

***Rewinding of a High Voltage Machine:  
Technical Features and Criteria That Should  
Be in the Service Specifications – A Practical  
Case***

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# ***INTRODUCTION***

- ***Winding Life Expectancy***
- ***Failure Rates***
- ***Standards***
- ***Repair Specification***
- ***Practical Case - Rewinding a 13.2 kV motor - Specification / Criteria Required / Reached***
- ***Conclusions and Recommendations***

# WINDING LIFE EXPENTANCY

- What is the **expected life** of an **asset**?
  - For industrial applications, machine owners expect a **useful life of 20 to 30 years** (to achieve this it is necessary to observe some premises)
  - However, owners do not always look at the **technical aspects they need** (they only consider cost and forget about reliability);
  - In other cases, the **technical expertise required** to prepare the purchase specification is lacking;
  - Several cases of critical machines (13.8 kV) that failed with less than 5 years of operation;
  - The expected life of the winding **will be strongly influenced by the purchase specification**, which must be accurate and done according to the intended application of the machine
  - There must be **an engineering judgment when it is specified**, having a confrontation of several distinct aspects (technical and managerial);
  - The longer the expected service life, the greater the costs involved in the purchase of the winding;

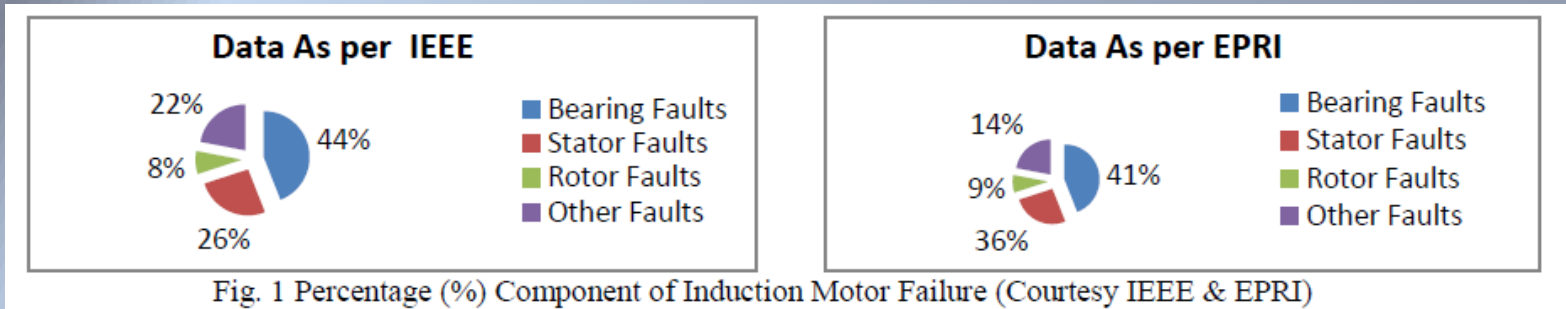
# WINDING LIFE EXPENTANCY

- Factors that directly influence the life of the insulation system
  - Constructive
    - Design - (**kV / mm, temperature and operating regime, materials used**)
    - Manufacture - (**processes, impregnation method, acceptance criteria**)
    - Mounting - (**Mounting Failures - Common Mistakes**)
  - Environmental, Operation and Maintenance
    - Stress: **Electrical, Mechanical, Thermal, Environmental**

