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Première édition
First edition
2001-08

Systèmes d'isolation électrique – Contraintes électriques produites par des impulsions de tension appliquées périodiquement –

Partie 2: Etat de l'art

Electrical insulation systems (EIS) – Electrical stresses produced by repetitive impulses –

Part 2: State of the art

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La CEI 62068-2, qui est un rapport technique, a été établie par le comité d'études 98 de la CEI: Systèmes d'isolation électrique (SIE)

Le texte de ce rapport technique est issu des documents suivants:

Projet d'enquête	Rapport de vote
98/122/CDV	98/129/RVC

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de ce rapport technique.

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTRICAL INSULATION SYSTEMS (EIS) – ELECTRICAL STRESSES PRODUCED BY REPETITIVE IMPULSES –

Part 2: State of the art

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IEC 62068-2, which is a technical report, has been prepared by IEC technical committee 98: Electrical insulation systems (EIS).

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
98/122/CDV	98/125/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

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0 Introduction

0.1 Vue d'ensemble

Une série de recommandations faisant partie de la CEI 62068 sera développée pour permettre l'évaluation des systèmes d'isolation électriques (SIE) sous contraintes électriques produites par des impulsions de tension appliquées périodiquement, et provenant de dispositifs d'électronique de puissance comme les onduleurs de tension.

L'influence de l'application de ces impulsions répétitives sur les systèmes d'isolation électrique (SIE) a été étudiée de manière approfondie et a été révisée au cours de la dernière décade (voir par exemple la référence [1])[1]. Cependant, les phénomènes de vieillissement dus aux tensions de choc ne sont encore pas bien compris et restent controversés comme par exemple pour le développement de tests d'évaluation.

0.2 Recherches associées aux développements de l'électronique de puissance

Récemment, des composants haute tension et hautes fréquences comme les IGBT (Transistor bipolaire à grille isolée: Insulated gate bipolar transistor) ont été développés et utilisés comme par exemple les transmissions pour moteur.

Les systèmes d'isolation électrique utilisés dans les appareils alimentés par convertisseurs comme les bobinage de moteur, sont exposés à plusieurs tensions de chocs répétées associées à des fronts de tension rectangulaires soumis à une modulation de largeur d'impulsion (MLI), et la durée de vie peut rapidement être réduite par des processus de vieillissements thermiques et/ou électriques. Le nombre d'articles sur ce sujet a rapidement augmenté dans les années 1990 et dans le monde entier. Plus particulièrement, les caractéristiques du vieillissement et les mécanismes induits ont intensivement été mesurés et étudiés sur des systèmes d'isolation comprenant des fils émaillés, des vernis et des films utilisés dans les moteurs Basse Tension, mais aussi sur des isolants de câbles destinés aux moteurs linéaires. De nombreux articles ont été préparés sur la rupture diélectrique des transformateurs et des appareillages à isolation gazeuse (GIS = Gaz Insulated Switchgear) provoquée par la résonance entre ces appareils, en haute fréquence.

[1] Le chiffre entre crochets se réfère à la bibliographie.

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0 Introduction

0.1 Overview

A series of parts of IEC 62068 will be developed for the evaluation of electrical insulation systems (EIS) under electrical stresses produced by repetitive impulses from power electronics devices such as inverters.

The influence of these repetitive impulses on electrical insulation systems (EIS) has been intensively investigated and reviewed in the last decade (see for example reference [1])[1]. Nevertheless, the ageing phenomena due to the surges are not yet well understood and controversial as to evaluation testing.

0.2 Research trend due to power electronics development

Recently, high-voltage high-frequency power devices such as IGBT (Insulated Gate Bipolar Transistor) have been developed and applied as motor drives.

Electrical insulation systems of inverter-fed apparatus such as motor windings are exposed to repetition of periodic surges coming from rectangular voltage under Pulse Width Modulation (PWM), and the insulation life may be shortened through thermal and/or electrical ageing. The number of papers on the subject increased rapidly in the 1990s all over the world. In particular, the ageing characteristics and mechanisms have been intensively measured and investigated on insulation systems including magnet wires, varnish and films used in low-voltage motors in addition to cable insulation for Maglev linear motors. Several papers have been prepared on the electrical breakdown of the transformer and GIS (Gas Insulated Switchgear) due to the resonance between the apparatus with high frequency.

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[1] The figures in square brackets refer to the bibliography.

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SYSTÈMES D'ISOLATION ÉLECTRIQUE – CONTRAINTES ÉLECTRIQUES PRODUITES PAR DES IMPULSIONS DE TENSION APPLIQUÉES PÉRIODIQUEMENT –

Partie 2: Etat de l'art

1 Domaine d'application

La présente partie de la CEI 62068 est un rapport technique qui traite du dernier état de l'art connu des travaux de recherches développés sur les phénomènes induits par les contraintes électriques produites par des impulsions de tension appliquées périodiquement. Ce rapport vise à obtenir d'une part une meilleure compréhension des phénomènes induits et d'autre part à établir des méthodes d'évaluation fiables.

2 Génération des impulsions de surtension de choc

Les phénomènes de réflexion des impulsions de choc produites par la commutation d'un onduleur placé en extrémité d'un câble peuvent provoquer le doublement, voire le triplement de la valeur initiale de la tension crête appliquée [2] [3]. Cette multiplication dépend des conditions existant dans le circuit électrique, et sa valeur crête s'atténue pendant la propagation. La distribution du potentiel dans le bobinage des moteurs n'est pas non plus linéaire comme on le verra en 4.3.1. Comme la valeur dV/dt de la tension de choc de l'onduleur augmente, le rapport du potentiel dans la première spire des bobinages du côté ligne augmente.

3 Phénomènes physiques liés au vieillissement

La compréhension des mécanismes de défaillance sous contraintes impulsionnelles répétées peut conduire à la proposition de méthodes d'évaluation de meilleure qualité.

