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APPROPRIATE TECHNIQUE FOR REDUCING THE HEAT GENERATED WHEN OPERATING A CIRCUIT BREAKER IN MEDIUM AND HIGH VOLTAGE SYSTEMS

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Abstract
When operating a circuit breaker, heat is generated. This heat could be enormous in medium and high voltage systems and could most times lead to undesirable situations like circuit break explosions and fire outbreak in the substation. This work used mathematical analysis to examine the parameters for heat generation when operating a circuit breaker in medium and high voltage systems namely: the resistance of the circuit breaker contact material, the current through the circuit breaker contact material and the time duration of the current through the circuit breaker contact material, and discovered that the interrupted current has approximately, a doubling effect on the value of the heat energy generated when operating a circuit breaker. Reduction in the value of the interrupted current via the use of series current limiting device is therefore an appropriate technique for mitigating this problem of enormous heat generation when operating a circuit breaker in medium and high voltage systems.

Keywords: Contact resistance, Heat, Kinetic energy, Total break time, Breaker ready time.

1. Introduction

The processes that result in electric arc production namely: field emission, thermionic emission and increase in mean free path, lead to high heat generation when operating a circuit breaker (Nagrath and Kothari, 2004).The heat resulting from the above processes when not checked often leads to contact melting in circuit breakers in medium and high voltage systems (Theraja and Theraja, 2012). Further unacceptable results from the excessive heat generated when operating circuit breakers in medium and high voltage systems are circuit breaker explosions and fire outbreak in substations (Gupta, 2012).

The key parameters for heat generation when operating circuit breakers are examined here, with a view to giving appropriate recommendations for mitigating the problem.

2.0 Material and methods

2.1 Contact resistance

Contact occurs when two surfaces touch. For the electric current, if it is a conductive material, it means a path for it to flow. Observation on a microscopic scale shows that the contact surface is actually rough even though it seems smooth to the unaided eye. In fact, as the microscope shows, the real contact between two surfaces happens through a number of small surfaces, called micro contacts, spread randomly inside the limits of the visible contact area. It is the sum of the areas of all the micro contacts that constitutes the effective contact area.

Since the resistance of an electrical contact is inversely proportional to the contact area, the smaller the effective area the greater the resistance.

2.1.1 Effect of the contact resistance
When a current **I** passes through an area **A** that has a resistance **R**, the Energy **E** absorbed by **A** is:

$$E = R \times I \times I \times t \tag{1}$$

Source: www.zensol.com

Where

E = heat energy generated
R = resistance of the material
I = the current through the material
t = the time duration of **I**

A's temperature **T is** directly related to **E** by the following equation:

$$E = \lambda \times T \tag{2}$$

Source: www.zensol.com

Where

λ = the function of the heat dissipation rate.

For a constant current **I**, if **R** increases, **E** then increases, leading to increasing temperature of the contact. If **T** continues to increase the material of the contact can reach its melting point, leading to its destruction (Zensol, 2007).

2.2 Average percentage reduction in the generated heat energy for reduced interrupted current when operating a circuit breaker
From (1), with the material resistance R taken to be constant since contacts are usually fabricated with identical materials (Mechprod, 2012) and the time duration of current t being constant as well, then (1) can be written as:

$$E = I \times I \times K \tag{3}$$

Where:

K is the constant term.

From (3), the equation for the corresponding reduction in the generated heat energy for a given reduction in the interrupted current when operating a circuit breaker is:

$$E\% = [1 - (1 - I\%)(1 - I\%)] \times 100 \tag{4}$$

Where:

I% = percentage reduction in the interrupted current
E% = corresponding percentage reduction in the generated heat energy.

From (4), table 1 is generated as shown below.

Table 1: Percentage reduction in the interrupted current and the corresponding percentage reduction in the generated heat energy when operating a circuit breaker

Serial no.	**I%**	**E%**
1	5.00%	9.75%
2	10.00%	19.00%
3	15.00%	27.75%
4	20.00%	36.00%
5	25.00%	43.75%
6	30.00%	51.00%
7	35.00%	57.75%
8	40.00%	64.00%

Taking average value from table 1,

$$\frac{\sum E\%}{\sum I\%} = \frac{309}{180} = 1.72$$

$$E\% = 1.72 I\% \qquad (5)$$

As can be seen in (5), the interrupted current reduction approximately has a doubling effect on reducing the heat generated when operating a circuit breaker.