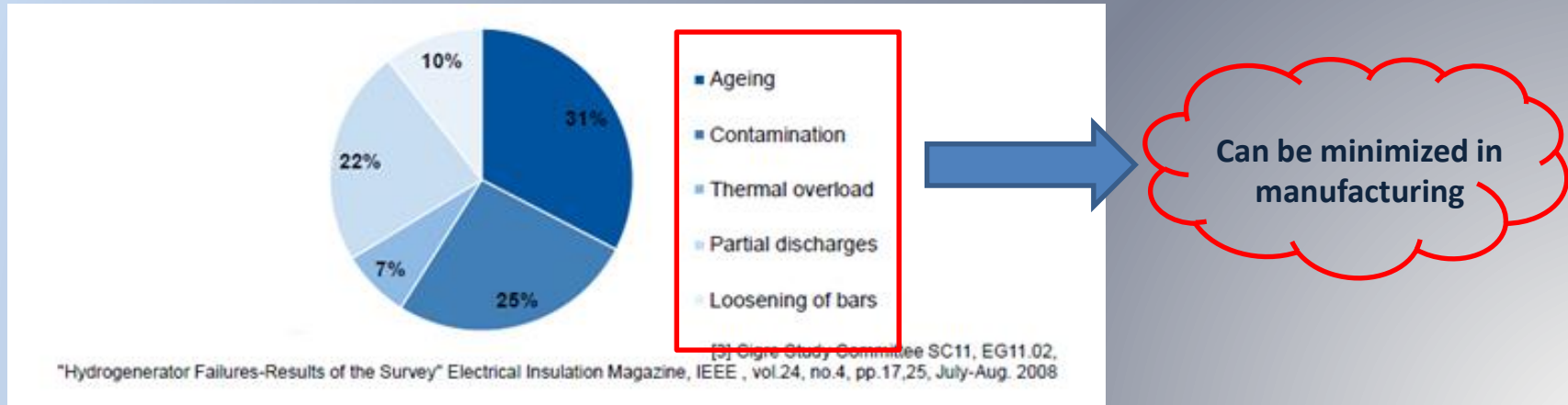
Stator	Thermal	Thermal aging, thermal overload, voltage variation, voltage unbalance, ambient, load cycling, starting and stalling, poor ventilation
	Electrical	Dielectric aging, transient voltages, partial discharge (corona), tracking
	Mechanical	Winding movement, damaged motor leads, improper rotor-to-stator geometry, abrasion, defective rotor, flying objects
	Environmental	Moisture, chemical, abrasion, poor ventilation, excessive ambient

# FAILURE RATES

- Failure rates in industrial application motors



- Stator failure rates



# STANDARDS

- Main Standards

<b>IEC 60034</b> - Rotating electrical machines;
<b>EN 50209</b> - Test of insulation of bars and coils of high-voltage machines;
<b>IEEE Std 1</b> - Standard General Principles for Temperature Limits in Rotating of Electrical Equipments and for the Evaluation of Electrical Insulation;
<b>IEEE Std 043</b> - Recommended Practice for Testing Insulation Resistance of Machinery;
<b>IEEE Std 62.2-2004</b> - Guide for diagnostic field testing of electric apparatus - electrical machinery;
<b>IEEE Std 95</b> - Recommended Practice for Insulation Testing of Large AC Rotating with High Direct Voltage;
<b>IEEE Std 115</b> - Test Procedures for Synchronous Machined;
<b>IEEE Std 118</b> - Standard Code Resistance Measurement;
<b>IEEE Std 429</b> - Standard Test Procedure for the Evaluation of Sealed Insulation Systems for Electrical Machinery Employing Form-Wound Stator Coils;
<b>IEEE Std 43</b> - Recommended Practice for Insulation Testing of Large AC Rotation Machinery with High Voltage at Low Frequency;
<b>IEEE Std 454</b> - Recommended Practice for the Detection and Measurement of Partial Discharges (Corona) During Dielectric Tests;
<b>IEEE Std 1799</b> - Recommended Practice for Quality Control Testing of External Discharges on Stator Coils, Bars, and Windings;

