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Damping resistor design consideration

Elassad Yann
MS Resistances
France

Audouard Bernard
MS Resistances
France

SUMMARY

Resistors have been used for more than 50 years in FACTs and HVDC systems filters; however, although being a relatively basic component, the fundamental data necessary for its conception, as well as the dramatic impacts on the final product are not widely understood. During the process of filter design, it is important to understand the effects of the different characteristics of the resistor to avoid unnecessary size (and cost) increase, as well as being able to identify critical specifications.
The scope of this paper is on metal resistors with natural air cooling. The considerations taken here are not necessary applicable to other resistor types (such as ceramic or with insulated material frame for example).

KEYWORDS

Damping resistor, Filter design

Yann.elassad@msresistances.com

Resistor's basics

The following paper shall discuss the effects of several ratings or specifications on the resistor. Although, most of the readers already know the basic resistor principles, it is important to mention again the mechanism and basic physics rules that dictates its behavior.

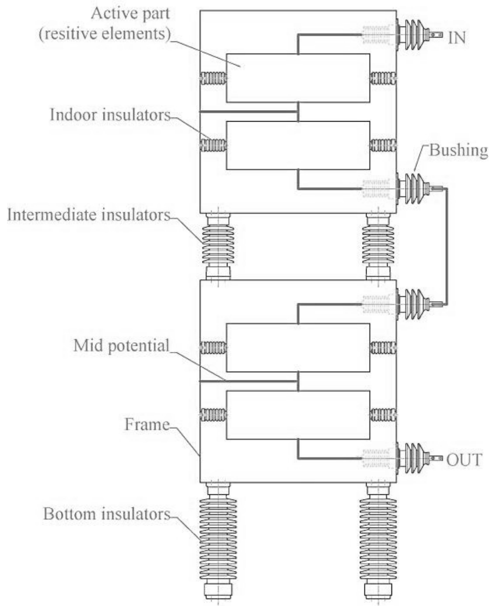

Figure 1: Typical architecture of a resistor using metal frame.

The most basic function of a resistor is to transform electric energy into thermal energy. However, depending on the type of load applied, the transformation mechanism may differ. In order to dissipate thermal energy, heat exchange must be done with the environment. The major mechanism is convection. Radiation and conduction can be neglected.
The basic convection formula being:

$$Q = h \times A \times dT \qquad (1)$$

With:
Q: heat transfer per unit of time
h: convective heat transfer coefficient
A: exchange surface
dT: temperature difference between exchange surface (resistive element) and air.

It is evident that no heat transfer is apparent when both resistive elements and ambient air are at the same temperature.
Therefore, the resistive element must first increase temperature before allowing the convection to take place.
Such mechanism is ruled by the formula:

$$\Delta\emptyset = \int_0^T \frac{Pdt}{mc} \qquad (2)$$

With
$\Delta\emptyset$: Temperature rise of the resistive element

T: total heating time
P: Power applied
m: Mass of the resistive element
c: specific heat of the resistive material

This mechanism is called adiabiatic heating (energy is stored without heat exchange with the environment).

As we can see through these formulas (1) and (2) both surface and weight of the resistive element play a central role in the resistor design. The surface characteristic of a resistive element defines its steady state behavior while its weight defines its dynamic behavior. Moreover, weight and surface characteristics have also an influence on the resistance value through the thickness of the resistive element. The thickness of the resistive element defines its resistance value and time constant. Shall the ratio of mass/surface be high, the time constant will be high and the resistance value will be low.

Besides metal resistor using an additional medium for heat transfer (such as ceramic rod) all metal resistors are bound by these 2 characteristics.
In general, it can be said that:

- High resistance value will require thin resistive element that will not be able to absorb high peaks of energy.
- Low continuous power with low resistance value will require thick resistive elements that will increase the time constant.

As seen through the convection formula (1), if the resistive element temperature is increased, more power can be dissipated with the same surface. For constant power, if the temperature is increased, the surface can be reduced and the resistor can be more compact.
However, limits must be placed on the resistive element temperature for the following reasons:

- Resistive element mechanical properties: Creep strength is to be considered, for example, after 100 000h (~12 years of operation) at 600°C the creep rupture strength of the AISI 310 is down to 80MPA (from 580MPA at ambient). [1]
- Resistive element corrosion: High temperature and successive heating-cooling cycles greatly affect the stainless steel self-protection by accelerating the pitting corrosion mechanism.
- Insulators material mechanical properties: Porcelain is affected by thermal shocks, and the cement used to fix the external fittings has temperature limitations.
- Frame corrosion protection: Hot dip galvanization protection starts peeling at 200°C.