2.3 Demonstration of the appropriate technique for reducing the heat generated when operating a circuit breaker, using series current limiting reactor technique.

The doubling effect of the reduction in interrupted current magnitude on the generated heat reduction when operating a circuit breaker can be demonstrated using a time and current graded protection scheme as shown in the network in figure 2. The followings were reached upon referring all the system impedances to a common base of 10MVA while noting that:

$\frac{(kV).(kV)}{impedance(Z)}$ = MVA:

7% impedance 4MVA transformer becomes $\frac{7}{100}$ x $\frac{10}{4}$ x 100 = 17.5% impedance on 10MVA base

0.04 ohms 11kV cable between stations H and G becomes $\frac{0.04 X 10}{11 X 11}$ x 100 = 0.33% impedance on 10MVA base.

0.24 0hms 11kV cable between stations J and H becomes $\frac{0.24 X 10}{11 X 11}$ x 100 = 1.98% impedance on 10MVA base.

22.5% impedance 30MVA transformer becomes $\frac{22.5}{100}$ x $\frac{10}{30}$ x 100 = 7.5% impedance on 10MVA base.

6.2 ohms 132kV overhead line between stations L and K becomes $\frac{6.2 X 10}{132 X 132}$ x 100 = 0.36% impedance on 10MVA base.

3500MVA 132kV source becomes $\frac{10}{3500}$ x 100 = 0.29% impedance on 10MVA base.

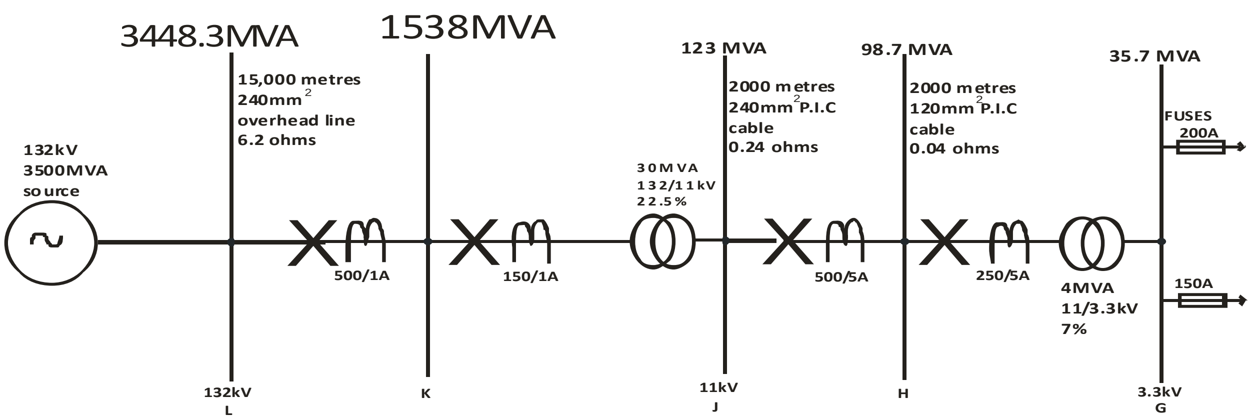
Now, the fault current or fault MVA contributed by the supply source is limited by the impedance between the supply source and the fault point, such that:

(1) The relay at station H is responsible for faults between stations H and G and as such sees the impedance between the supply source and the fault point, namely: (17.5 + 0.33 + 1.98 + 7.5 + 0.36 + 0.29)% = 27.96% impedance for a fault at its remote end (i.e. at or very close to station G), or (27.96 – 17.5 – 0.33)% = 10.13% impedance for a fault at its station. This means that the relay at station H can clear a minimum fault level of $\frac{10}{27.96\%}$MVA = 35.7MVA and a maximum fault level of $\frac{10}{10.13\%}$MVA = 98.7MVA.

(2) The relay at station J is responsible for faults between stations J and H and as such sees the impedance between the supply source and the fault point, namely: (27.96 – 17.5 – 0.33)% = 10.13% impedance for a fault at its remote end (i.e. at or very close to station H), or (10.13 – 1.98)% = 8.15% impedance for a fault at its station. This means that the relay at station J can clear a minimum fault level of $\frac{10}{10.13\%}$MVA = 98.7MVA and a maximum fault level of $\frac{10}{8.15\%}$MVA = 123MVA.