Un travail très important a été réalisé et a permis de déduire que les ruptures d'isolation étaient dues à un effet synergique de l'action des décharges partielles, de l'échauffement diélectrique et de la création d'une charge d'espace. Chaque analyse est plus ou moins en relation avec les phénomènes qui suivent. Bien que la référence détaillée ne soit pas donnée dans ces paragraphes, l'analyse de la partie suivante consacrée aux machines tournantes peut être source utile d'informations.

3.1 Décharges partielles (DP)

Les décharges partielles (DP) peuvent être un des mécanismes les plus défavorables aux systèmes d'isolation électriques. Les SIE des appareils basse tension comme les moteurs ont été conçus pour fonctionner sans décharge partielle avec des tensions alternatives inférieures au seuil d'apparition des décharges. Avec des impulsions de surtension, cependant, ces conditions d'absence de décharges partielles ne durent en général pas.

3.2 Effet de la polarité des tensions d'impulsion

L'effet de la polarité de la tension a été étudié avec un train d'impulsions bipolaires ou unipolaires (positives ou négatives). Le temps jusqu'à la rupture pour des impulsions positives est plus long que pour des impulsions négatives. La rupture se produit encore plus rapidement en bipolaire. Ce phénomène peut s'expliquer par la différence existant dans la formation de la charge d'espace.

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ELECTRICAL INSULATION SYSTEMS (EIS) – ELECTRICAL STRESSES PRODUCED BY REPETITIVE IMPULSES –

Part 2: State of the art

1 Scope

This part of IEC 62068 is a technical report dealing with the latest available state of the art of the research on the phenomena induced by the electrical stresses produced by repetitive impulses. This report aims at a better understanding and establishment of specified evaluation methods.

2 Generation of overvoltage surges

The reflections of the switching surge from an inverter at the cable terminal may double or triple the value of the original peak voltage [2] [3]. The multiplication depends upon the circuit condition and the peak value attenuates during propagation. The potential distribution along motor windings is not linear as mentioned in 4.3.1. As the *dV/dt* of the inverter surge increases, the potential ratio in the first turn of line-side windings increases.

3 Physical ageing phenomena

The understanding of failure mechanisms under repetitive impulse conditions can lead to better evaluation methods.

Extensive work has been carried out and indicated that the failures of insulation are due to a synergetic effect of partial discharge, dielectric heating and space charge formation. Each report is more or less related to the following phenomena. Although the detailed citation is not given in these subclauses, the analysis in the next clause on rotating machines may be useful.

3.1 Partial discharges (PD)

Partial Discharges (PD) can be one of the most influential phenomena of electrical insulation systems. The EIS of low-voltage apparatus such as motors have been designed for PD-free operation under a.c. voltage lower than PD inception voltage. Under over-potential impulse condition, however, the PD-free condition does not stand in general.

3.2 Effect of the polarity of pulse voltages

The polarity effect was examined under a bipolar and a unipolar pulse wave (positive and negative). The failure time under positive pulse is longer than that under negative pulses. The failure time under bipolar pulses is shortest. This phenomenon may be explained by the difference in space charge formation.

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3.3 Effet de la fréquence des tensions d'impulsion

L'effet de la fréquence sur la durée de vie a été étudié. Au dessus d'une fréquence de seuil, le niveau de dégradation de l'isolation des fils augmente. Ce résultat a été expliqué par l'échauffement diélectrique dans la couche isolante.

3.4 Chargement de la surface

En utilisant des mesures de décroissance des charges sur différents matériaux diélectriques, le rôle de la polarité des impulsions est démontré [4].

3.5 Autres effets importants

Les effets de la température, de l'humidité, et/ou de l'air ambiant (tel que l'existence d'ozone) sont particulièrement étudiés du point de vue de leur impact sur la durée de vie des échantillons soumis à contraintes impulsionnelles répétitives.

4 Machines tournantes

4.1 Etudes générales

Ces références [5] [6] [7] [8] [9] [10] [11] décrivent principalement les conséquences d'une alimentation basse tension par onduleur pour les machines tournantes. Différentes règles sont données et sont associées à la longueur du câble, la nature du composant de commutation. Leurs auteurs préconisent la normalisation des essais. La référence [9] détaille les règles de réparation ou les spécifications destinées aux machines asynchrones.

4.2 Identification de la tension (des contraintes)

Les transistors IGBT peuvent avoir des temps de montée entre 50 ns et 200 ns. Par conséquent il est présenté une nouvelle étude, dédiée à l'application des contraintes électriques des systèmes d'isolation résultant de la distribution non linéaire de la tension dans le bobinage des machines tournantes quand ces systèmes sont soumis à des trains d'ondes à front raide de forme carrées d*V*/d*t*, répétitives (plutôt qu'à des essais de formes d'onde impulsionnelle). Les amplitudes et les temps de montée des impulsions générées par des variateurs de vitesse (ASD: Adjustable Speed Drive), induites sur les bornes des machines, sont mesurées. Ces références [12] [13] [14] [15] [16] [10] [17] [18] présentent les résultats obtenus (généralement sur les machines tournantes) de la distribution des tensions tant dans le bobinage qu'aux bornes de connexion du moteur.

Ces références donnent également des lois de comportement pour la détermination de la longueur de câble ou pour l'installation de transistor IGBT.

4.3 Modélisation

4.3.1 Distribution de tension

Ces références [19] [20] [21] [22] [23] [24] [25] donnent ou proposent des modèles capables d'expliquer la distribution de tension et la propagation des impulsions dans le bobinage en fonction de diverses caractéristiques de la machine (type de bobinage, type de câble, type d'émail, diametre du fil).

4.3.2 Vieillissement multicontraintes

Ces références [26] [27] sont les premières tentatives d'une compréhension du vieillissement des matériaux isolants utilisés dans le bobinage quand ils sont alimentés par des onduleurs. Ils sont de nature très générale. Récemment, une nouvelle approche a été formulée, résumant les nouveaux développements dans ce domaine et proposant l'identification exacte du rôle de chacun des paramètres [28].