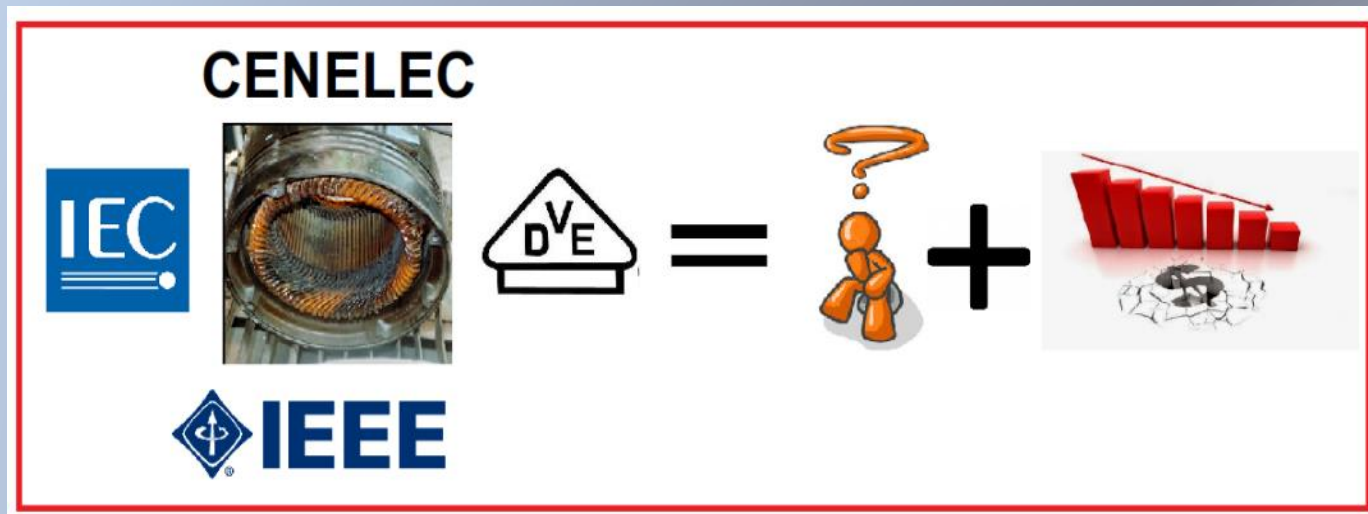
# STANDARDS

- Main Standards

<b>IEEE Std 522</b> - Guide for Testing Turn-to-Turn Insulation on Form-Wound Stator Coils for Alternating-Current Rotating Electrical Machines;
<b>VDE-0530</b> - Standard Specification for Rotating Electrical Machines;
<b>IEEE 432</b> - Guide for Insulation Maintenance for Rotating Electric Machinery (5 hp to less than 10 000 hp);
<b>IEEE 1043</b> - Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils;
<b>IEEE 1434</b> - Guide to the Measurement of Partial Discharges in Rotating Machinery
<b>IEEE 1553</b> - Trial-Use Standard for Voltage Endurance Testing of Form-Wound Coils and Bars for Hydrogenerators;
<b>IEEE 1068</b> - Recommended Practice for the Repair and Rewinding of Motors for the Petroleum and Chemical Industry
<b>IEC 60270</b> - High-voltage test techniques - Partial discharge measurements
<b>API Std 546</b> - Brushless Synchronous Machines 500 kVA and Larger;
<b>ISO 1940/1</b> - Mechanical vibration - Balance quality requirements for rotors in a constant (rigid) state - Part 1: Specification and verification of balance tolerances.
<b>ISO 10816-3</b> - Mechanical vibration Evaluation of machine vibration by measurements on rotating parts;

# STANDARDS

- **Various standards** on machine windings (series IEC 60034, IEEE, VDE, ETC);
- However, many **are not objective** in the criteria of "pass" or "fail";
- User is not always **able to specify the repair correctly, quickly, consciously and objectively**;
- Often this causes **unavailability and consequent financial loss**;
- Sometimes the user doesn't know **what he needs**;
- So, we can say: **"anyone who does not know what he wants, buys (and pays !!!!) anything"**.