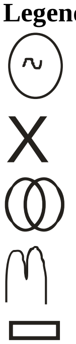
(3) The relay at station K is responsible for faults between stations K and J and as such sees the impedance between the supply source and the fault point, namely: (10.13 – 1.98)% = 8.15% impedance for a fault at its remote end (i.e. at or very close to station J), or (8.15 – 7.5)% = 0.65% impedance for a fault at its station. This means that the relay at station K can clear a minimum fault level of $\frac{10}{8.15\%}$MVA = 123MVA and a maximum fault level of $\frac{10}{0.65\%}$MVA = 1538MVA.

(4) The relay at station L is responsible for faults between L and K and as such sees the impedance between the supply source and the fault point, namely: (8.15 – 7.5)% = 0.65% impedance for a fault at its remote end (i.e. at or very close to station K), or (0.65 – 0.36)% = 0.29% impedance for a fault at its station. This means that the relay at station L can clear a minimum fault level of $\frac{10}{0.65\%}$MVA = 1538MVA and a maximum fault level of $\frac{10}{0.29\%}$MVA = 3448.3MVA.



Source: General Electric Company (GEC) protective relay application guide
Figure 2: Time and current graded protection scheme

Legend to figure 2



AC generator

Circuit breaker

Power/distribution transformer

Current transformer

Fuse

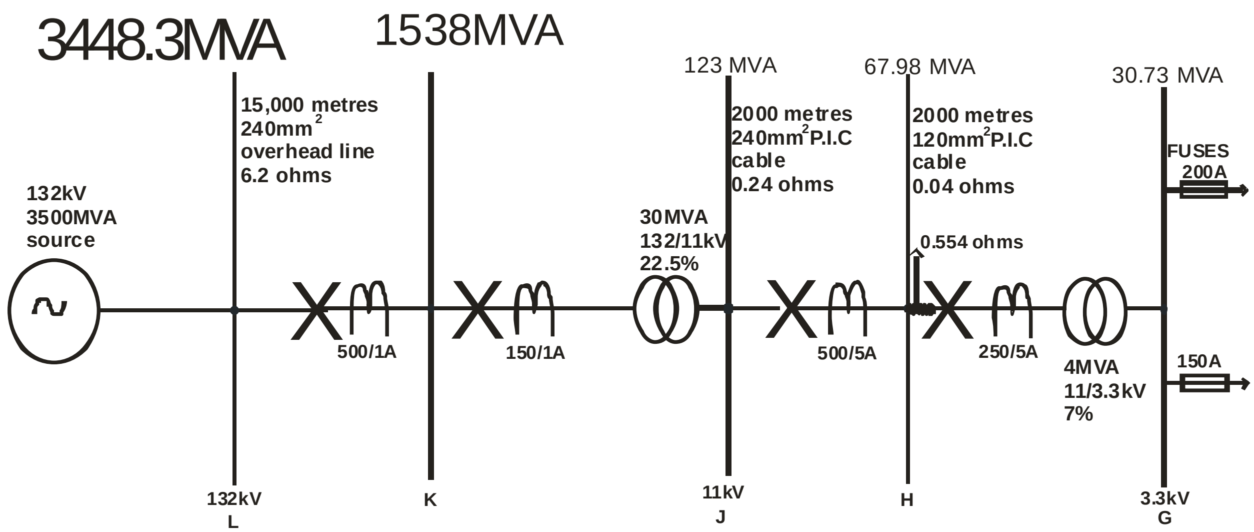
If we consider a fault occurring at station H, the circuit breaker at this station will interrupt 98.7MVA i.e.,

$$\frac{98700000}{\sqrt{3}\times\ 11000} = 5180\text{A at 11KV}).$$

Applying a series current limiting reactor of 0.554 ohms at this station H as shown in figure 3, we have the following result:

1. 0.554 ohms on 10MVA base at 11kV equals $\frac{0.554\times100\times10}{11\times11} = 4.58\%$ impedance

2. Total impedance from supply source to this point is now (10.13+4.58)% = 14.71% impedance
3. Fault level on the 10MVA base now becomes $\frac{10}{14.71\%} = 67.98MVA$
4. Interrupted current now is $\frac{67980000}{\sqrt{3}\times 11000} = 3568A$ at 11kV