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3.3 Effect of frequency of pulse voltages

The frequency dependence of the failure time was examined. Above a threshold frequency, the degradation rate of the wire insulation increases. The result was explained with the dielectric heating in the insulation layer.

3.4 Surface charging

Using charge decay measurements on different dielectric materials, the role of the polarity of impulse is demonstrated [4].

3.5 Other important effects

The effects of temperature, moisture and/or ambient atmosphere such as ozone on the insulation life of the samples under repetitive impulse condition are reported.

4 Rotating machines

4.1 General studies

The papers [5] [6] [7] [8] [9] [10] [11] mainly describe the effect of feeding low-voltage rotating machines by inverters. Different laws related to cables length, the role of the nature of the switch, and the need for standardization of testing are given. Reference [9] indicates repair laws or specification for asynchronous machines.

4.2 Voltage (stress) identification

IGBT drives can have rise times of 50 ns to 200 ns. Thus, a new study on electrical stress of insulation systems due to the non-linear voltage distribution of mush-wound motors when subjected to repetitive steep d*V*/d*t* square-pulse waveforms (rather than impulse wave testing) is presented. Magnitude and rise time of the repetitive ASD (Adjustable Speed Drive) surge-voltage transient induced on the machine terminals are reviewed. Papers [12] [13] [14] [15] [16] [10] [17] [18] present results (generally on equipped rotating machines) of voltage distribution both in the winding and at the motor terminal.

They also give rules for cable length determination or IGBT installation.

4.3 Modelling

4.3.1 Voltage distribution

Papers [19] [20] [21] [22] [23] [24] [25] give or propose models able to explain voltage distribution and propagation in the winding according to different characteristics (type of winding, type of cable, type of enamel, wire gauge).

4.3.2 Multistress ageing

Papers [26] [27] are a first attempt to approach the ageing of winding insulating materials when fed by inverters. They are very general. A recent one intends to summarize new developments in this field and to propose an evaluation of the impact of the different parameters [28].

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4.4 Phénomènes physiques

Tableau 1 – Résumé des caractéristiques principales des différentes alimentations utilisées pour étudier l'impact de fronts de tensions périodiques

Réf.	Forme de l'onde	Amplitude	Fréquence	Temps de montée (s) ou front de tension (kV/µs)	Rapport cyclique (%)	Essai typique	Critère de défaillance
[29]	Carré	±2,5 kV	60 Hz à 20 kHz	25 ns	10 à 50	U_{pp} – 2000 V 20 kHz 50 % *T* = variable	Chute de tension
[30]	Carré	+1,25 kV	60 Hz à 20 kHz	50 ns	10 à 50	U_{pp} – 2000 V 20 kHz 50 % *T* = variable	Chute de tension
[31]	Carré	+1,75 kV	60 Hz à 20 kHz	50 ns	10 à 50	U_{pp} = 1900 V 20 kHz 50 % *T* = 90 °C et 180 °C	Chute de tension
[32]	Sinus	2,5 kV	45 Hz à 6,5 kHz	–	–	U_{pp} – 1750 V 1050 Hz *T* = variable	Fusible
[33]	Sinus	4,5 kV 3 kV 1,8 kV	50 Hz 500 Hz 15 kHz	–	–	Toutes *T* = 140 °C	Fusible
[34]	Impulsions	±2 kV	5 kHz	0,2 / 20 µs 0,1 / 5 µs	Inconnu	U_p – ±1400 V	Passage d'un courant
[35]	Carré	±2 kV	10 kHz	1 kV / µs	10 à 50	U_p – ±1500 V 10 kHz 1 kV/µs *T* = 20-80 °C	Fusible Mesure du courant
[36]	Impulsions	22 kV–40 kV (crête)	18,5 kHz	0,2 µs / 6,5 µs		Toutes	Eclateur
[37]	Sinus	6 kV (crête) 6 kV (crête)	50, 250, 500 Hz 1, 2,5, 5 kHz	–	–	Toutes	Aucune
[38]	Impulsions	12 kV	Jusqu'à 60 kHz	NG	16	Toutes	Inconnu
[39]	Carré Superposé sur une tension alternative 50 Hz Carré	0,5 U_0 (jusqu'à 920 V) +6 kV	24 kHz 20 kHz	0,8 µs / 2 µs 3 µs	– 20	Celle c Toutes	Aucune Inconnu
[40]	Impulsion	4 kV	ND	9 ns / 16 ns	ND	ND	ND
[41]	Carré	±7 kV	2 Hz à 20 kHz	0,3 µs / 1 µs	(largeur: 1-100 µs)	Unipolaire 1 kHz	Aucune
[42]	Carré	10 kV (crête-crête)	Jusqu'à 25 kHz	Jusqu'à 8 kV/µs	10-50	Toutes	Chute de tension
[43]	Impulsion	600 V + surtension (OS)	10 kHz	120 ns	Durée de OS = 2,5 µs	Celle c	Aucun

NOTE La définition du front de montée (dV/dt)' n'est pas toujours la même. Parfois c'est la différence entre les valeurs à 10 % et à 90 % de la tension mesurée (ce qui est la véritable définition), alors que dans d'autre cas il s'agit simplement de V_{max} / t_{r})

OS signifie «Suroscillation»
ND signifie «Non décrit»;
Aucune signifie qu'aucune autre mesure que la durée de vie n'est entreprise;
Toutes signifie que la totalité de la configuration a été testée.

