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Effect of Diode Arc-back fault on Short Circuit stress of Power Converter Transformer

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***Abstract*--In polypropylene petrochemical plants power adjustable speed drives (ASDs) are normally used to drive extruder or pump machines required by this type of industrial process. Each one of these ASDs is fed by a dedicated converter transformer which supplies a diode-front-end rectifier in the input converter part of the ASD.**

In case one diode of the input rectifier is faulted and becomes short-circuited, the converter transformer can be subjected to a dynamic short circuit stress being higher than that due to a fault occurring just at transformer terminals: this phenomenon is called diode arc-back fault in technical literature.

Simulations are carried out by means of EMTP-ATP software in order to show the effect of diode arc-back fault on the dynamic peak short circuit currents to which transformer windings are exposed.

***Keywords*: arc-back, diode, diode front end (DFE), converter transformer, short circuit current.**

I. Introduction

THE application of adjustable speed drives (ASDs) which feed machines like extruders or pumps, has become in the latest years a common practice for polypropylene chemical plants, especially on the medium voltage distribution (rated voltage from 3.3 kV to 11 kV).

These ASDs are most always fed at medium voltage distribution levels by dedicated multi-winding converter transformers [1]: the multi-winding transformer, having a typical arrangement of 3-winding or 5-winding, is needed for selecting the most appropriate inverter output voltage to the driven motor, to provide an input EMC filter for the conducted emissions originating from the medium voltage supply, and to realize a multi-pulse reaction at line supply side for the reduction of harmonic currents injected into the network from the converter input rectifier [2], [11].

The most common type of input rectifier is the DFE – diode front end, since normally there is no need for regenerating power towards the supply network and thus it is not necessary to use an AFE – active front end rectifier, made instead of forced-commutated valves [1], [2].

The capability of the drive input converter transformer windings and relevant output terminals to dynamically withstand a short circuit fault is usually demonstrated by relevant manufacturer through a calculation procedure according to applicable international standards [3], [4]. For assessing the mechanical stress due to the short circuit event, the most common design approach followed by the transformer manufacturer is to calculate the let-through short circuit current for the scenario of a three-phase fault occurring just at one of the secondary windings of the multi-winding converter transformer, while the possibility of a single diode arc-back fault event occurring in the converter input rectifier is normally disregarded at all.

The novelty of this work consists in highlighting the due importance of taking always into the account the diode arc-back fault event [5], [12], when evaluating the worst type of short circuit fault to which a converter transformer supplying a DFE rectifier can be subjected, avoiding that the manufacturer underestimates the mechanical stress against short circuit for transformer windings as well as for output transformer terminals.

A. System Data

The electrical scheme of a typical industrial ASD, which drives a medium voltage pump motor (3 MW rated power at 3.3 kV), is shown in Fig. 1. The input converter transformer 11/1.7/1.7 kV is three-winding type, and the two secondary windings have a phase shift of 30 degrees between them in order to realize a 12-pulse DFE rectifier.

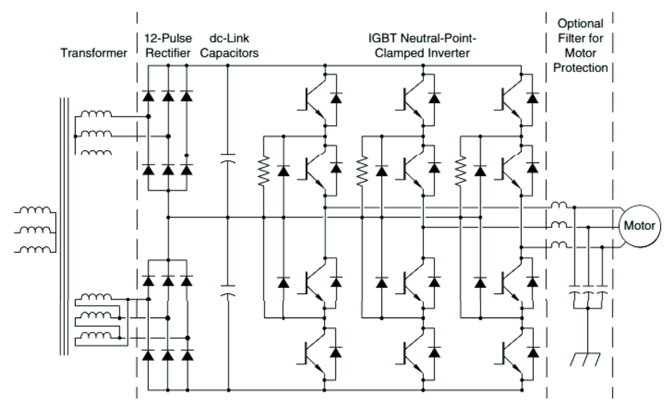

Fig. 1. 12-pulse diode-front end rectifier of the power ASD under study

Main electrical parameters for the network components are reported in the Appendix.

B. Modeling

For the aim of numerical simulation by ATP (Alternative Transient Program) [6], the electrical network is simplified and modeled as shown in Fig. 2, following the general guidelines presented in [7].

All equivalent impedances of the network components are

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referred to the transformer secondary rated voltage (1.7 kV) and to the primary-to-secondary transformer winding power (2 MVA), as described in detail into the Appendix.