Without standard specifying temperature rise limits acceptable on damping resistors, a generally accepted temperature rise limit is provided by the IEEE C57.32 standard for neutral grounding resistor [2]:

- Continuous duty: 385°C
- Less than 10 minutes (intermittent load): 760°C

The continuous duty maximum temperature rise of 385°C is protecting against creep by preventing the stainless steel alloy (usually austenitic type) from reaching the limit

temperature of 480°C (considering that ambient temperature can reach 50°C) to which the creep phenomenon starts to appear.
The intermittent duty (less than 10minutes) maximum temperature rise of 760°C is protecting the alloy against pitting corrosion.

FACTS and HVDC systems are usually designed for a lifetime of 30 years (or above), therefore, great care must be taken in the resistor temperature calculation.

Resistance VS power

The formula to be considered for damping resistor is:

$$P = R \times I^2 \quad (3)$$

When designing a filter, engineers usually do not have the liberty of choosing the harmonic current to apply on the resistor as it is a basic value given during the harmonics analysis. However, the resistance value is adjustable through the quality factor.
One should keep in mind that the continuous power to be dissipated by the resistor has a linear correlation with the surface of the active part. This has substantial influence on the frame (through the volume of the active part and energy to dissipate) and insulation (through the weight of the active part).

Inductance

In general, the inductance is preferred to be minimal for damping resistors in order not to interfere with the tuning of the filter. A maximum R/Lω ratio is usually prescribed.
The inductance of the active part is linked to the technology used (stamped grids, wire wounded elements….etc) and usually proportional with the resistance value.

Insulation

The insulation criterion for a damping resistor is generally the impulse voltage (Switching impulse voltage or lightning impulse voltage). Three particular withstand are required:

- HV to ground
- LV to Ground
- HV to LV (or across)

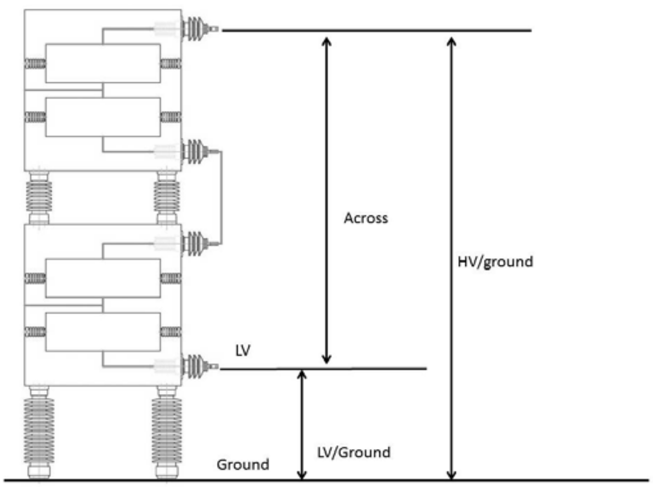

Figure 2: Basic Insulation Levels

Each insulation criterion has its own influence.

- HV to ground, as we can see through the figure 2, is essentially linked with the bushing and the post insulators.
- The LV to ground is similar to the previous, whereas the intermediate insulators have no influence.
- The HV to LV insulation is more critical as it is linked to the internal insulation. Moreover, testing the impulse voltage withstand across the resistor is problematic due to the low impedance between the 2 points. Some resistors having low resistance value are practically impossible to test due to the energy needed.

Resistor frame size should be limited for the following reasons:

- Footprint
- Transport
- Price

One should keep in mind the minimum insulator length as per IEC 60273 [3]:

Lightning impulse voltage (kV)	Insulator length (mm)
125	305
150	305
170	445
200	475
250	560
325	770
450	1020
550	1220
650	1500
750	1700

Table 1: Insulator length as per IEC 60273

For example, the width of a 325kVpeak insulated frame is:
W (mm) = 770 x 2+ active part width + bushings length + frame thickness (negligible)
The same rule is applied for the length and height.

Some insulation techniques are usually followed to reduce resistor frame size:

- Connect the active part mid-point to the frame to reduce the internal insulation
- Divide the resistor in several frames insulated from each other.

Effect of temperature on the insulation

The active part temperature has 2 major effects on the insulation:

- It defines the insulator material: Epoxy and other composites insulators using organic material usually cannot withstand high temperature.
- It defines the insulator length: The breakdown voltage of the air is function of its temperature through a negative correlation. Therefore, with increasing temperature, the internal insulators length must be increased.

The effect of altitude also needs to be considered if the resistor is to be installed at an altitude higher than 1000m.