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4.4 Physical studies

Table 1 – Summary of the main characteristics of the different power supplies used when studying the impact of periodical fronts

Ref.	Voltage waveform	Magnitude	Frequency	Rise time (s) or front (kV/µs)	Duty cycle (%)	Typical	Failure criteria
[29]	Square	±2,5 kV	60 Hz 20 kHz	25 ns	10 50	U_{pp} = 2000 V 20 kHz 50 % *T* = variable	Voltage collapse
[30]	Square	±1,25 kV	60 Hz-20 kHz	50 ns	10-50	U_{pp} = 2000 V 20 kHz 50 % *T* = variable	Voltage collapse
[31]	Square	±1,25 kV	60 Hz-20 kHz	50 ns	10-50	U_{pp} = 1900 V 20 kHz 50 % *T* = 90 °C and 180 °C	Voltage collapse
[32]	Sinus	2,6 kV	45 Hz 6,6 kHz			U_{pp} = 1760 V 1050 Hz *T* = variable	Fuse
[33]	Sinus	4,5 kV 3 kV 1,8 kV	50 Hz 500 Hz 15 kHz	–	–	All *T* = 140 °C	Fuse
[34]	Pulses	±2 kV	5 kHz	0,2 / 20 µs 0,1 / 5 µs	Unknown	U_p = ±1400 V	Current trip
[35]	Square	±2 kV	10 kHz	1 kV / µs	10-50	U_p = ±1500 V 10 kHz 1 kV/µs *T* = 20-80 °C	Fuse Measure of current
[36]	Pulses	22 kV-40 kV (peak)	12,5 kHz	0,2 µs / 6,5 µs	–	All	Circuit-breaker
[37]	Sinus	6 kV (peak) 6 kV (peak)	50, 250, 500 Hz 1, 2,5, 5 kHz	–	–	All	None
[38]	Pulses	12 kV	up to 60 kHz	NG	15	All	Unknown
[39]	Square superimposed on a.c. 50 Hz	0,5 U_r (up to 920 V)	24 kHz	0,8 µs / 2 µs	–	This one	None
	Square	±5 kV	20 kHz	3 µs	20	All	Unknown
[40]	Pulse	4 kV	NG	9 ns / 18 ns	NG	NG	NG
[41]	Square	±7 kV	2 Hz - 20 kHz	0,3 µs / 1 µs	(width: 1-100 µs)	Unipolar 1 kHz	None
[42]	Square	10 kV (peak-peak)	up to 25 kHz	up to 8 kV / µs	10-50	All	Voltage collapse
[43]	Pulse	600 V + overshoot (OS)	10 kHz	120 ns	Duration of OS = 2,5 µs	This one	None

NOTE The definition of the rise front (dV/dt) is not always the same. Sometimes it is the difference between the values of 10 % and 90 % of the measured voltage (which is the real definition), whereas in other cases it is just V_{max} / t_{rise}).

OS: overshoot

NG: not given

None: measurement other than lifetime is performed;

All: the entire configuration has been tested;

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Tableau 2 – Type d'échantillons et systèmes supposés être représentés

Réf.	Echantillons	Systèmes réels et applications envisagées
[29]	Paires twistées	MTBT, MTAO, BA
[30]	Paires twistées	MTBT, MTAO, BA
[31]	Paires twistées	MTBT, MTAO, BA
[32]	Paires twistées	MTBT, MTAO, BA
[33]	Paires twistées	MTBT, MTAO, BA
[34]	Bobines ou motorettes	MTBT, MTAO, BA, MTHT, BF
[35]	Paires twistées Films minces de polymère	MTBT, MTAO, BA
[36]	Bobines	MTHT, SI, BF
[37]	Films minces de polymère	Inconnu
[38]	Films minces de polymère	Composants TV
[39]	Paires twistées	MTBT, MTAO, BA
[40]	Paires twistées	MTBT, MTAO, BA
[41]	Inconnu	Air
[42]	Echantillons de bobines	MTBT, MTAO, BA, MTHT, BF
[43]	Couche sur couche	MTBT, MTAO, BA

«MTBT» est une Machine Tournante Basse Tension
«TV» signifie Télévision
«MTAO» est une Machine Tournante Alimenté par Onduleur
«BA» signifie est à Bobinage Aléatoire
«MTHT» est une Machine Tournante Haute Tension
«SI» signifie Soumis à Impulsion de choc
«BF» est un Bobinage Formé

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Table 2 – Type of samples and what they are supposed to represent

Ref.	Samples	Real systems and intended applications
[29]	Twisted pairs	LVRM, RMFI, RW
[30]	Twisted pairs	LVRM, RMFI, RW
[31]	Twisted pairs	LVRM, RMFI, RW
[32]	Twisted pairs	LVRM, RMFI, RW
[33]	Twisted pairs	LVRM, RMFI, RW
[34]	Coils samples or motorettes	LVRM, RMFI, RW, HVRM, FW
[35]	Twisted pairs Thin polymer films	LVRM, RMFI, RW
[36]	Coils	HVRM, SS, FW
[37]	Thin polymer films	Not defined
[38]	Thin polymer films	TV-components
[39]	Twisted pairs	LVRM, RMFI, RW
[40]	Twisted pairs	LVRM, RMFI, RW
[41]	Unknown	Air
[42]	Coil samples	LVRM, RMFI, RW, HVRM, FW
[43]	Layer to layer	LVRM, RMFI, RW

LVRM: low-voltage rotating machine
TV: television
RMFI: rotating machine fed by inverters
RW: random wound
HVRM: high-voltage rotating machine
SS: subjected to surge
FW: formed wound

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Table 3 – Type d'échantillons et de mesures réalisées

Réf.	Echantillons	Mesures
[29]	Paires twistées	Spectroscopie diélectrique, alternatif 50 Hz, PDIV, rupture diélectrique et durée de vie
[30]	Paires twistées	PDIV en alternatif 50 Hz, rupture diélectrique et durée de vie
[31]	Paires twistées	PDIV en alternatif 50 Hz, rupture diélectrique et durée de vie + Impact de contraintes mécaniques (mise en forme)
[32]	Paires twistées	Mesure de durée de vie
[33]	Paires twistées	Mesure de durée de vie
[34]	Bobines ou motorettes	Mesure de durée de vie, mesure des DP en haute fréquence
[35]	Paires twistées Films minces de polymères	Mesure de durée de vie, spectroscopie diélectrique, Mesure du potentiel de surface
[36]	Bobines	Mesure de durée de vie
[37]	Films minces de polymères	Mesure de durée de vie
[38]	Films minces de polymères	Mesure de durée de vie
[39]	Paires twistées	Mesure de durée de vie
[40]	Paires twistées	Rupture diélectrique
[41]	Inconnu	Mesure des DP
[42]	Bout de bobinage	Mesure de durée de vie, Mesure des DP Mesure du potentiel de surface
[43]	Couche sur couche	TSC, Mesure des DP