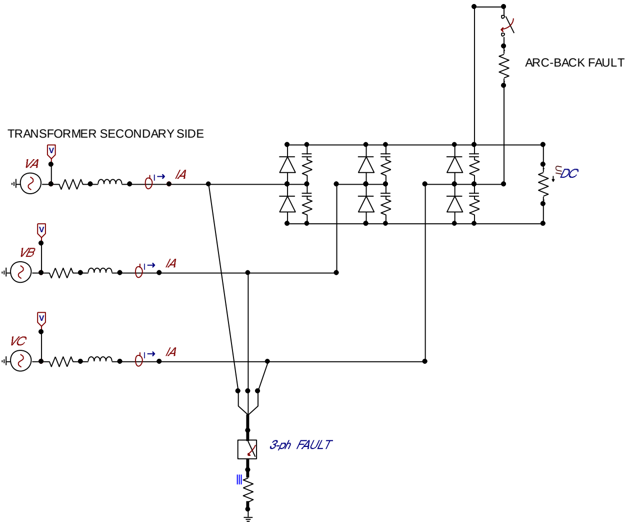

Fig. 2. EMTP-ATP model for the aim of short circuit simulations

Only the network components, being strictly necessary for the aim of simulating a short circuit on the secondary winding side of the converter transformer, are modeled. Therefore, the modeling is carried out only up to the bridge rectifier, without the necessity of taking into account also the DC bus, the multi-level inverter and the motor, considering that by using a DFE rectifier converter neither the inverter nor the motor are able to contribute to a short circuit current fault occurring just on the upstream supply line side of the rectifier [8].

The transformer short circuit impedance and the network supply short circuit impedance are modeled as R-L components. The actual transformer vector group is slightly more complicated than a simple three-winding arrangement, as it is shown and explained into the Appendix: anyway, in order to grasp in simplified way the essence of the diode arc-back fault phenomenon, the transformer group is intentionally simplified as Yy star connection windings.

The diode rectifier fed by one secondary transformer winding is modeled as a six-diode bridge configuration, each diode being provided with its parallel R-C snubber to avoid voltage spikes. Only one among two diode rectifiers is modeled because the three-phase fault is simulated occurring at just one of the two secondary transformer windings, as well as only one short-circuited faulted diode of just one rectifier is simulated.

The three-phase short circuit fault is realized by means of a three-phase switch closing at a certain time, while the diode arc-back short circuit fault is simulated by a means of a switch in parallel to one diode of the rectifier bridge.

II. Pre-Analysis and Discussion

Before performing numerical simulations, few theoretical topics from existing technical literature are first analyzed and discussed.

A. Diode Arc-Back Phenomenon

It is well known from IEC standards for short circuit current calculation [8], that only reversible static converter-fed drives (for example, rolling mill drives) are considered for contribution to the initial symmetrical and peak three-phase short circuit currents, if the rotational masses of the motors and the static equipment provide reverse transfer of energy for deceleration (a transient inverter operation) at the time of short circuit. Therefore, DFE converter drives are excluded from this possibility.

However, IEEE standards for short circuit current calculation [5], recommends that the design of a DFE converter takes into consideration the phenomenon of arc-back current.

As shown in Fig. 3, an arc-back diode current occurs when a single diode loses its semiconducting properties, forms a physical connection, and continues to conduct.

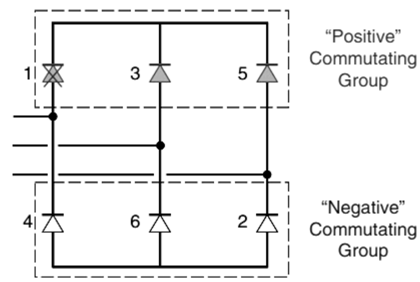

Fig. 3. Single diode failure in Diode-front-end rectifier

As shown in Fig. 4, fault current “Ia” through the failed diode is the sum of currents “Ib” and “Ic” from the other two diodes of the same commutating group that have not failed, thus increasing total fault current above bolted short circuit conditions without this phenomenon.

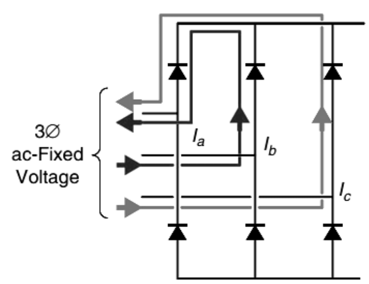

Fig. 4. Initial fault current path for diode “a” failure

The greatest arc-back current occurs in a converter at no-load operating conditions, and its peak value can theoretically reach 137 % of the peak value of a bolted three-phase short circuit [5], as is shown also in the formulas in the Appendix.