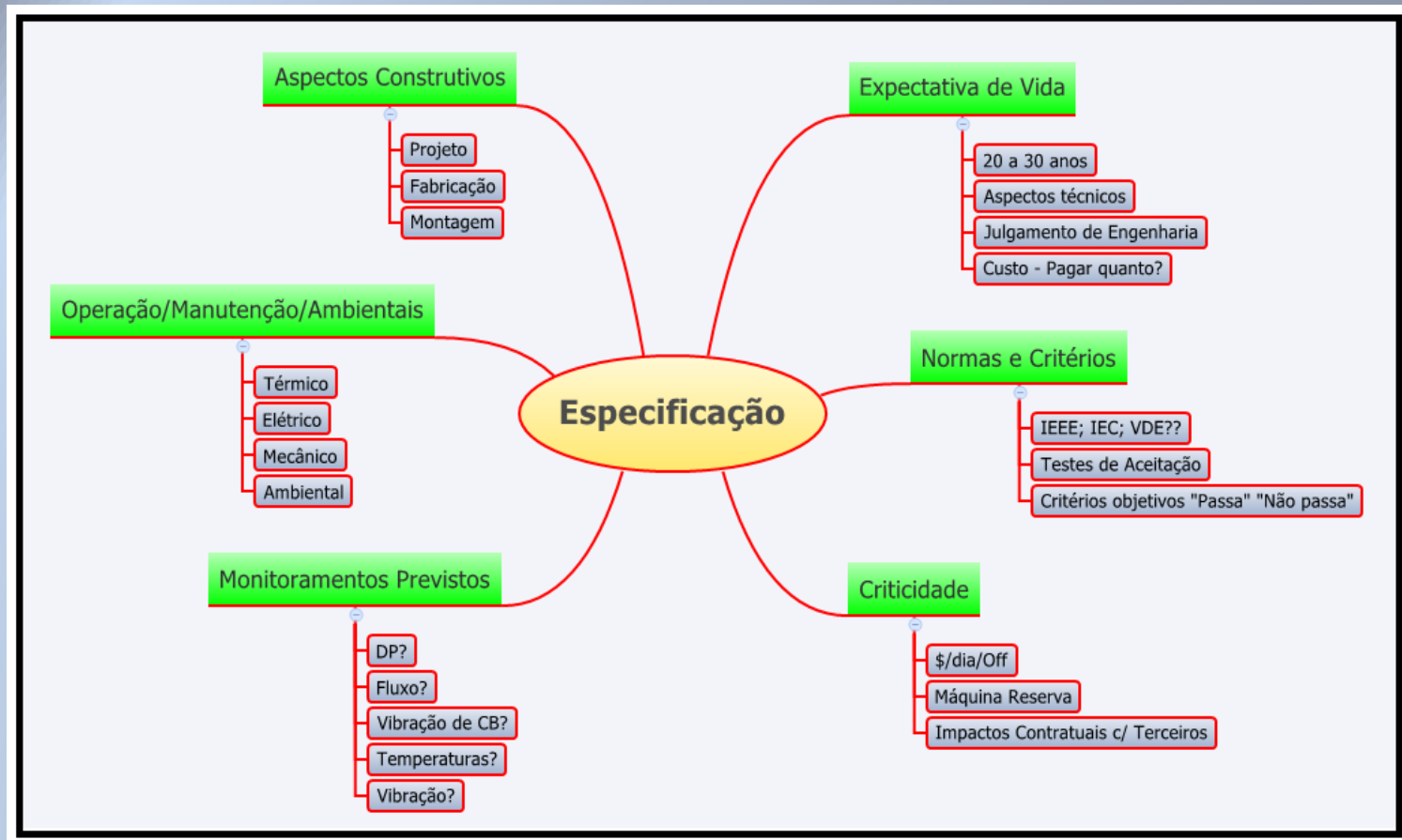


# STANDARDS

- IEC cites two acceptance tests (**HIPOT - GROUNDWALL and Surge Test - STRAND**);
- IEEE / ANSI C50.12 and C50.13 and NEMA MG1 recommend **HIPOT and insulation resistance measurement by IEEE 043**.
- IEEE 1665 is a general guide for rewinds.
- The adoption of standards in a specification cannot be generic (for example, **one can not cite "compliance with current standards"**).
- Objective **criteria "pass" or "fail" (quantitative)** should be explicitly present in the specification.

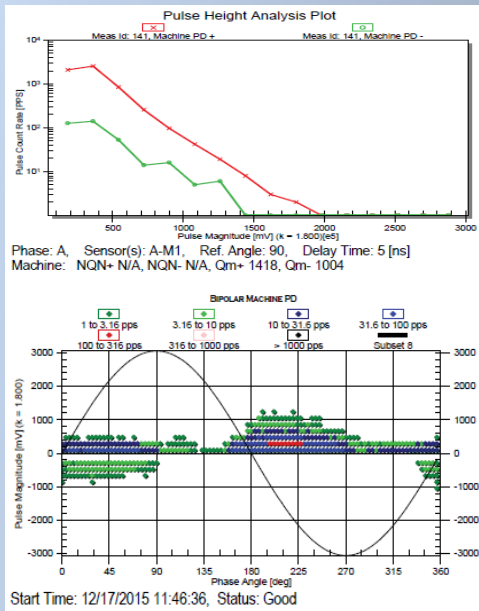
# REPAIR SPECIFICATION - INSULATION SYSTEM

- The rewinding specification of a critical high-voltage machine **should consider:**