TSC signifie «Courants stimulés thermiquement» (Thermally Stimulated Current)
DP signifie «Mesures de décharges partielles»

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Table 3 – Type of samples and type of measurements performed

Ref.	Samples	Measurements
[29]	Twisted pairs	Dielectric spectroscopy, a.c. 60 Hz PD threshold, breakdown and life time measurements
[30]	Twisted pairs	AC 60 Hz PD threshold, breakdown and lifetime measurements
[31]	Twisted pairs	AC 60 Hz PD threshold, breakdown and lifetime measurements + impact of mechanical stress
[32]	Twisted pairs	Lifetime measurements
[33]	Twisted pairs	Lifetime measurements
[34]	Coils samples or motorettes	Lifetime measurements, high-frequency PD measurements
[35]	Twisted pairs Thin polymer films	Lifetime measurements, dielectric spectroscopy, Surface potential measurements
[36]	Coils	Lifetime measurements
[37]	Thin polymer films	Lifetime measurements
[38]	Thin polymer films	Lifetime measurements
[39]	Twisted pairs	Lifetime measurements
[40]	Twisted pairs	Breakdown measurements
[41]	Unknown	PD measurements
[42]	Coil samples	Life-time measurements, PD measurements, Surface potential measurements
[43]	Layer to layer	TSC, PD measurements

TSC: thermally stimulated current
PD: partial discharge measurements

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Tableau 4 – Résumé des principaux résultats

Réf.	Echantillons	Principaux résultats
[29]	Paires twistées	Développement de nouveaux émaux
[30]	Paires twistées	Développement de nouveaux émaux
[31]	Paires twistées	Développement de nouveaux émaux
[32] [33]	Paires twistées Paires twistées	Développement de nouveaux émaux Développement de nouveaux émaux
[34]	Bobines ou motorettes	Définition de la fiabilité (V< PDIV= aucun danger ; Rôle de la fréquence, f, et t_r sur PDIV Rôle de la température, charge de surface
[35]	Paires twistées Films minces de polymères	Deux types de vieillissement, le premier impliquant les DP, le second l'existence d'une charge d'espace, Création d'une charge d'espace surfacique
[36]	Bobines	Définition des tensions admissibles.
[37]	Films minces de polymères	Augmente la connaissance des DP
[38]	Films minces de polymères	Deux types de vieillissement, le premier impliquant les DP, le second l'existence d'une charge d'espace,
[39]	Paires twistées	Durée de vie diminue quand on utilise un onduleur
[40]	Paires twistée	Développement de générateur
[41]	Inconnu	Influence du temps séparant des DP
[42]	Bout de bobines	Influence du temps de repos sur la durée de vie, pas d'influence de la forme de tension sur le PDIV
[43]	Couche sur couche	Existence d'une charge d'espace

PDIV signifie « Tension d'apparition des décharges»
DP signifie «Mesures de décharges partielles»

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Table 4 – Summary of the main results

Ref.	Samples	Main results
[29]	Twisted pairs	Development of a new enamel
[30]	Twisted pairs	Development of a new enamel
[31]	Twisted pairs	Development of a new enamel
[32]	Twisted pairs	Development of a new enamel
[33]	Twisted pairs	Development of a new enamel
[34]	Coils samples or motorettes	Assessment of reliability (V < DIV = no risk of failure) Role of frequency, t_r and f_r on DIV Role of the temperature, surface charges
[35]	Twisted pairs Thin polymer films	Two main regions of ageing one related to PD action and the other to space charge existence, Surface space charge built up
[36]	Coils	Voltage-level requirement for surge limitation
[37]	Thin polymer films	Increase PD characteristics knowledge
[38]	Thin polymer films	Two main regions of ageing: one related to PD action and the other to space charge existence.
[39]	Twisted pairs	Lifetime is reduced when using inverter
[40]	Twisted pairs	Development of a new generator
[41]	Unknown	Influence of the time between two PDs
[42]	Coil samples	Influence of the rest time on lifetime, no influence of the voltage shape on DIV
[43]	Layer to layer	Space charge existence

DIV: discharge inception voltage

PD: partial discharge measurements

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Tableau 5 – Résultats de l'étude: Dépendance des résultats observés des caractéristiques de la tension

Réf.	Amplitude	Fréquence	Front ou temps	Polarité
[29]	$L \approx 1/V^n$	$L \approx b/f$ pour $f < 5$ kHz $L \approx c/f^2$ pour $f > 5$ kHz	$\approx f(t_r)$, $t_r < 80$ ns $\approx f(t_f)$, $t_f > 80$ ns	L en bipolaire plus court qu'en unipolaire
[30]	$L \approx 1/V^n$	$L \approx b/f$	ND	ND
[31]	$L \approx 1/V^n$	ND	ND	ND
[32]	$L \approx 1/V^n$	$L \approx b/f$	NE	NE
[33]	$L \approx 1/V^n$	$L \approx b/f$	–	–
[34]	$L \approx 1/V^n$	$L \approx b/f$	PDIV= $V_i = f$ (t_r et t_f) ($V_i \downarrow$, $t_r \uparrow$, $V_i \uparrow$, $t_f \uparrow$)	L en bipolaire plus court qu'en unipolaire
[35]	$L \approx 1/V^n$ pour $U > V_i$ L = f (de la nature du matériau) pour $U < V_i$	$L \approx b/f$ pour $U > V_i$ L = f (de la nature du matériau) pour $U < V_i$	L indépendant de dV/dt pour $U > V_i$ L dépendant de dV/dt pour $U < V_i$	L en bipolaire plus court qu'en unipolaire
[36]	$L \approx 1/V^n$	NE	Influence des éclateurs	NE
[37]	ND	$L \approx f^{-m}$		
[38]	2 régions de vieillissement $L \approx 1/V^n$ pour $U > V_i$ $L \approx f$ pour $U < V_i$	L ≈ nombre d'impulsions $L \approx f^{-1}$	Pas ou faible	ND
[39]	$L \approx 1/V^n$	L ↓ quand f ↑	Influence du PDIV (↑ quand t_r ↑)	ND
[40]				
[41]	Q_{max} ↑			
[42]	$L \approx 1/V^n$	L ≈ nombre de pulses	Pas d'influence	Faible ou nul
[43]	–	–	–	–