B. Mechanical stress due to Short Circuit

It is well known from technical literature that short circuit currents cause several types of electromagnetic forces in transformer windings [9], [10]. Axial short circuit forces with core-type transformers and radial short circuit forces with shell-type transformers, respectively, are very sensitive to the relative positions of the windings holding ampere-turns of opposite sign [3].

With core-type transformer, as is the case under study, the following main electromagnetic forces can be considered [3]:

- radial inward (compression) or outward (tensile) force on each physical winding;
- maximum axial compression force on each physical winding.

The electromagnetic forces are in general proportional to the squared current, independently of the type of transformer windings arrangement [9], [10].

The same proportional dependency of the square-current applies also to the bending stress caused by the electro-dynamic forces between transformer output terminal leads [4].

Therefore, the diode arc-back phenomenon increases bracing requirements for both transformer windings and output terminals by the square-of-fault current increase, that is the square of 137% which gives 188%, and must be properly considered when selecting equipment bracing.

C. Study case

Two types of faults are simulated and compared: the former is a three-phase short circuit occurring at output terminals of one of two secondary transformer windings and it is the fault type on the basis of which the manufacturer of the converter transformer provided the calculation of electromagnetic stress inside the transformer windings, while the latter is a diode arc-back short circuit occurring in one of the six diodes of the bridge rectifier supplied by one of the two secondary transformer windings.

III. Results

The results of numerical simulations are shown graphically in the following figures. Phase over-currents (instantaneous peak values) on secondary transformer winding voltage level, are chosen as the most significant magnitudes in order to evaluate the worst short circuit impact.

A. Three-phase short circuit fault

A three-phase short circuit fault is simulated on the terminals of one secondary winding of the three-winding converter transformer. The time instant of the fault occurrence (0.025 s) is chosen such as to reach the highest peak on one of the three phases.

The resulting phase currents are shown in the Fig. 5, while an enlarged zoom view of the same short circuit phase currents is shown in Fig. 6.

The dynamic peak current of 21 kA is reached on one phase after almost 10 ms (half a cycle) from the fault occurrence, while the other two phases assume the same value of 10.5 kA (half the peak) and are both of the opposite sign with respect to the phase reaching the peak, due to the condition of three-phase balanced circuit.

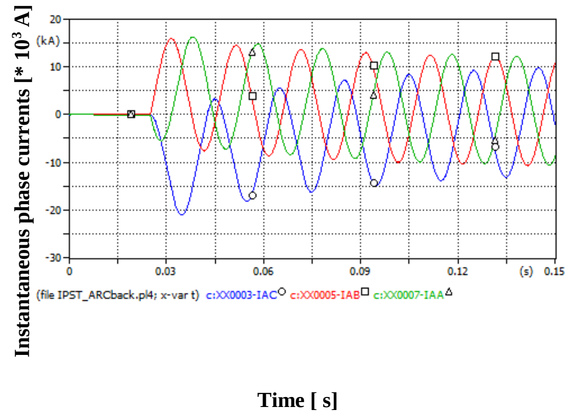

Fig. 5. Three-phase fault currents, transformer secondary side

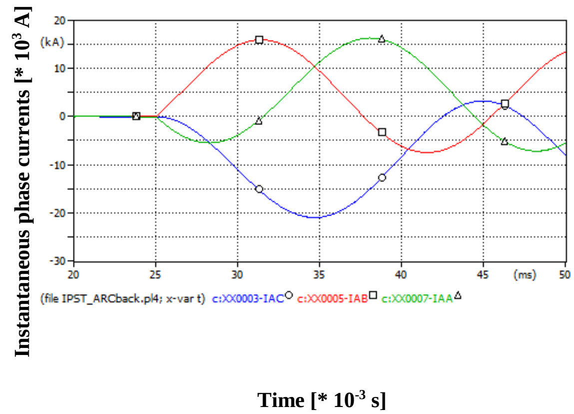

Fig. 6. Three-phase fault currents, transformer secondary side (Zoom view)

B. Diode arc-back short circuit fault

Now an arc-back fault current is simulated: the faulted diode is that shown in previous Fig. 2, and it is where the maximum fault current will flow. The resulting short circuit phase currents are shown in the next figure.