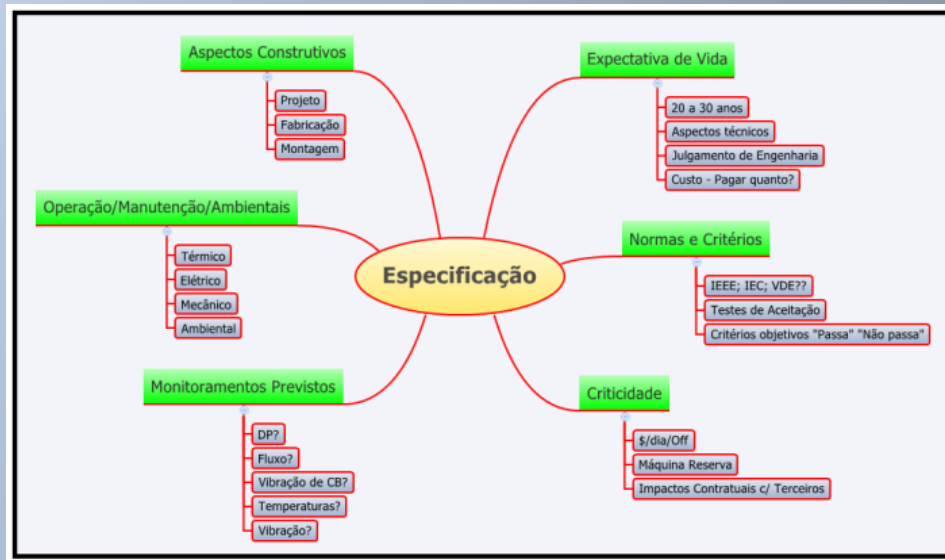
# Practical Case - Rewinding a 13.2 kV motor – SCENARIO

- Synchronous Motor installed in 2001 (3MW, 13.2kV, propane gas compressor drive);
- **Continuous operation (S1);**
- **Failure** of triggered equipment causes **severe plant unavailability;**
- Machine does not have "backup";
- **Daily loss** of profit of approximately **\$ 250,000.00;**
- Maximum reduction in downtime;
- Monitored machine with PD online, vibration, temperatures of windings and bearings;
- DP measurements indicated **severe degradation of the insulation system;**
- **Severe damaging in damper windings;**
- Machine **with "one foot on the grave";**



# Practical Case - Rewinding a 13.2 kV motor – **STRATEGY**

- The strategy adopted was the complete overhaul of the machine, observing all the considerations below, **OPTIMIZING THE TIME OF UNAVAILABILITY, BY MANUFACTURING A NEW WINDING BEFORE THE MACHINE STOPPED AND FOLLOWING ALL THE ESTABLISHED RULES.**



- However, the **machine failed** before beginning the production of the coils !!!  
**However, specification was ready and supplier practically already contracted** (optimization of the term by at least 90 days);

# ***Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED***

## **New Stator Winding Technical Requirements**

- In addition to the criteria involving magnetic core, rotor and mechanical parts, requirements were considered "heavy" for the stator insulating system (which we consider to be one of the weak links of the machine) that were divided into 3 stages:

**1 - APPROVAL OF COIL PROTOTYPES**



**2 - MANUFACTURE OF THE NEW WINDING**



**3 - MOUNTING**

# Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED

## 1 - APPROVAL OF COIL PROTOTYPES

### General Technical Requirements for New Stator Winding

	Expectativa de Vida	Sistema de Impregnação	Gradiente de Tensão	Material Isolante (Groundwall)			Material isolante dos fios (Strand)
				Tipo	Classe	Composição	
<b>Exigido (Espec)</b>	25 ANOS	SVPI / RR	2,5KV/mm	TERMOFIXO	F	EP+MICA	BASE DE FIBRA VIDRO
<b>Utilizado</b>	-	RR	2,5KV/mm	TERMOFIXO	F	EP+MICA	BASE DE FIBRA VIDRO

