activated, which disconnects the battery from the system. For batteries with 24 cells, the minimum voltage is 24 * 1.7 = 40.8V.

Another important parameter is the minimum voltage at which the powered equipment still works properly. With quality equipment, it is usual that the minimum working voltage is equal to 70% of the nominal voltage. So for a 24 cell system, where the nominal voltage is 48V, the minimum voltage should be 48 * 0.7 = 33.6V.

Of course, the resistance of the distribution line, which is RD = ρ * l / S, is also important. For the design of distribution lines, it is usually assumed that the current density is $1A/mm^2$, providing that if the lines are longer than several tens of meters, the engineer must check for the heating of the connecting wires. Current densities of up to $10A/mm^2$ may be considered.

As a rule, fuses in DC circuits react slower than corresponding fuses in alternating current circuits, primarily due to the creation of an electric arc at the moment of fuse reaction. Applying arc "stretching" techniques achieves good effects, but even so, the response of the fuse is slow and it is not good to rely on various types of capacitors to "iron" the voltage in transient modes, although some improvements can be achieved.

In accordance with the above, there are two main methods available to protect the rest of the devices in the system in the event of a short circuit in one of the distribution branches.

2 Dual distribution

The highest reliability is achieved by doubling the DC distributions (fig.2). In order to be able to use double distribution, it is necessary that each load or group of loads in the system has a dual internal power supply. For each of the dual local power supplies, the distribution current is routed through a separate distribution from a separate battery. The batteries are separated from each other by a diode switch so that a voltage drop on one battery does not cause a voltage drop on the other. However, despite the high reliability, due to the high price, the dual distribution principle is applied only when the required level of system reliability is so high that the high cost is justified.
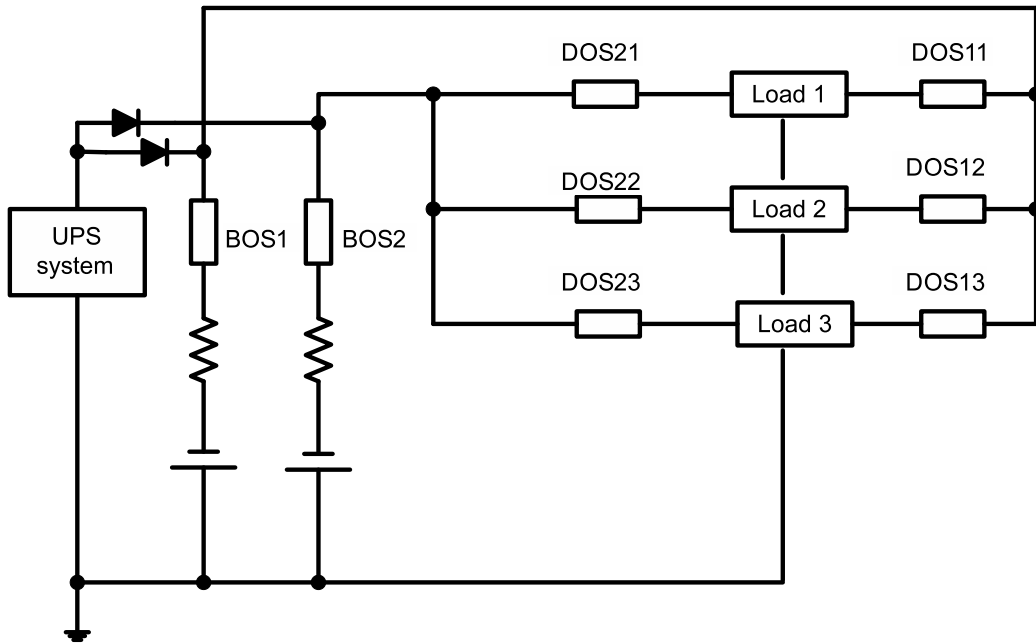
Fig.2. Dual DC distribution in the system with uninterruptible power supply

3 High ohmic distribution

The most commonly used system to achieve increased reliability is often called "high ohmic distribution". It is realized by limiting the current in the distribution branches to a predetermined value, so that even in the event of a short circuit on any load, the distribution voltage on the other branches remains within the permitted limits.

In the following text, we will give an example how to design a high ohmic DC distribution.