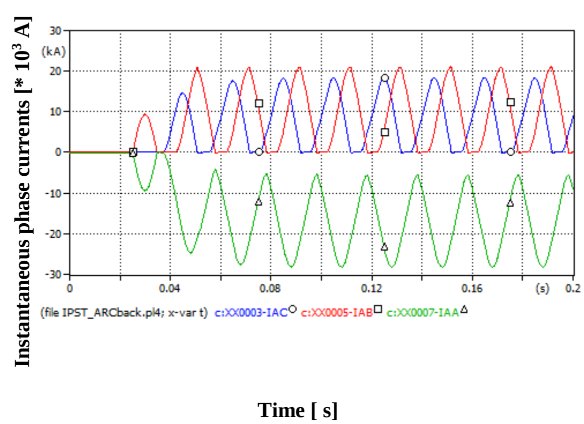

Fig. 7. Diode arc-back fault phase currents

As can be seen, after an initial transient, the fault currents maintain the same shape.

In the following figure, an enlarged zoom view of the short circuit phase currents is shown.

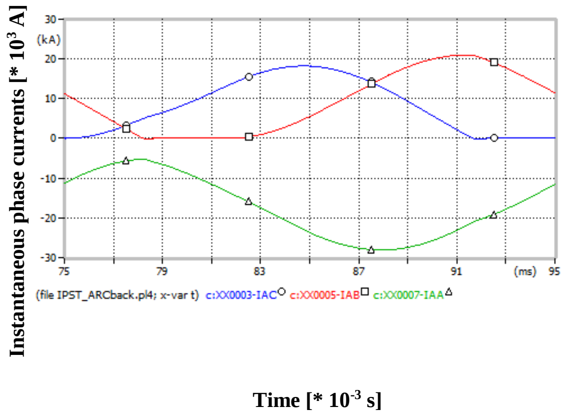

Fig. 8. Diode arc-back fault phase currents (Zoom view)

As can be seen, the phase with the faulted diode reaches the maximum peak value of 28 kA at the instant of 0.087 s, that is almost 3 cycles (60 ms) after the instant of fault occurrence. The other two un-faulted phases are half this peak value and opposite in sign, similarly to what happened for a balance three-phase short circuit.

This type of diode fault, similarly to what happens for the three-phase short circuit fault, is cleared typically within 200 ms from the instant of fault occurrence by the over-current protection relay installed on the primary feeder side of the converter transformer, which acts as back-up protection for a fault happening on the secondary side of the converter transformer.

The ratio between the diode arc-back current dynamic peak and the three-phase current dynamic peak amounts to:

$$r = \frac{Ip_{arc-back}}{Ip_{3-phase}} = 1.33 \qquad \text{p.u.} \qquad (1)$$

where:

r	ratio between arc-back peak current and 3-phase peak current
$Ip_{arc-back}$	peak of arc-back current (28 kA)
$Ip_{3-phase}$	peak of three-phase current (21 kA)

The factor of equation (1) is a bit lower than the maximum theoretical value of 1.37 p.u. mentioned in paragraph II.B, because the circuit is not purely inductive.

Therefore, the mechanical stresses calculated by the converter transformer manufacturer will have to be rescaled proportionally by a factor equal to the square of 1.33 p.u., that is each stress has to be multiplied by 1.77 p.u.

C. Comparison with manufacturer design limits

The manufacturer of the converter transformer provided the calculated values vs. design withstand values for the electromagnetic forces acting on windings (calculation though proprietary software based on FEM / MoM methods) and on output terminals (calculation based on IEC procedure [4]), in case of a three-phase short circuit at secondary windings.

Here after, only the type of stresses which become critical in case of a diode arc-back fault are summarized; the complete information is reported in the Appendix.

<u>Calculated stresses vs. Allowable limits:</u>

- First Half of HV primary zig-zag winding:
  Axial Compression stress = 14.2 N/mm^2 vs. 20 N/mm^2
- Second Half of HV primary zig-zag winding:
  Axial Compression stress = 12.4 N/mm^2 vs. 20 N/mm^2
- LV secondary winding output terminals:
  Bending moment stress = 80.99 N/mm^2 vs. 180 N/mm^2

<u>Arc-Back fault stresses vs. Allowable limits:</u>

- First Half of HV primary zig-zag winding:
  Axial Compression stress = 25.1 N/mm^2 vs. 20 N/mm^2
- Second Half of HV primary zig-zag winding:
  Axial Compression stress = 21.9 N/mm^2 vs. 20 N/mm^2
- LV secondary winding output terminals:
  Bending moment stress = 143.4 N/mm^2 vs. 180 N/mm^2

As can be seen from the above results, the safe margins existing between the allowable design values and the actual calculated values for the axial compression stresses of primary HV winding are too low: in case of a diode arc-back fault these limits would be exceeded and the HV winding would be damaged. Due to these reasons, the transformer manufacturer was requested to upgrade the mechanical stiffness and anchorage of the affected winding.