### Requirement to present technical information (comment)

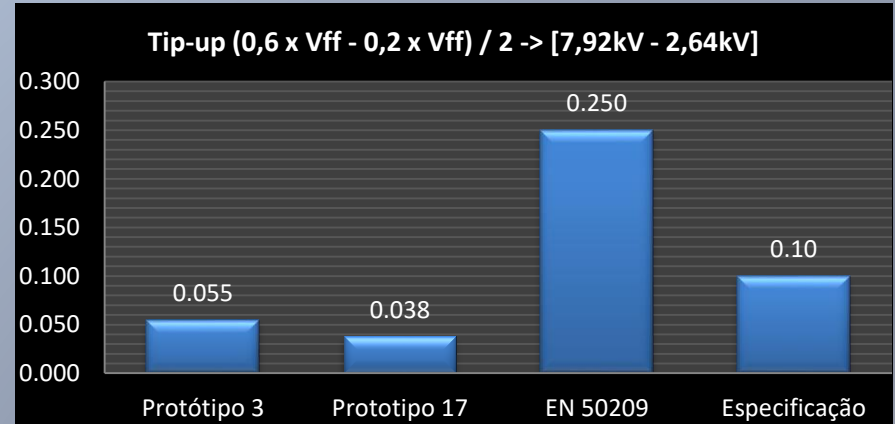
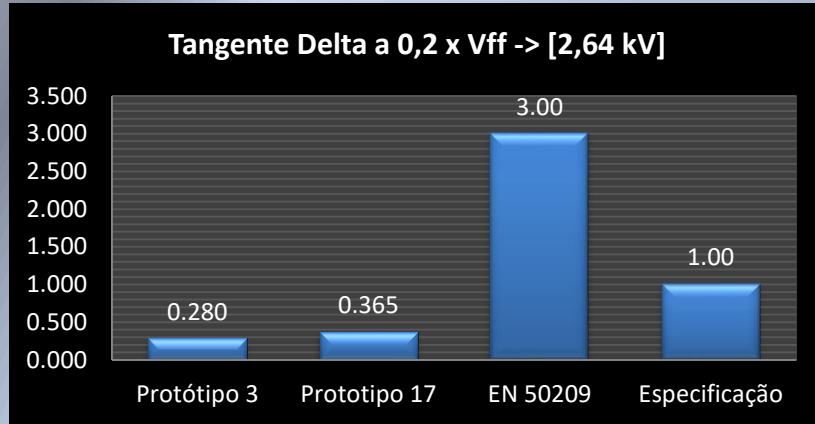
### Acceptance Criteria - Prototype Approval and Manufacturing Release

- Implementation of a set of 10 tests for approval of prototypes.

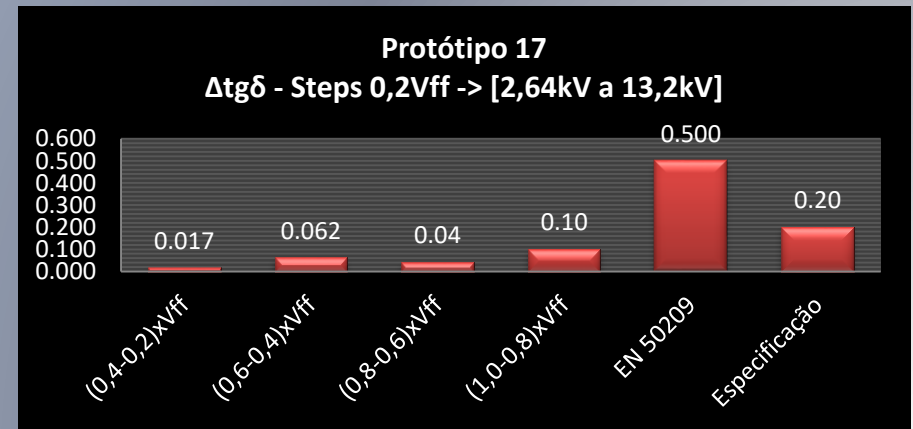
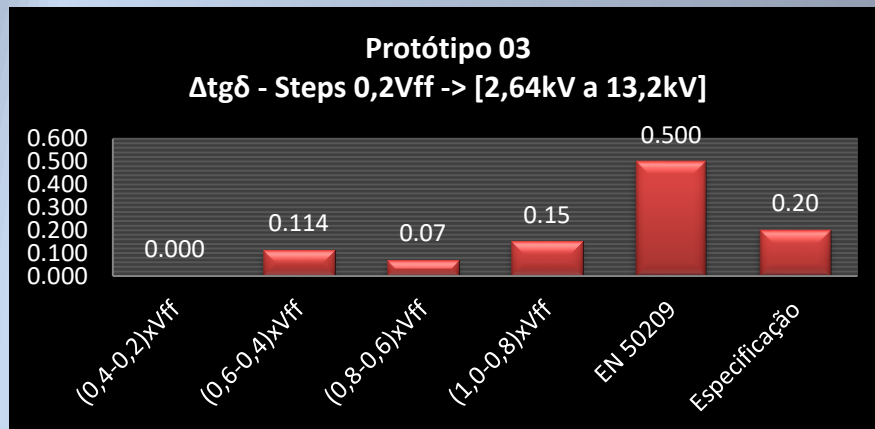
ETAPA DE APROVAÇÃO DOS PROTOT		Perdas dielétricas ( $Tan\delta$ a $0,2xU$ )	TIPUP - [ $Tan\delta(0,6xU) - Tan\delta(0,2xU)]/2$ )	$\Delta tan\delta$ with steps $0,2xU$	
<b>Número de Amostras Testadas</b>		100%	100%	100%	
<b>Norma Referenciada</b>		EN 50209	EN 50209	EN 50209	
<b>Critério Norma</b>		3% (100%)	0,25% (95%) / 0,3% (5%)	0,5% (95%) / 0,6% (5%)	(machines up to 11kV)
<b>Critério Especificação</b>		1% (100%)	0,1% (100%)	0,20%	
<b>Valores Atingidos</b>	<b>Protótipo 03</b>	<b>0,280%</b>	<b>0,055%</b>	<b>0,153% (1)</b>	
	<b>Protótipo 17</b>	<b>0,365%</b>	<b>0,038%</b>	<b>0,100% (2)</b>	
<b>NOTAS</b>					
1- Maior valor encontrado nos steps; ocorreu no step de 0,4 p/ 0,6					
2- Maior valor encontrado nos steps; ocorreu no step de 0,8 p/ 1					

# Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED

## Comparative Tg Delta and TIPUP obtained, normative value and specification



## Comparative Delta Tg Delta obtained, normative value and specification



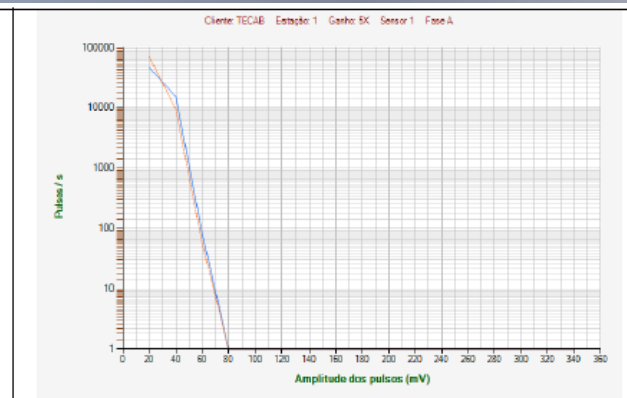
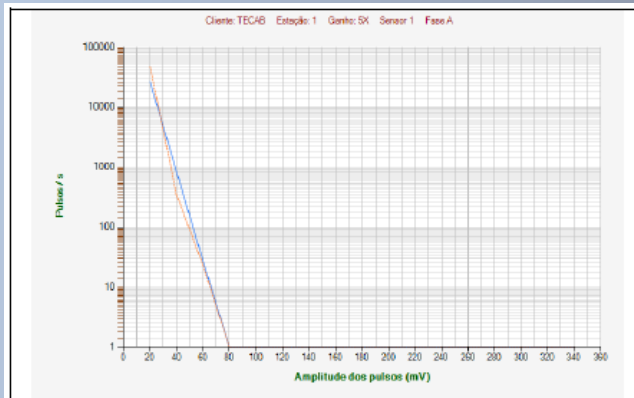
# Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED

## Acceptance Criteria - Prototype Approval and Manufacturing Release

ETAPA DE APROVAÇÃO DOS PROTOT		<i>DP Offline</i>	<i>Blackout Test</i>	<i>Surge Test</i>
<b>Número de Amostras Testadas</b>		100%	100%	100%
<b>Norma Referenciada</b>		IEEE 1434	IEEE 1434	IEEE 522
<b>Critério Norma</b>		-	-	3,5*PU (STEPS DE 25%)
<b>Critério Especificação</b>		50mV	s/ pto a 1,2*Un (9,2kV)	3,5*PU (STEPS DE 25%)
<b>Valores Atingidos</b>	<b>Protótipo 03</b>	<b>68mV (3)</b>	<b>Aprovado e sem pontos</b>	<b>15KV (4)</b>
	<b>Protótipo 17</b>	<b>69mV (3)</b>	<b>Aprovado e sem pontos</b>	<b>15KV (4)</b>
<b>NOTAS</b>				
3- Apesar do valor ter extrapolado 50mV, os valores foram aceitos, em virtude de os valores de TIPUP e Tanδ serem muito baixos.				
4- Realizado ensaio individual nos protótipos com 15kV				