NOTE Les test décrits dans [29] à [34] et [36] à [43] sont toujours développés pour des tensions $V > V_i$.

b, *c*: sont des constantes

L: est la durée de vie

NE: signifie «Non étudié»

ND: signifie «Non décrit»

Q_{max}: est la charge maximale pendant la décharge

t_r: est le temps de montée

t_f: est le temps de descente

V_i: est la tension de seuil de décharge

V_B: est la tension de rupture

≈: signifie «proportionnel à»

↑: signifie augmente

↓: signifie diminue

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Table 5 – Output of the study: Dependence of the observed results of voltage characteristics

Ref.	Voltage magnitude	Frequency	Front or rise time	Polarity
[29]	$L \propto 1/V^n$	$L \propto b/f$ for $f < 5$ kHz $L \propto c/f^2$ for $f > 5$ kHz	$\propto f(t_r)$, $t_r < 80$ ns $\neq f(t_r)$, $t_r > 80$ ns	L under bipolar voltage shorter than under unipolar
[30]	$L \propto 1/V^n$	$L \propto b/f$	NG	NG
[31]	$L \propto 1/V^n$	NG	NG	NG
[32]	$L \propto 1/V^n$	$L \propto b/f$	NS	NS
[33]	$L \propto 1/V^n$	$L \propto b/f$		
[34]	$L \propto 1/V^n$	$L \propto b/f$	DIV – $V_i = f$ (t_r and t_f) (V_i ↓, t_r ↑, V_i ↑, t_f ↑)	L under bipolar voltage shorter than under unipolar
[35]	$L \propto 1/V^n$ for $U > V_i$ $L = f$ (of the nature of the material) for $U < V_i$	$L \propto b/f$ for $U > V_i$ $L = f$ (of the nature of the material) For $U < V_i$	L independent of dV/dt for $U > V_i$ L dependent of dV/dt for $U < V_i$	L under bipolar voltage shorter than under unipolar
[36]	$L \propto 1/V^n$	NS	Influence on arresters	NS
[37]	NG	$L \propto f^{-m}$	–	–
[38]	Two ageing regions $L \propto 1/V^n$ for $U > V_i$ $L \propto f$ for $U < V_i$	$L \propto$ number of pulses $L \propto f^{-1}$	No or small impact	NG
[39]	$L \propto 1/V^n$	L ↓ when f ↑	Influence on DIV (↑ when t_r ↑)	NG
[40]				
[41]	Q_{max} ↑	–	–	–
[42]	$L \propto 1/V^n$	$L \propto$ number of pulses	No influence	Small or no impact
[43]	–	–	–	–

NOTE The tests performed by [29] to [34] and [36] to [43] were always developed for $V > V_i$.

b, c: constants
L: lifetime
NS: not studied
NG: not given
Q_{max}: maximum charge during the discharge
t_r: rise time
t_f: fall time
V_i DIV
V_b: voltage breakdown
∝: proportional to
↑: increase
↓: decrease

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Tableau 6 – Résultats de l'étude: Dépendance des résultats observés sur d'autres paramètres

réf.	Température	Imprégnation	Divers
[29]	$L \propto 1/T$	Compatibilité des nouveaux matériaux avec les vernis	«Pas de relation directe entre V_t et L» PDIV plus faible
[30]	$L \propto 1/T$	Double imprégnation multiplie la durée de vie par 25	PDIV plus faible
[31]	$L \propto 1/T$	–	Rôle du bobinage
[32]	Pas de variation jusqu'à 250 °C	–	–
[33]	NE	L décroît quand imprégné	PDIV plus faible
[34]	NE	L croît quand imprégné	«Pas de différence entre un pur sinus et un carré en ce qui concerne la rigidité»
[35]	L ↘ quand T ↗	L décroît quand imprégné	
[36]	–	–	Rôle des protections
[37]	Influence de la fréquence sur l'augmentation de T	–	Q_{max} et le nombre de pulses ↗ quand f ↗
[38]	Influence de la fréquence sur l'augmentation de T	–	–
[39]	L ↘ quand T ↗	L croît quand imprégné	–
[40]			
[41]	–	–	Q_{max} ↑ quand durée ↑
[42]	–	–	Rôle du temps de repos
[43]			Démonstration claire de l'existence d'une charge d'espace

«L» est la durée de vie
T est la température
DIV est la tension de seuil de décharge
NS signifie "n'est pas étudié"
Q_{max} est la charge maximale pendant la décharge
«V_t» est la tension de rupture

4.5 Autres études associées

4.5.1 Décharges partielles

Existence de décharges partielles (DP) dans les machines tournantes alimentées par onduleur [44] [45]

Caractéristiques des DP pour les tensions sinusoïdales en hautes fréquences [46] [47]

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Table 6 – Output of the study: Dependence of the observed results on other parameters

Ref.	Temperature	Impregnation	Miscellaneous
[29]	$L \propto 1/T$	Compatibility between the new enamel and varnish	No direct relation between V_b and L DIV lower
[30]	$L \propto 1/T$	Double dipping multiplies life by 25	DIV lower
[31]	$L \propto 1/T$	–	Role of the deformation during winding
[32]	Unchanged up to 250 °C	–	–
[33]	NS	L decreases when impregnated	DIV lower
[34]	NS	L increases when impregnated	No difference between pure sinus and square as regards breakdown
[35]	$L \downarrow$ when $T \uparrow$	L decreases when impregnated	
[36]			Role of surge protection
[37]	Influence of frequency on T rise		Q_{max} and discharge pulse number $\uparrow$ when $f \uparrow$
[38]	Influence of frequency on T rise		
[39]	$L \downarrow$ when $T \uparrow$	L increases when impregnated	–
[40]	–	–	–
[41]	–	–	$Q_{max} \uparrow$ when width $\uparrow$
[42]	–	–	Role of the rest time
[43]	–	–	Clear demonstration of SC existence.