The bending stress on LV winding output terminals is instead still within the withstand limit.

IV. CONCLUSIONS

Analysis of converter design and operating experience show that diode arc-back failure of semiconductor rectifiers is the most common fault of converter systems. The calculation of arc-back currents, as recommended by IEEE standard 551, is an important concern in the theory and applications of converter systems, although it still needs to be completed addressed by IEC standard 60909.

When a converter transformer feeds an adjustable speed drive having a diode front end (DFE) input rectifier, the transformer manufacturer almost always neglects the effect of a single diode fault on the dynamic peak of short circuit current to which the transformer windings and output terminals can be subjected, but the manufacturer considers only the let-though three-phase short circuit current for a fault just happening on the secondary terminals of the transformer. This design approach is deemed not acceptable since it can easily underestimate the real stress on some windings and on some output terminal conductors, as it was easily demonstrated by simulations.

For industrial applications of multi-winding transformers supplying DFE converters, the following engineering design approach is highly recommended when assessing the dynamic withstand capability of the transformer against short circuit:

- calculate the maximum three-phase short circuit for a fault occurring at the output terminals of one of the secondary windings;
- rescale the three-phase short circuit current by a factor of 1.37 p.u. due to the event of diode arc-back fault in the converter input rectifier;
- then calculate the electromagnetic stresses inside the transformer windings and inside the output terminals.

In this paper simplified models for both the multi-winding converter transformer and for the DFE diode rectifier have been used, just for the aim of best highlighting the phenomenon of diode arc-back fault. In future this work could be further improved by modeling the complete 12-pulse diode rectifier and by simulating a more sophisticated and complete three-phase transformer model (e.g. BCTRAN or HYBRID models available in ATP software [6]) which takes into account also the zero-sequence transformer impedance.

V. Appendix

A. Electrical Network Component Data

TABLE I
SUPPLY MEDIUM VOLTAGE NETWORK

Equipment	Parameters
Network Supply to the adjustable speed drive	11 kV rated voltage
	50 Hz rated frequency
	500 MVA Max. 3-ph. short circuit power
	26.24 kA symmetrical (RMS) Max. 3-ph short circuit current
	X/R ratio 20

The actual arrangement of the windings of one phase of the multi-winding transformer is represented in the following drawing (the arrangement for the other phases is similar):

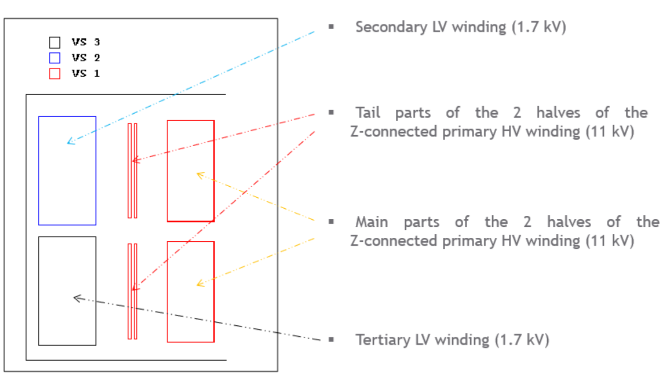

Fig. 9. Winding arrangement of multi-winding converter transformer

The vector group of the transformer is Zy11:45d10:45, which means that:

- the primary winding (Z) has a Star/Zig-zag connection;
- the secondary LV star winding (y11:45) is shifted +7.5 degrees with respect to the primary winding;
- the tertiary LV delta winding (d0:45) is shifted -22.5 degrees with respect to the primary winding;
- the angular shift between the secondary and tertiary windings is therefore 30 degrees (12-pulse reaction).

Since in the industrial plant there was another identical ASD motor fed from the same 11 kV busbar, the above type of vector group was intentionally selected for the aim of realizing globally a 24-pulse reaction seen from the 11 kV supply system, thus reducing further the global harmonic current injection towards the 11 kV supply system.

In fact, the other ASD motor is fed by a similar three-winding transformer having the vector group Zy0:15d11:15, which means that the star-winding is shifted -7.5 degrees with respect to primary zig-zag-winding, while the delta-winding is shifted + 22.5 degrees with respect to the primary winding.

