A brake resistor perspective on voltage ratings

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Preface

Customers for brake resistors often ask for as high voltage rating as possible, but where does the voltage rating requirement come from, and what is the real limit according to AC_{rms} and DC ratings. How do the UL (Underwriters Laboratories) and IEC (International Electrotechnical Commission) standards correlate and what can be expected from the insulation, regarding lifetime and extreme conditions like overload and high temperature. Housing temperature above 200°C and even up to 375°C in worse case.

Working in Europe with American standard voltages gives an extra need to understand the different requirements on system level. But the deeper insight also issue a better understanding for what is actual tested and at what conditions.

Participating in the IEC Technical committee 109 gave first of all a good talk with a group of experts with a profound knowledge but also a better understanding of the standards, and a more horizontal view of the standards regarding insulation- and voltage requirements.

IEC 60038 - IEC standard voltages
IEC 60664 - Insulation coordination for equipment within low-voltage systems
IEC 60270 - High voltage test techniques – Partial discharge measurements
IEC 61180 - High-voltage test techniques for low-voltage equipment
IEC 60439-1 Low-voltage switchgear and controlgear assemblies
IEC 61800-5-1 - Adjustable speed electrical power drive systems
IEC 50124-1 Railway applications - Insulation coordination

UL 508 - Industrial Control Equipment
UL 347 - Medium-Voltage AC Contactors, Controllers, and Control Centers
UL 840 - Insulation Coordination Including Clearances and Creepage Distances for Electrical Equipment
UL 60947-1 - Low-Voltage Switchgear and Controlgear

IEC ratings

Voltage ratings are divided into three main areas, having different risk according to the nature physics.

IEC voltage range	AC	DC	Defined risk
High Voltage	>1000V_{rms}	>1500V	Electric arcing
Low Voltage	50-1000V_{rms}	120-1500V	Electric shock
Extra-Low Voltage	<50V_{rms}	<120V	Low risk

The High Voltage area is further divided into:

MV (Medium Voltage) 1.1kV to 72.5kV,
HV (High Voltage) 110kV to 475kV, and
EHV (Extra High Voltage) >500kV.

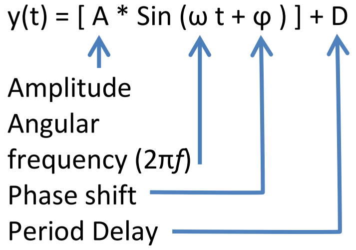
For motor controlled devices, it is often seen that a 400V system is transformed up to 690V. Here the currents are smaller and thus resulting in smaller rated equipment such as cables, transformers, switchboards, and other equipment, which also reduces the energy losses.

Within the low voltage group. following are the standardised grid ratings (IEC 60038):

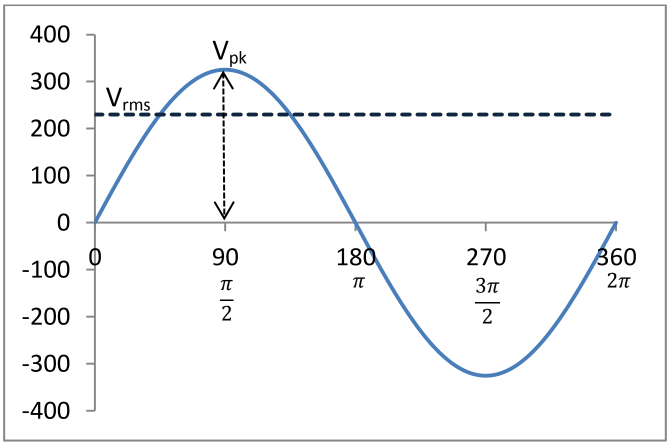
AC systems having a nominal voltage between 100V and 1000V inclusive and related equipment	
Three-phase system (3-4 wire)	
Nominal voltage V	
50Hz	60Hz
-	120/208
230[c]	240[c]
230/400[a]	230/400[a]
-	277/480
-	480
-	347/600
-	600
400/690[b]	-
1000	-

[a] The value of 230/400V is the result of the evolution of 220/380V and 240/415V systems which has been completed in Europe and many other countries.
[b] The value of 400/690V is the result of the evolution of 380/660V systems which has been completed in Europe and many other countries.
[c] The value of 200V or 220V is also used in some countries.
[d] The value of 100/200V are also used in some countries on 50Hz or 60Hz systems.