Protection degree

The protection degree is a fundamental specification for damping resistor. Due to the constant heat that must be exchanged with the environment, ventilation is necessary.
It is to be mentioned that for maintenance and lifetime purposes, only natural cooling is applicable. In order to increase the lifetime, it is preferable to keep the resistor element as passive as possible. Hence, forced cooling is not recommended.
Therefore, the IP protection degree is considered carefully. The usual protection degree for outdoor use is IP23; any protection degree above, will reduce the cooling and therefore will increase the frame size.

Corrosion

In the race for increased reliability and increased lead time between maintenance, corrosion protection of resistor is one of the main characteristics to consider.
Corrosion protection is also affected by temperature, restricting the use of material to the ones that can withstand high temperature. Therefore, paint is to be excluded in most cases.

Manufacturers are usually left with 2 main possibilities:

- Stainless steel frames
- Galvanized Steel frames

The galvanization protection lifetime is linearly dependent of the thickness of the zinc coating.
There are 2 main galvanization processes: electro galvanization and hot dip galvanization, the main difference being the coating thickness.
Hot dip galvanization is to be chosen for greater thickness and therefore longer lifetime.

Maintenance

Maintenance intervals play an important part in the resistor frame dimensions.
A resistor is a passive component, without any moving part (besides dilatation) and therefore requires minimum maintenance.
The only regular maintenance action to be considered is the cleaning of insulators. Shall we wish to lengthen the maintenance interval; the creepage distance on insulators can be increased.
Insulation being a substantial part of the resistor frame dimensions; any increased creepage distance affects the overall price.

T° coefficient of resistance

The following concept has been proposed by Mr Roger Mathys from Mathys AG, electrical engineer, specialized in industrial power systems (SVC and harmonic filters) since 1980.

While designing a damped filter, part of the choice to be made is to balance between harmonics absorption and network stability to transients.
Harmonic current absorption is linked to the sharpness of the tuned filter through the quality factor Q.
For C type filters:

$$Q = \frac{R\omega_0 C}{\omega_0^2 LC - 1} \quad (4)$$

As we can see through the above formula, the quality factor is proportional to the resistance value.
A sharply tuned filter will absorb a large part of the harmonic current it is tuned to; however, it will leave the system more vulnerable to transients and other higher order harmonics.
Capacitors and reactors being tuned to the harmonic frequency, the balance between harmonic current absorption and transient protection is to be decided through the resistance value.
A resistor using a high positive temperature coefficient of resistance can help with this situation by increasing the quality factor when harmonic distortion is high. [4]

Specially where filter configurations are implemented with no or very low fundamental losses in the resistor. Then the filter quality factor can vary significantly with the resistor temperature.

Alloys used for the active part of damping resistors have a resistance value that is dependent of the temperature. The temperature coefficient of resistance links the temperature increase with the resistance change through the formula:

$$R_2 = R_1[1 + \alpha(\emptyset_2 - \emptyset_1)] \quad (5)$$

Where:
R_2 and R_1 are the resistance value in ohm at the temperatures $\emptyset_2$and $\emptyset_1$. α is the temperature coefficient of resistivity between $\emptyset_2$and $\emptyset_1$. It is to be noted that the temperature coefficient is a function of the temperature.
Let us compare 2 alloys commonly used: AISI 304 and NiCr 601.

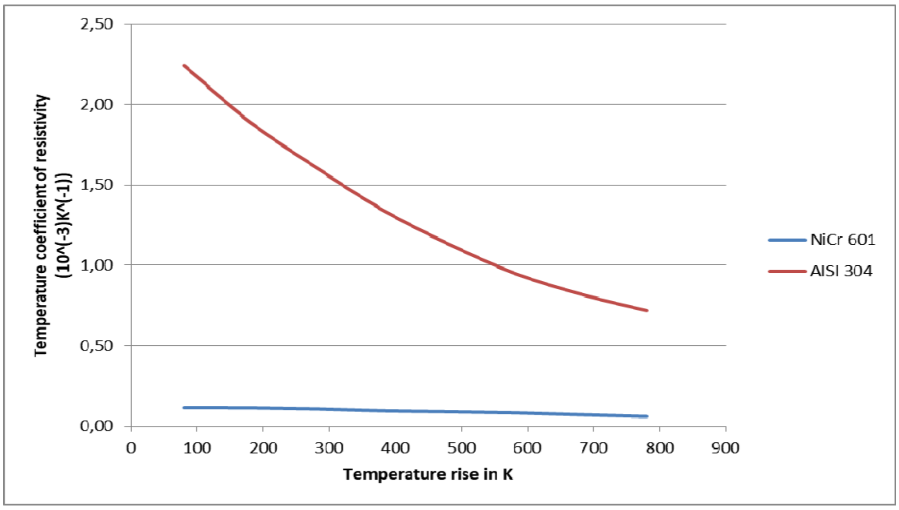

Figure 3: Temperature coefficient in relation with the temperature for the alloys NiCr 601 and AISI 304

AISI 304 has a higher temperature coefficient of resistance compared to NiCr 601; therefore, the variation of resistance with temperature will be much higher.
The temperature of the resistive element being proportional to the power dissipated, and therefore linked to the square of the harmonic current flowing through the resistor, the variation of resistance (and therefore variation of quality factor) in relation with the harmonic current can be estimated.