L: lifetime
T: temperature
DIV: discharge inception voltage
NS: not studied
Q_{max}: maximum charge during the discharge
V_b: the voltage breakdown

4.5 Other related studies

4.5.1 Partial discharges

PD existence in rotating machines fed by inverters [44] [45]

PD characteristics under high-frequency sinusoidal voltages [46] [47]

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4.5.2 Mesures en ligne

La référence [48] propose une surveillance fondée sur la somme des tensions entre ligne et neutre. Selon cette technique il serait également possible d'apprécier la défaillance des semi-conducteurs utilisant cette méthode.

La référence [49] suggère que le vecteur courant d'espace soit un bon marqueur du vieillissement.

La référence [50] propose, et a développé un système capable, de compter le nombre de tensions de choc et de détecter les décharges partielles pendant les tests de fonctionnement tant en ligne qu'hors ligne.

La référence [51] donne la possibilité d'identifier et de localiser les origines des DP grâce à leur modélisation.

4.5.3 Mesures hors ligne

Les références [52] [53] recommandent et détaille un test d'aptitude à supporter des impulsions, et un test en impulsion concernant le développement de décharges de type couronne entre spires.

La référence [54] propose une méthode permettant de rechercher la possibilité de tester l'effet de couronne grâce à un essai en impulsion.

4.5.4 Guide de fiabilité

Les références [55] [56] propose un choix du câble d'alimentation assurant une liaison correcte entre moteur et onduleur.

Les références [57] [58] [59] proposent des limitations concernant les impulsions.

Les références [60] [61] [62] proposent et décrivent des filtres non dissipatifs susceptibles de réduire les surtensions à l'entrée des bornes des machines.

5 Autre systèmes électriques

5.1 Transformateurs [1]

Les références [63] [64] décrivent des études sur l'alternatif avec des chocs de foudre (onde 1,2/50 µs) pour des combinaisons différentes d'huile et de papier. Les principales conclusions sont qu'aucun «phénomènes de décharge partielle en courant alternatif n'est déclenché par des tensions de choc de foudre lorsque la tension de 50 Hz pré-appliquée est inférieure à 50 % de la valeur efficace de la tension alternative d'apparition des décharges partielles pour toutes les combinaisons de polarité, et que les valeurs crêtes de claquage de la tension superposée sont réduites de 10 % à 19 % pour une seule impulsion de choc de foudre appliquée avec un faible facteur de remplissage diélectrique solide à liquide (SLPF: solid-to-liquid dielectric packing fraction) de papier imprégné d'huile dans un modèle d'échangeur intermédiaire de chaleur, mais la différence de tension de claquage existant entre la tension superposée et l'unique choc de foudre est très petite pour un fort facteur SLPF avec le papier imprégné d'huile, c'est-à-dire supérieur d'environ 30 %».

La référence [65] démontre le rôle de la distribution de tension qui peut excéder la valeur crête pendant la propagation (ces résultats sont observés dans les machines tournantes).

[1] Les impulsions sont utilisées comme outils mais il est possible d'en déduire les tenues intéressantes.

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4.5.2 On-line measurements

Reference [48] proposes a condition monitoring based on the sum of line-to-neutral voltage. According to it, it would also be possible to detect semiconductor switch faults using this method.

Reference [49] suggests that the space vector current is a good indicator of ageing.

Reference [50] proposes to, and has developed, a system able to count the number of surges and to detect PD during both off-line and on-line operations.

Reference [51] claims that it is possible to identify PD sources and location via their modelling.

4.5.3 Off-line measurements

References [52] [53] recommend and discuss surge withstand capability and test in surge as regards corona between turns.

Reference [54] proposes a method to investigate the possibility of corona testing via surge test.

4.5.4 Reliability guidelines

References [55] [56] propose a selection of power cable assuring a correct link between motor and inverter.

References [57] [58] [59] propose surge limitation.

References [60] [61] [62] propose and describe non-dissipative filters able to reduce overvoltage at the motor terminals.

5 Other electrical systems

5.1 Transformers[1)]

References [63] [64] describe studies of a.c. with lightning impulses (1,2/50 µs) for combination of oil and paper. The main conclusions are the following: no "a.c. PD phenomena are triggered by lightning impulse voltage when the preapplied 50 Hz voltage is less than 50 % of the r.m.s. value of the a.c. PD inception voltage for all combinations of polarities, and peak breakdown values of the superimposed voltage are reduced by 10 % to 19 % for a single applied lightning impulse with a low solid-to-liquid dielectric packing fraction (SLPF) for oil-impregnated paper in the intercooler model, but the difference in breakdown voltage between the superimposed voltage and a single lightning impulse is very small for a high SLPF for oil-impregnated paper, i.e. above about 30 %".

Reference [65] demonstrates the role of the voltage distribution that can exceed the peak value during propagation (such results are observed in rotating machines).

1) Impulse voltage is used as a tool but interesting behavior may be derived.

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Les références [66] [67] proposent une méthode de contrôle utilisant des impulsions de faible niveau de tension pour déterminer la défaillance des bobines et distinguer leur localisation (entre spires ou entre spires et masse).

Certains travaux ont été réalisés dans des transformateurs à isolation gazeuse avec des impulsions afin de déterminer le rôle des gaz [68].

5.2 Appareillage à isolation gazeuse (GIS)

Les références [69] [70] étudie la dégradation de modèles d'entretoises sous contraintes répétées. La tension de seuil de décharge (DIV) augmente avec le nombre d'impulsions subies alors que la tension V_b décroît.