Key for the sine equation is:



By plotting this into an excel spreadsheet following graph can be drawn:



So the sine of a nominal 230V system is having an amplitude or peak value at 325,27V

RMS value is related to the power produced when the voltage is applied over a resistor R.

This power is P = V^2/R, here the power is the same for DC voltage and AC_{rms} voltage, but this is not the case regarding brake resistor usage.

When rectifying alternating current (AC) to direct current (DC), the DC voltages are then no longer equal to the rms value of the supply. The DC voltages changes according to the used type of rectifier.

RMS

The standardized nominal voltages are all rms values (root mean squared). Meaning that it is the root of an integral of the mean of squared sinusoidal waveform, or the square of the function that defines the continuous-time waveform.

$$y_{rms} = \sqrt{\frac{1}{T}\int_0^T y^2(t)dt} =$$

$$\sqrt{\frac{1}{T}\int_0^T A^2 sin^2(2\pi f t)dt} \Rightarrow y_{rms} = \frac{A}{\sqrt{2}}$$

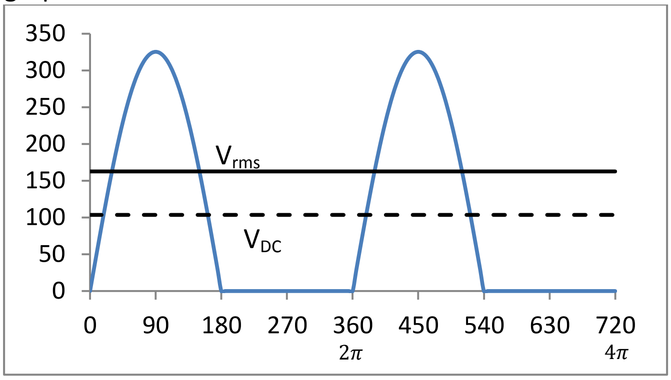
...Where A for amplitude is equal to the peak voltage V_{pk} in an electric system.

Half-wave rectification

The no-load output DC voltage of an ideal half wave rectifier for a sinusoidal input voltage is:

$$V_{rms} = \frac{V_{pk}}{2} \quad and \quad V_{DC} = \frac{V_{pk}}{\pi}$$

By plotting this into an excel spreadsheet following graph can be drawn:

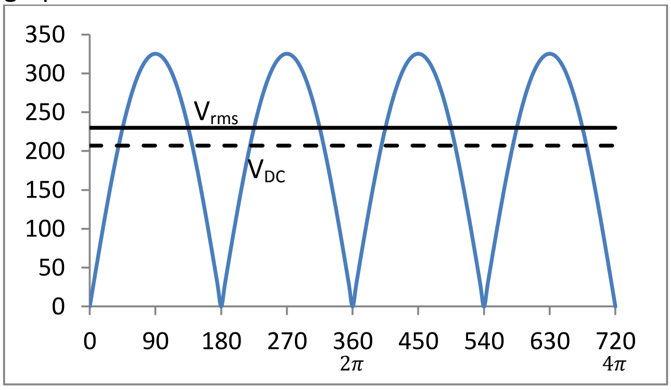


Full-wave rectification

The average and root-mean-square no-load output voltages of an ideal single-phase full-wave rectifier are:

$$V_{rms} = \frac{V_{pk}}{\sqrt{2}} \quad and \quad V_{DC} = V_{avg} = \frac{2V_{pk}}{\pi}$$

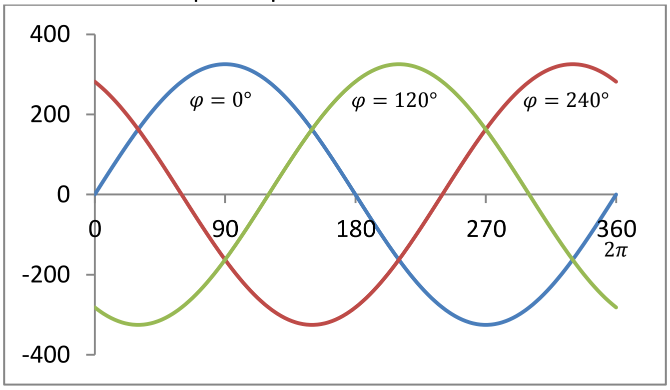
By plotting this into an excel spreadsheet following graph can be drawn:



Three-phase rectifiers

Single-phase rectifiers are commonly used for power supplies for some equipment. However, for most industrial and high-power applications, three-phase rectifier circuits are the norm. As with single-phase rectifiers, three-phase rectifiers can take the form of a half-wave circuit, a full-wave circuit using a center-tapped transformer, or a full-wave bridge circuit.

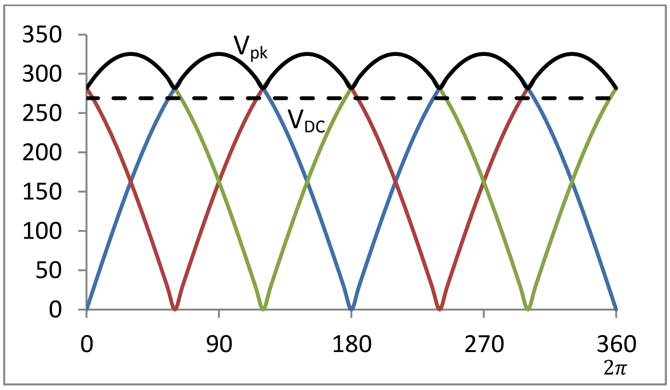
Standard three-phase plot:



Three-phase, half-wave rectification

A three-phase, half-wave circuit with three diodes, one connected to each phase, is the simplest type of threephase rectifier. But this setup suffers from high harmonic distortion on both the AC- and DC-connections.

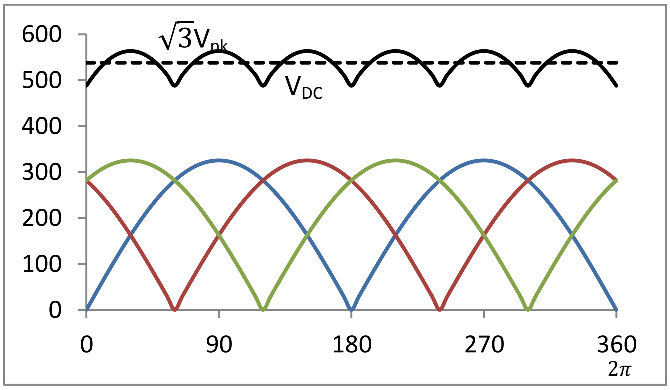
$$V_{DC} = V_{avg} = \frac{3\sqrt{3}V_{pk}}{2\pi}$$



Three-phase, full-wave rectification

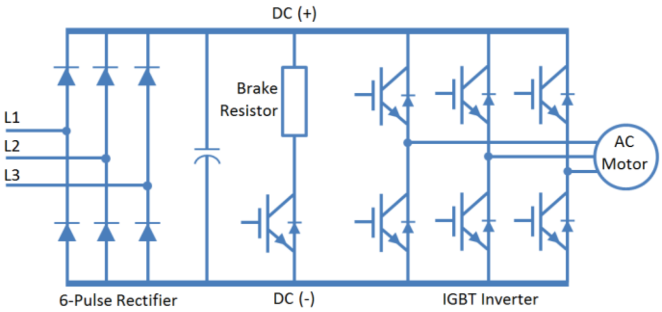
For a three-phase full-wave diode rectifier, the ideal, no-load average output voltage is:

$$V_{DC} = V_{avg} = \frac{3\sqrt{3}V_{pk}}{\pi}$$



Adjustable power drive voltages

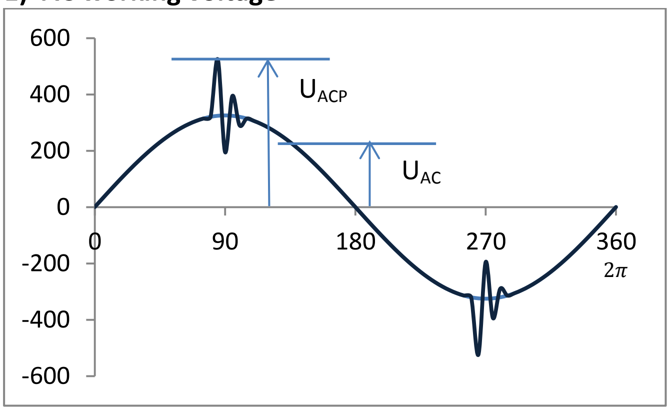
In electric motor drive systems the voltage over the motor is a product of the input which rectifies the 3-phases into a DC bus, and the pulsed inverted output given by IGBT's (Insulated-Gate Bipolar Transistor's) that can be switched with different frequency and different pulse patterns and hence control the motor speed and direction.



The DC bus is stabilised with a capacity but different kind of noise raises the peak performance of the insulation system. Here the Break Resistor is mounted with a controllable IGBT to have an on-time only when the break energy comes from the motor by acting as a generator. Otherwise the resistor will just act as a permanent load. During break situations, where the motor acts as a generator, the DC bus voltage can increase above the level defined by the grid voltages, since the IGBT controller is the only limiting circuit for the generation of high voltages. And the free-wheeling diodes of the IGBT's now act as a rectifier.

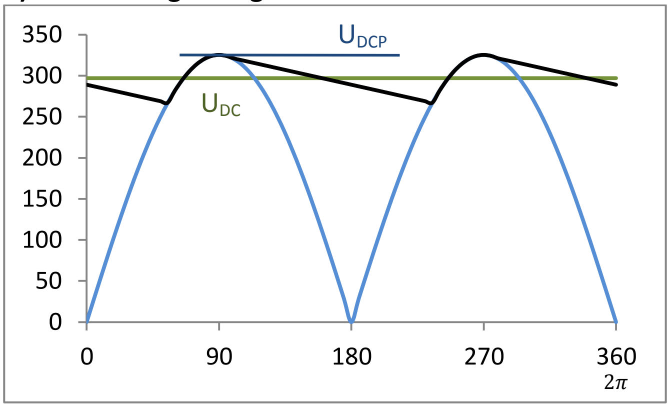
The standards for electrical power drive systems referrers to three voltage scenarios:

1) AC working voltage



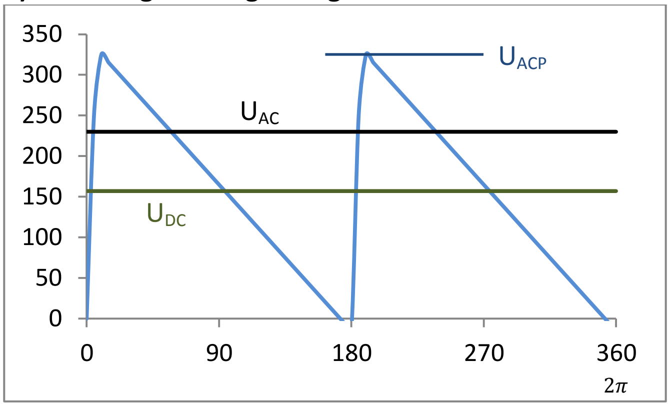
Typical waveform for AC working voltage, where the working voltage has an rms value U_{AC} and a recurring peak value U_{ACP}.

2) DC working voltage



UDC mean voltage
UDCP recurring peak voltage

3) Pulsating working voltage



Typical waveform for pulsating working voltage.
The working voltage has a mean value UDC and a recurring peak value UACP, caused by a ripple voltage of r.m.s. value UAC greater than 10 % of UDC.

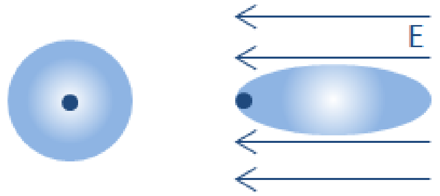
The physics of dielectric strength

Dielectric strength is the maximum electric field strength that an insulating material can withstand intrinsically without breaking down. At breakdown, the material electrons are no longer bound and the applied electric field is accelerating them to velocities that can liberate additional electrons. Such a breakdown occurs in nanoseconds, resulting in the formation of an electrically conductive path and creating a disruptive discharge through the material destroying its insulating capability.