The global result is to have four secondary transformer windings being shifted 15 degrees among each other in such a way to realize a 24-pulse reaction on the 11 kV supply primary side.

TABLE II
CONVERTER TRANSFORMER

Equipment	Parameters
Three-winding Transformer dedicated to the supply of Gear Pump Motor (3MW motor at 3.3 kV)	4 / 2 /2 MVA rated power
	11 kV / 1.7 kV / 1.7 kV rated voltage ratio
	Zy11:45d10:45 Vector group
	50 Hz rated frequency
	Core-type
	Z_{12} = 8% (ref. 2 MVA) Primary to secondary impedance
	Z_{13} = 8% (ref. 2 MVA) Primary to tertiary impedance
	Z_{23} = 8% (ref. 2 MVA) Secondary to tertiary impedance
	X/R ratio 20

For the simulation of the circuit model shown in Fig. 2, transformer and supply network impedances are calculated referred to the transformer secondary voltage (1.7 kV) and to the transformer base power (2 MVA). In the calculation, the impedance is approximated to the reactance due to X/R = 20:

Network impedance Z_N:

$$Z_N = 1 \text{ p.u.} * (2 \text{ MVA} / 500 \text{ MVA}) = 0.004 \text{ p.u.} \quad (2)$$

Z_N is the per unit impedance of the supply network

(Network + Transformer) impedance Z_T:

$Z_T = Z_N + Z_{12} = 0.004$ p.u. + 0.08 p.u. = 0.084 p.u. (3)

Z_N is the per unit impedance of the supply network

Z_{12} is the per unit impedance of the transformer (primary-to-secondary winding)

$Z_T = 0.084$ p.u. * [(1.7 kV)^2 / 2 MVA] = 0.121 ohm (4)

Z_T is the combined impedance of network and transformer

The total impedance Z_T is finally split into inductance L_T and resistance R_T:

$L_T \approx Z_T / (2 * \pi * 50) = 385$ mH (5)

$R_T \approx Z_T / (X/R) = 0.00605$ ohm (6)

TABLE III

ELECTROMAGNETIC STRESSES INSIDE TRANSFORMER WINDINGS

Type of Winding	Type of Stress	Calculated value (N/mm^2)	Allowable value (N/mm^2)
Primary 1st half of zig-zag	Radial compression	0	27
	Radial tensile	10.5	72
	Axial compression	14.2	20
Primary 2nd half of zig-zag	Radial compression	0	27
	Radial tensile	11.4	72
	Axial compression	12.4	20
Secondary	Radial compression	8.4	54
	Radial tensile	0	81
	Axial compression	0.9	20
Tertiary	Radial compression	8.4	54
	Radial tensile	0	81
	Axial compression	0.9	20

TABLE IV

ELECTRODYNAMIC STRESSES BETWEEN OUTPUT TERMINALS

Output Terminals	Type of Stress	Calculated value (N/mm^2)	Allowable value (N/mm^2)
HV Primary side	Bending moment	33.81	180
LV Secondary side Tertiary side	Bending moment	80.99	180

B. Formulas for diode Arc-back fault current

The general expression of the diode arc-back fault current (dynamic peak value) is given by the following equation [5]:

$$Ip_{arc-back} = I_m \left[1 + 2 * cos\left(\alpha + \frac{\pi}{6}^{rad}\right)\right] * \left[1 - \left(\frac{1}{4}\right)^n\right] \quad (7)$$

where:

α	=	firing angle (it is null for a diode rectifier)
n	=	number of periods from the start of fault
I_m	=	$\sqrt{2}$ times the bolted 3-phase fault $I_{3\text{-phase}}$
$I_{3\text{-phase}}$	=	3-phase short circuit fault current (RMS)
$Ip_{arc\text{-back}}$	=	dynamic peak of arc-back fault current

The non-damped dynamic peak value, with $\alpha = 0$ and with the number of periods "n" approaching infinity, thus becomes:

$$Ip_{arc\text{-back}} = 2.73 * I_m = 1.37 * Ip_{3\text{-phase}} \quad (8)$$

where:

$Ip_{3\text{-phase}}$	=	dynamic peak of 3-phase bolted fault, which is equal to $Ip_{3\text{-phase}} = 2 * I_m$ for a purely inductive circuit [8]
$Ip_{arc\text{-back}}$	=	dynamic peak of arc-back fault current

VI. ACKNOWLEDGMENT

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