La référence [71] est une justification de l'utilisation d'impulsions de tension.

La référence [72] propose l'électroluminescence, (c'est-à-dire la luminescence lors de l'application d'un champ électrique), comme outil de détection des décharges partielles sous tensions impulsionnelle dans des GIS.

La référence [73] montre qu'au point triple, l'impact de la forme d'onde de la tension est faible en comparaison des propriétés du matériau.

5.3 Câbles d'alimentation

Il existe un nombre limité de recherches quant à l'influence de contraintes impulsionnelles sur l'isolation des câbles. L'influence du câble d'alimentation des bobines de propulsion des moteurs synchrones linéaires a été étudiée. Dans ce cadre un générateur de tension a été développé, et la tension de claquage ainsi que la longueur des arborescences au cheminement des feuilles de polyéthylène réticulé (XPLE) ont été étudiés [74].

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References [66] [67] propose a monitoring method using low-voltage impulse to determine the coils collapse and to distinguish the failure location (turn-to-turn or turn-to-ground).

Some work has also been carried out on gas-insulated transformers [68] under impulse voltage in order to demonstrate the role of gas.

5.2 Gas Insulated Switchgear (GIS)

References [69] [70] study the degradation of insulating spacer models in repeating impulse voltage. DIV increases against the number of impulse voltage whereas V_b decreases.

Reference [71] is a justification for using impulse voltages.

Reference [72] proposes electroluminescence (i.e., the luminescence under the application of an electric field) as a tool to detect PD under impulse voltage in GIS.

Reference [73] shows that at the triple point the impact of the voltage waveform is small compared to the material properties.

5.3 Power cables

There is a limited research on the influence of inverter surge on cable insulation. The influence of the feeder cable of propulsion coils of linear synchronous motor was investigated. For this purpose, a voltage generator was developed and the breakdown voltage and the elongation of the water tree of XLPE (cross-linked polyethylene) pressed sheet were investigated [74].

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....

Q2 Please tell us in what capacity(ies) you bought the standard *(tick all that apply)*. I am the/a:

- purchasing agent ❑
- librarian ❑
- researcher ❑
- design engineer ❑
- safety engineer ❑
- testing engineer ❑
- marketing specialist ❑
- other...

Q3 I work for/in/as a: *(tick all that apply)*

- manufacturing ❑
- consultant ❑
- government ❑
- test/certification facility ❑
- public utility ❑
- education ❑
- military ❑
- other...

Q4 This standard will be used for: *(tick all that apply)*

- general reference ❑
- product research ❑
- product design/development ❑
- specifications ❑
- tenders ❑
- quality assessment ❑
- certification ❑
- technical documentation ❑
- thesis ❑
- manufacturing ❑
- other...

Q5 This standard meets my needs: *(tick one)*

- not at all ❑
- nearly ❑
- fairly well ❑
- exactly ❑

Q6 If you ticked NOT AT ALL in Question 5 the reason is: *(tick all that apply)*

- standard is out of date ❑
- standard is incomplete ❑
- standard is too academic ❑
- standard is too superficial ❑
- title is misleading ❑
- I made the wrong choice ❑
- other ....

Q7 Please assess the standard in the following categories, using the numbers:
(1) unacceptable,
(2) below average,
(3) average,
(4) above average,
(5) exceptional,
(6) not applicable

- timeliness ....
- quality of writing....................................
- technical contents....................................
- logic of arrangement of contents ....
- tables, charts, graphs, figures
- other ....

Q8 I read/use the: *(tick one)*

- French text only ❑
- English text only ❑
- both English and French texts ❑

Q9 Please share any comment on any aspect of the IEC that you would like us to know:

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Q1 Veuillez ne mentionner qu'**UNE SEULE NORME** et indiquer son numéro exact: *(ex. 60601-1-1)*

....

Q2 En tant qu'acheteur de cette norme, quelle est votre fonction? *(cochez tout ce qui convient)* Je suis le/un:

agent d'un service d'achat ☐
bibliothécaire ☐
chercheur ☐
ingénieur concepteur ☐
ingénieur sécurité ☐
ingénieur d'essais ☐
spécialiste en marketing ☐
autre(s)...

Q3 Je travaille: *(cochez tout ce qui convient)*

dans l'industrie ☐
comme consultant ☐
pour un gouvernement ☐
pour un organisme d'essais/ certification ☐
dans un service public ☐
dans l'enseignement ☐
comme militaire ☐
autre(s)...

Q4 Cette norme sera utilisée pour/comme *(cochez tout ce qui convient)*

ouvrage de référence ☐
une recherche de produit ☐
une étude/développement de produit ☐
des spécifications ☐
des soumissions ☐
une évaluation de la qualité ☐
une certification ☐
une documentation technique ☐
une thèse ☐
la fabrication ☐
autre(s)...

Q5 Cette norme répond-elle à vos besoins: *(une seule réponse)*

pas du tout ☐
à peu près ☐
assez bien ☐
parfaitement ☐

Q6 Si vous avez répondu PAS DU TOUT à Q5, c'est pour la/les raison(s) suivantes: *(cochez tout ce qui convient)*

la norme a besoin d'être révisée ☐
la norme est incomplète ☐
la norme est trop théorique ☐
la norme est trop superficielle ☐
le titre est équivoque ☐
je n'ai pas fait le bon choix ☐
autre(s) ....

Q7 Veuillez évaluer chacun des critères ci-dessous en utilisant les chiffres
(1) inacceptable,
(2) au-dessous de la moyenne,
(3) moyen,
(4) au-dessus de la moyenne,
(5) exceptionnel,
(6) sans objet

publication en temps opportun ....
qualité de la rédaction...........................
contenu technique ....
disposition logique du contenu ....
tableaux, diagrammes, graphiques, figures ....
autre(s) ....

Q8 Je lis/utilise: *(une seule réponse)*

uniquement le texte français ☐
uniquement le texte anglais ☐
les textes anglais et français ☐

Q9 Veuillez nous faire part de vos observations éventuelles sur la CEI:

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