Factors affecting dielectric strength is; thickness of the specimen, operating temperature, increase in frequency and increase in humidity. The field strength, at which breakdown occurs, depends on the respective geometries of the dielectric insulator and the electrodes with which the electric field is applied. Also, dielectric materials usually contain tiny defects, and the practical dielectric strength will only be a fraction of the intrinsic dielectric strength of an ideal, defect-free, material.

When the atoms or molecules of a dielectric material are placed in an external electric field, the nuclei is pushed with the field resulting in an increased positive charge on one side while the electron cloud is pulled against it resulting in an increased negative charge on the other side.

The example shown here is on atom level:

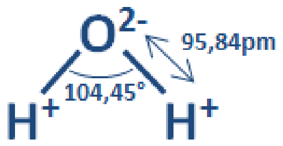


To the left is an atom with the positive core and the negative electron cloud. To the right is the same atom in an electric field.

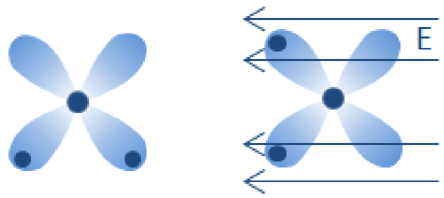
This process is known as polarisation and a dielectric material in such a state is said to be polarised. There are two principal methods by which a dielectric can be polarised. The first is called stretching but on molecular scale it is more normal having rotational polarisation.

Rotation occurs only in polar molecules — those with a permanent dipole moment like the water molecule.

The phenomena is based on a molecule having one side with a negative charge and the other with positive charges.



The water molecule has a dielectric strength 80 times that of nitrogen (a nonpolar molecule that is the major component of air). Nonpolar molecules and atoms stretch, while polar molecules stretch and rotate, and when released they will fall back into a relaxed state. Some insulators will remain in their polarized state for hours, days, years, or even centuries.

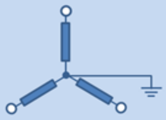
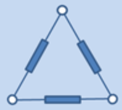


When this rotation occurs in larger scale where molecules are bound together in solids, heat is developed due to friction. When an AC field is present the rotational heating weakens the material over time and the dielectric strength is breaking down way more rapid than if it was only exposed to a DC field.

Overvoltage categories and system voltages

Insulation between the surroundings and circuits which are connected directly to the supply mains shall be designed according to the impulse voltage, temporary overvoltage, or working voltage, whichever gives the most severe requirement.

Here, the over voltage that can be present, is relating to the usage and connectivity to the supply mains. This is divided into four categories; the first applies to equipment connected to a circuit with transient reduction.

System voltage Maximum value of rated operational voltage to earth (V)		Nominal voltage of the supply system (V)		Impulse withstand voltage rating (1.2/50µs) at 2000m U_i (kV)				Insulation distance Clearance, Creepage (mm)
				Overvoltage category				
AC_{rms}	DC			IV	III	II	I	Pollution degree 2
50	71	-	-	1,5	0,8	0,5	0,33	0,2
100	141	66/115	66	2,5	1,5	0,8	0,5	0,5
150	212	120/208 127/220	115, 120 127	4	2,5	1,5	0,8	1,5
300	424	220/380, 230/400 240/415, 260/440 277/480	220,230 240, 260 277	6	4	2,5	1,5	3,0
600	849	347/600, 380/660 400/690, 415/720 480/830	347, 380, 400 415, 440, 480 500, 577, 600	8	6	4	2,5	5,5
1000	1410	-	660 690, 720 830, 1000	12	8	6	4	8,0

The second applies to portable tools or plug-connected equipment. The third category applies to equipment connected in fixed installations with switchable equipment. And category four applies to equipment permanently connected at the origin of an installation. Here in connection with outdoor open lines subjected to lightning transients.