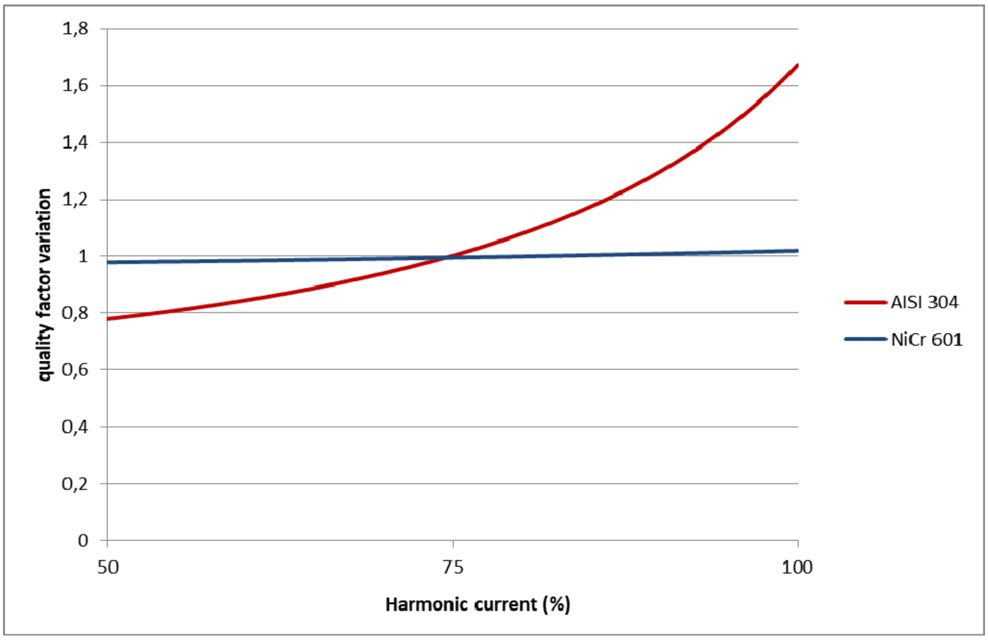

Figure 4: Variation of the quality factor Q with the harmonic current flowing in the resistor

When designing a resistor, the highest harmonic distortion is chosen. However, most of the time, the harmonic distortion is at a lower level.
Let us consider that a quality factor of 1 is recommended for a good balance between harmonic current absorption and transient protection; such situation representing an harmonic distortion of 75% (of total harmonic distortion) which is the usual load on the filter.

When using the AISI 304, if the harmonic distortion goes down to 50%, the quality factor is reduced to 0.8 providing more damping. Therefore, the network is more protected against transients, while the total harmonic distortion is below the acceptable level.
When the harmonic distortion increases, reaching its maximum value, the quality factor increases to 1.6, therefore, providing more absorption of the harmonic current.
However, by using the NiCr 601 which is more stable, the quality factor has a negligible variation.
Shall the engineer prefer the variation demonstrated above; such information should be communicated to the resistor manufacturer who can evaluate the alloy to be used.
It is to be noted that such variation is not applicable to HVDC systems where the source of harmonics is fixed.

Resistor specification

Below are the essential data that need to be provided to the resistor manufacturer in order to design the resistor:

- Resistance ratings
  - Resistance at nominal current
  - Tolerance on resistance
  - Maximum R/ Lω ratio
- Current ratings
  - Nominal harmonic current (RMS or list of harmonic currents)
  - Maximum continuous current
  - Temporary current (maximum value and duration)
  - Transient currents (Peak value and time to crest)
- Voltage ratings:
  - Impulse voltage (High voltage to earth, low voltage to earth and voltage across the resistor)
- Creepage distances (mm/kV)
  - High voltage to earth, low voltage to earth and high voltage to low voltage
- Environment:
  - Ambient temperature, humidity, altitude, seismic, wind, pollution

Any other information such as maximum footprint, IN/OUT positioning or special characteristics that the engineer considers as important shall be mentioned as well.

Conclusion

Although calculating and defining the main specifications for a damping resistor in a filter is a relatively easy task for an experienced engineer, understanding the effects of every data takes several years of experience. This paper summarized the most important aspects of a damping resistor and detailed their effects on the final product.

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