Source: General Electric Company (GEC) protective relay application guide
Figure 3: Effect of Current Limiting Reactor of 0.554 ohms reactance installed at station H

Legend to figure 3

AC generator

Circuit breaker

Power/distribution transformer

Current transformer

Fuse

It can be observed that this series current limitation technique applied here has reduced the interrupted current magnitude from 5180A to 3568A.
The percentage reduction in the interrupted current is:

$$\frac{5180-3568}{5180}\times 100 = 31.12\%$$

Using (3), 31.12% reduction in the interrupted current means that:

$E = I^2 K$ **becomes**

$$E = [0.69I]^2 K = 0.69^2 I^2 K$$

Or

$$E = 0.48 I^2 K$$

This obviously is 52% reduction in the heat energy generated for the 31% reduction in the interrupted current magnitude. This can straightly be calculated using (4) or (5), with negligible error, i.e.:
Using (4),

$$E\% = [1-(1-0.31)(1-0.31)]\times 100 = 52.4\%$$

Or by using (5),

$$E\% = 1.72 \times 31\% = 53.32\%$$

2.4 Kinetic energy requirement, W_{KIN}, of circuit breakers
The kinetic energy requirement, W_{KIN}, of circuit breakers is influenced by the total break time t0 of the circuit breaker, the minimum arc-gap distance and the mass of the moving contact rod of the circuit breaker.

The reliability of circuit breakers is directly related to the number of moving parts. Switching of high short circuit currents involves high reliability and shortest operating times (Pflaum and Muller, 1974). A short break time as well as short make/break time is necessary to reduce the electro-dynamic stresses of switchgears and generators (Bachofen, 1980) and (Schaad, 1980). If the total break time t0 of a circuit breaker is reduced, the minimum arc-gap distance would have to be attained in an approximately reduced duration. According to Bachofen et al, (1982), the breaker ready time, tBR, relates with the total break time t0 of a circuit breaker as follows:

$$tBR = t0 - \frac{1}{2f} \quad (6)$$

Where

f = the system frequency.
tBR = breaker ready time
t0 = total break time of circuit breaker

Since the speed of contact travel increases in inverse proportion to the breaker ready time, tBR, the velocity, V, of the contact travel relates with the minimum arc-gap distance and the breaker ready time, tBR, as follows:

$$V = \frac{Minimum \quad arc \quad gap}{tBR} \quad (7)$$

Kinetic energy $W_{KIN} = \frac{MV^2}{2}$ (8)

Where

M = the mass of the moving contact rod of the circuit breaker
V = the velocity of the moving contact.

This implies that $W_{KIN} \propto V^2$, (the mass, M, being constant).

For ease of calculation, since we are only investigating the proportion of change in quantities examined, the constant term is taken as unity. This is appropriate since in a given equation, no matter the value of the constant term, the variable term determines the proportion of change in the value.

From (7), with minimum arc-gap distance being constant, Velocity, $V \propto \frac{1}{tBR}$

Or

$$V^2 \propto \frac{1}{[tBR][tBR]}$$

Such that

$$V^2 = \frac{k}{[tBR][tBR]} \quad (9)$$

Where the constant term k is taken as 1 m^2.

Hence,

$$W_{KIN} = K1 \times (t_{BR})^{-2}$$

Where the constant $K1 = \frac{mass}{2}$ = 1kg (for ease of calculation)

Such that applying (6)

$$W_{KIN} = \frac{1}{\left[t0 - \frac{1}{2f}\right]\left[t0 - \frac{1}{2f}\right]} \quad (10a)$$

To examine how the variations in the total break time t0 can affect the kinetic energy requirement W_{KIN}, we generate tBR using (6) and then use (10a).