The table in the top is now combined so that the test voltage rating is related to the system voltage and the nominal motor equipment voltages. The test pulse U_i is defined as 1.2µs rise time by 50µs tail. Last is the corresponding creepage and clearance distance for pollution degree 2 regarding sand-filling that can occasionally be in a moist condition and thereby having temporary conductivity.
Brake resistors must be sand filled to dissipate the heat from the resistor wire. They are cement casted in the ends of the profile, but nor the casting or the aluminium used for the profile is vapour thight and the nature of a hot element cooling is to drag moist from the air, while the heated overpressure inside now becomes normalised, and thereby is dragging air inside.

Notes to the table ratings are: The phase to ground voltage for most systems, is equivalent to dividing the phase-to-phase voltage by √3. When the supply voltage is rectified AC, the system voltage is the rms value of the source AC before rectification, taking into account the supply earthing system. This note is not normally known. This means that a component in the rectified system may experience a higher voltage than its system rating!

Voltages generated by the secondaries of transformers providing galvanic insulation from the supply mains are considered to be system voltages for the determination of impulse voltages.

Test voltages for verifying clearances			
Distance (mm)	U_i (kV)	U_{AC} (kV)	U_{DC} (kV)
0.01	0.33	0.23	0.33
0.04	0.52	0.37	0.52
0.1	0.81	0.5	0.7
0.5	1.55	0.84	1.19
1.5	2.56	1.39	1.97
2	3.1	1.69	2.39
2.5	3.6	1.96	2.77
3	4.06	2.21	3.13
3.5	4.51	2.45	3.47
4.5	5.33	2.9	4.1
5.5	6.09	3.32	4.69
8	7.82	4.26	6.02
11	9.95	5.4	7.63
14	12.2	6.61	9.35
18	15.1	8.17	11.6
22	17.8	9.68	13.7
25	19.9	10.8	15.3
32	24.5	13.3	18.8
40	29.5	16.	22.7
60	41.6	22.6	31.9
90	58.5	31.7	44.9

Railway

In the railway standard, a table is found for converting test voltages, and even though it is not to be used for routine testing, it gives a fine comparison of the three different test voltages that can be selected from; U_i is the amplitude of the 1,2/50 impulse test voltage, U_{AC} is the rms value of the power frequency test voltage, and U_{DC} is the value of the DC test voltage. If the voltages are not exactly matched, then linear interpolation between adjacent values is permitted.

High Voltage testing

Testing can be categorized into testing of dielectric materials and testing on complete equipment.
The tests on dielectrics are generally measures of permittivity, dielectric loss per unit volume, and dielectric strength. Whereas tests on complete equipment are measurement of capacitance, power factor or total dielectric loss, the ultimate breakdown voltage or flash over. Dielectric breakdown is a physical destructive test, where high voltage withstand test i.e. twice the rated voltage, but less than breakdown, is accepted as a test limit.

The dielectric strength of a given material depends on chemical and physical properties of the material, but also on different factors like; thickness, shape of the sample, previous electrical and thermal treatment of the sample, arrangement of the electrodes, and contact between electrodes and the sample, waveform and frequency of the applied voltage, temperature and humidity when the test is carried out and moist content of the sample.

Cracks and impurities can lead to unexpected breakdown, but also the presence of voids and cavities in the insulation material.

The term insulation coordination was originally introduced to arrange the insulation levels of the different components in the transmission system in such a manner that an insulation failure, if it did occur, would be limited to the place on the system where it would result in the least damage.

Now the insulation coordination contains the selection of the electric strength of equipment in relation to the voltages which can appear on the system for which the equipment is intended.

- Consideration shall be given to the extent that partial discharges can occur in solid insulation or along surfaces of insulation.
- The highest rms voltage which can occur in the system, equipment or internal circuits shall be used for basic insulation. The voltage is determined for supply at rated voltage and under the most challenging combination of other conditions within the rating of the equipment.
- In air, the partial discharges can occur at peak voltages in excess of 300V, which is the Paschen minimum. Failure is by gradual erosion or treeing leading to puncture or surface flashover, and partial discharge behaviour is dependent on the frequency of the applied voltage. Ceramic insulators can tolerate discharge throughout their anticipated lifetime.
- Heating causes degradation of the insulation, for example, by volatilization, oxidation or other long-term chemical changes. However, failure is due to mechanical reasons like embrittlement leading to cracking and electric breakdown. This cannot be tested in short time since thousand hours of testing would be required
- The DC test voltage shall be raised uniformly from 0V to the value specified within 5s and be held at that value for at least 60s. The tripping current shall be 100mA or for test voltages above 6kV to the highest possible value. For routine testing the tripping current may not be less than 10 mA.