The following shortcuts are used in the figures and in the text:

Ru - the internal resistance of the battery

Rv - wire conductor resistance (distribution line)

Rd - added branch resistance

OS - fuse

Vb - battery voltage

Vd - DC distribution voltage

Vp - load voltage

Ib - battery current

Id - load current

3.1 Example 1: Short circuit on a classic distribution branch

1. Maximum branch current 10A

2. Length of distribution line 10m

3. Added resistance in the distribution branch Rd=0

Assuming that the maximum permitted current density in the conductor wire is $1A/mm^2$, the conductor cross-section will be $10mm^2$.

The resistivity of the distribution line will be:

$$Rv_1 = \rho * l / S = 1.68 * 10^{-8}\Omega m * 10m / 10^{-5}m^2 = 16.8m\Omega$$

The current through the short circuited line in the case of a short circuit at the end of the line (considering that the short circuit current is much higher than the nominal currents through the other non-short-circuited lines) is:

$$Isc_1 = Vb / (Ru + Rv_1) = 48 / (48 + 16.8) * 10^{-3} = 740.74A$$

The DC distribution voltage is:

$$Vd = Vb - Ru * Isc_1 = 48 - 48 * 10^{-3} * 740.74 = 12V$$

which is far less than the minimum input voltage necessary for the operation of powered equipment (33.6V). It is clear that in the event of a short circuit, the system crashes.

3.2 Example 2: Short circuit on the same branch (1) in the High-Ohmic distribution variant:

The starting parameters in example 1 and 2 differ only in that an additional resistance (Rd) is inserted in the considered branch of the distribution.

Distribution voltage:

Vd = Vb – Ru * Isc_1

Hence, the short circuit current is:

Isc_{1max} = (Vb – Vdmin) / Ru = (48 – 40.8) / 48 * 10^{-3} = 150A

Calculate the required additional resistance:

Isc_1 = Vb / (Ru + Rv_1 + Rd_1) hence:

Rd_1 = Vb / Isc_1 – Ru - Rv_1

Rd_1 = 48 / 150 – 48 * 10^{-3} – 16.8 * 10^{-3} = 201.2 mΩ

Rounded: Rd_1 = 0.2Ω

If the calculated resistance is added to the distribution branch, the occurrence of a short circuit at the end of the distribution line will not cause the other branches of the uninterruptible power supply system to fail because the distribution voltage remains within the limits even in short circuit conditions. After the fuse reaction, the DC distribution voltage returns to nominal values.

3.3 Checking the voltage value on consumers in other branches of the system

Branch 2

Let's assume that in branch 2 the maximum allowed current value is 5A and that the length of the distribution line is 15m.

For the current density of 1A/mm^2, the resistance of distribution line 2 will be:

Rd_2 = 1.68 * 10^{-8} Ωm * 15m / 5 * 10^{-6}m^2 = 50.4mΩ

For simplicity, let's assume that the additional resistance of the distribution is equal in all branches:

Rd_1 = Rd_2 = Rd_3 = 0.2Ω

It means that the total resistance of the branch is 0.25Ω

Voltage drop at maximum branch current:

U = 0.25 * 5 = 1.25V

That is, the voltage at the point of load connection at the maximum branch current during a short circuit on branch 1 amounts to:

Up = 40.8 - 1.25 = 39.55V

which is significantly higher than the permitted minimum operating voltage of the load.

We can also check the situation in the third branch with an equivalent procedure.

4 Conclusion

The principle of operation of high ohmic distribution is described, the basic design parameters are given, as well as examples of the design procedure.

High ohmic distribution makes it possible to completely eliminate the influence of a short circuit in one branch on other distribution branches at a low cost.

The main disadvantage is that the high ohmic distribution introduces additional losses into the system, which consequently lead to a decrease in the autonomy of the uninterruptible power supply system. These losses range within a few percent and in practice do not significantly affect system autonomy. This is easily demonstrated by calculating the ratio of the energy dissipated in the additional resistances of the distribution in relation to the total energy accumulated in the battery.

In properly designed high ohmic DC distribution systems with high-quality batteries, the reduction in autonomy should be up to 1%.

Power that dissipates as heat in added distribution resistors, is also a drawback. This heat must be "taken out" from the system in some way to cool the resistors and other elements of the system, which in some cases can result in increase of the size of the DC distribution.

In this text, the influence of the inductive component of the distribution cables on the transient phenomena that occur at the moment of a short

circuit is not considered, because in the high ohmic distribution they are overdamped and there are no voltage shocks at the connections of the load. In classical distribution, the dynamics of transients can be such that it leads to equipment outages in branches that are not short-circuited, and in the worst case, to a damaged input stage of the DC/DC converters.