If for instance, the mass of the moving contact M is no longer constant but increasing,

$$W_{KIN} \propto \frac{M}{[tBR][tBR]}$$

And (10a) becomes

$$W_{KIN} = \frac{M}{\left[t0 - \frac{1}{2f}\right]\left[t0 - \frac{1}{2f}\right]} \quad (10b)$$

However, from the expressions:

$$Mass = volume \times density$$

$$Mass = area \times lenght \times density$$

Mass is proportional to area, A, i.e.

$$M \propto A$$

From (8), for constant velocity and varying mass,

$$W_{KIN} \propto M \quad (10c)$$

Such that

$$W_{KIN} \propto A \quad (10d)$$

2.4.1 The effect of total break time t_o on W_{KIN}

How the variations in the total break time t0 can affect the kinetic energy requirement W_{KIN}, can be analyzed by generating the breaker ready time tBR using (6) i.e.:

$tBR = t0 - \frac{1}{2f}$, and then using (10a) i.e.:

$$W_{KIN} = \frac{1}{\left[t0 - \frac{1}{2f}\right]\left[t0 - \frac{1}{2f}\right]}$$

Using (6) at t0 = 50ms, f = 50Hz

$$tBR = 0.05 - \frac{1}{2 \times 50} = 40ms.$$

Using (10a)

$$W_{KIN} = \frac{k}{[tBR][tBR]} = \frac{1}{[0.04][0.04]} = 625 joules.$$

Where, the constant k is taken as unity (in kg-m^2), for ease of calculation since we are only interested in the proportion of change.

For t0 = 33.3ms

$$tBR = 0.0333 - \frac{1}{2 \times 50} 23.3ms.$$

$$W_{KIN} = \frac{1}{[0.0233][0.0233]} = 1842 joules,$$ for k equal to 1kg-m^2.

The result gotten above means that reduction in the total break time, t0, of the circuit breaker by a factor of 1.50 could result to as much as an increase in the kinetic energy requirement, W_{KIN}, of the circuit breaker by a factor of 2.95.

The curve arising from (10a) for a 50Hz system, for the values of t0 between 0.0280 seconds and 0.0500 seconds are shown in figure 4, while the derived relationships between the total break time, t0 and breaker ready time, tBR; between the breaker ready time, tBR and the kinetic energy requirement, W_{KIN}; and between the total break time, t0 and the kinetic energy requirement, W_{KIN} are respectively presented in tables 2, 3 and 4.

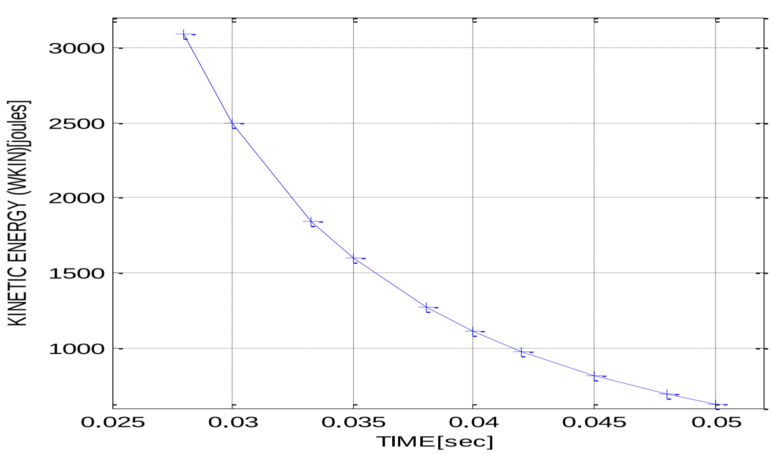


Figure 4: The curve of Circuit Breaker total break time (t0) against the kinetic energy requirement (W_{KIN})

Table 2: total break time and the corresponding breaker ready Time for a 50Hz system

Serial no.	Total break time, t0 (in seconds)	Breaker ready time, tBR (in seconds)
1.	0.0500	0.0400
2.	0.0480	0.0380
3.	0.0450	0.0350
4.	0.0420	0.0320
5.	0.0400	0.0300
6.	0.0380	0.0280
7.	0.0350	0.0250
8.	0.0333	0.0233
9.	0.0300	0.0200
10.	0.0280	0.0180

Table 3: breaker ready time and the corresponding kinetic energy requirement for a 50Hz system

Serial no.	Breaker ready time, tBR (in seconds)	Kinetic energy requirement, W_{KIN} (in kilo Joules)
1.	0.0400	0.6250
2.	0.0380	0.6925
3.	0.0350	0.8163
4.	0.0320	0.9766
5.	0.0300	1.1111
6.	0.0280	1.2755
7.	0.0250	1.6000
8.	0.0233	1.8420
9.	0.0200	2.5000
10.	0.0180	3.0864