In UL - the production test voltage differs from the prototype voltage test in time and impact level:

Production line test conditions						
Equipment rating (V)	Condition A			Condition B		
	AC	DC	Duration (s)	AC	DC	Duration (s)
250 or less	1000+2V[a]	1400	60	1200+2V[a]	1700	1
>250	1000+2V[a]	1000+2.8V[a]	60	1200+2.4V[a]	1700+3.4V[a]	1
a Maximum rated voltage						

Conclusion

When going through all the standards within the relevance of brake resistor technology, it is seen that a link between the rated voltage and the referenced test voltage, other than a factor that is multiplied, is missing. This completely lack of knowledge about the actual situation, and the question; at what conditions occasional moist gets the Impulse withstand voltage rating to its limit?, needs to be followed up with implementation tests on a prototype installation each time a new product is put on the market.

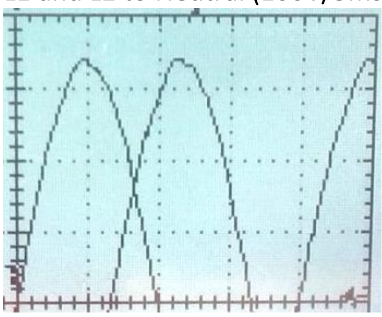
Harmonics are dealt with in other standards relating to supply equipment. Here rules are set with maximum peak values and a requirement for filtering transient noise in general.

In the end it is a matter of Equipment failure or cardiologic failure due to electric shock where a human body have a resistance in that order that a current higher than 30mA interferes with the biologic voltage level that drives the heart.

Hence 30mA is the maximum current that is allowed to run in a grounding system or chassis, and this limit is representing the sum of all leakage current coming from various equipment.

Actual voltages measured in the Danotherm test-lab:

L1 and L2 to Neutral (100V/5ms per Decade)

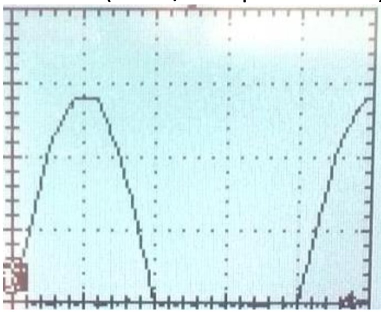


V_{pk} = 338V
V_{rms} = 234,1V
Phase dist. = 6,6ms

$$\varphi^{\circ} = \Delta t \cdot 360 \cdot f$$

Phase angle = 118,8°

L1 to L3 (200V/5ms per Decade)

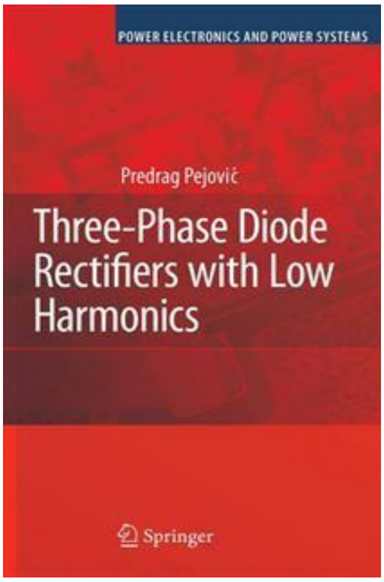


V_{pk} = 560V
V_{rms} = 407,6V

In both cases the lab-voltages are a little higher that the standard voltages.

References – Further reading

Three-Phase Diode Rectifiers with Low Harmonics
ISBN 978-0-387-32936-9



Articles and papers found on the web:

http://www.circuitstoday.com/polyphase-rectifiers

Adjustable Frequency Drives—Low Voltage Application Guide – www.eaton.com

"RMS Power"
– Article by Roy Lewallen, w7el@eznec.com