Table 4: Total break time and the corresponding kinetic energy requirement for a 50Hz system

Serial no.	Total break time, t0 (in seconds)	Kinetic energy requirement, W_{KIN} (in kilo Joules)
1.	0.0500	0.6250
2.	0.0480	0.6925
3.	0.0450	0.8163
4.	0.0420	0.9766
5.	0.0400	1.1111
6.	0.0380	1.2755
7.	0.0350	1.6000
8.	0.0333	1.8420
9.	0.0300	2.5000
10.	0.0280	3.0864

3.0 Results and Discussions

From section 2.2, R, the material resistance is constant. The time duration of **the current** t is also kept constant since as seen from section 2.4.1, lowering the total break time t0 of a circuit breaker leads to an increase in the kinetic energy requirement W_{KIN} of the circuit breaker and hence an increase in the circuit breaker cost. Increasing the total break time t0 on the other hand will lead to an increase in the electro-dynamic stresses of the switchgear.
From (2), if E increases, T increases also. However, from (1), for a constant resistance R, if I increases, E increases. The meaning of this is that if I will continue to increase, **T** continues to increase and the material of the contact can reach its melting point, leading to its destruction. An appropriate technique for reducing the heat generated when operating a circuit breaker in medium and high voltage systems is the use of series current limiting reactor demonstrated in section 2.3.

From section 2.4.1, the values for kinetic energy requirement of the circuit breaker at any required total break time can be read from the graph shown in figure 4. The graph has a negative slope and clearly shows a rapid growth in kinetic energy requirement for little reduction in the total break time. Table 2 shows a direct relationship between circuit breaker total break time t0 and circuit breaker ready time tBR. However, decrease in t0 and tBR cause astronomical rise in the circuit breaker kinetic energy requirement W_{KIN}. The meaning of these is that reduction in the total break time of a circuit breaker increases the cost of the circuit breaker.

4.0. Conclusion

Reduction in the value of the interrupted current has been shown in this paper as the only way to reduce the heat generated when operating a circuit breaker. The use of series current limiting reactor demonstrated in section 2.3 is therefore the appropriate technique for reducing the heat generated when operating a circuit breaker in medium and high voltage systems to avoid contact melting that frequently results from severe short circuit faults.

5.0 Recommendation

This technique is highly recommended for growing power utilities where increasing demand for energy and network expansions lead to short circuit levels of more than the installed capacity of the circuit breakers. The use of this technique in growing power utilities is necessary to ensure that the heat generated in the circuit breakers during short circuit current interruption does not lead to contact melting and explosions.

References

[1] Bachofen, F., 1980. A new range of SF_6 outdoor circuit breaker type HGF 100. Sprecher News, 1-6.

[2] Bachofen, F., Steinegger, P. and Glauser, R., 1982. A novel solution for high speed SF_6 puffer type power circuit breakers of high rated capability with low operating mechanism energy. International Conference on Large High Voltage Electric Systems, CIGRE WG 13-07. Paris, 11-18 September, 1-8.

[3] GEC (1987). Protective Relay Application Guide. England: GEC Measurements Plc. 129 – 134.

[4] Gupta, J.B., 2012. A Course in Power Systems (Switchgear and Protection). S.K. Kataria & Sons Publishers, New Delhi.

[5] Nagrath, I.J. and Kothari, D.P., 2004. Power System Engineering. Tata McGraw-Hill Publishing Company Limited, New Delhi.

[6] Pflaum, E. and Muller, B., 1974. Suitable means to insure the reliability of high voltage circuit-breaker. International Conference on Large High Voltage Electric Systems, CIGRE WG 13-05 Report, Paris, 10-16 October, 1-7.

[7] Schaad, W., 1980. The practical design of the HGF 100 range of SF6 outdoor circuit breakers. Sprecher News, 1-8.

[8] Theraja, B.L. and Theraja, A.K., 2012. A Textbook of Electrical Technology. S. Chand & Company Ltd, New Delhi.

[9] http://www.mechprod.com/blog/bid/318509/Contacts-and-Contact-Dynamics-in-Circuit-Breakers-Contact-Resistance

[10] http://www.zensol.com/Articles/ZensolJan-Fev2007.pdf