ETAPA DE APROVAÇÃO DOS PROTOT		<i>Pintura Condutiva</i>	<i>Tensão aplicada (Hipot Vca) - Parte Reta</i>	<i>Tensão aplicada (Hipot Vca) - CB</i>	<i>Voltage Endurance Test</i>
<b>Número de Amostras Testadas</b>		100%	100%	100%	100%
<b>Norma Referenciada</b>		Não normalizado	NEMA MG1	NEMA MG1	IEEE 1043 / 1553
<b>Critério Norma</b>		-	2kV+3	-	3,75 a 4,4*Un; 90/135°C; 250/400h
<b>Critério Especificação</b>		0,8 a 1,2 kohm/square	4*U (52kV) - 1 min	2,5*U(33kV) - 10s	32kV;120°C; 250h (1a)/400h (3 rest)
<b>Valores Atingidos</b>	<b>Protótipo 03</b>	<b>0,94 (5)</b>	<b>Aprovado</b>	<b>Aprovado</b>	<b>Suportou 400h (6)</b>
	<b>Protótipo 17</b>	<b>0,87 (5)</b>	<b>Aprovado</b>	<b>Aprovado</b>	<b>Suportou 400h (6)</b>
<b>NOTAS</b>					
5- Valor médio calculado através de 3 pontos de medição na perna de topo e 3 na perna de fundo					
6- Os dois (4 pernas) protótipos suportaram o VET, durante 400 horas, T=120°C e V=32kV, sem necessidade de correção do revestimento condutivo					
7- Após término do VET, os protótipos passaram por novo ensaio de TIPUP, sendo obtidos os valores de 0,163 e 0,158, respectivamente, bem superiores aos valores iniciais obtidos, entretanto, <b>ainda em atendimento ao valor normativo de 0,25%</b> .					
8- Após término do 2º TIPUP, o protótipo 17 passou novo teste de aplicada, suportando 42 kV, quando houve ruptura na região da luva. Não houve dano na parte reta.					
9- O protótipo 03, após 2º TIPUP suportou 50kV durante aproximadamente 1min, quando houve ruptura na parte.					

# Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED



# Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED

## 2 - MANUFACTURE OF THE NEW WINDING

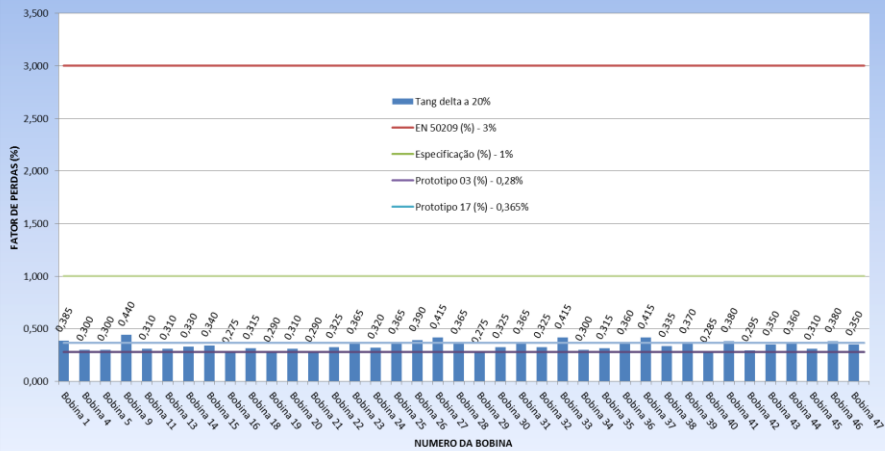
ETAPA DE FABRICAÇÃO	<i>Perdas dielétricas (Tanδ a 0,2xU)</i>	<i>TIPUP - [Tanδ(0,6xU) - Tanδ(0,2xU)]/2)</i>	<i>Δtanδ with steps 0,2xU</i>	
<i>Número de Amostras Testadas</i>	100%	100%	100%	
<i>Norma Referenciada</i>	EN 50209	EN 50209	EN 50209	
<i>Critério Norma</i>	3% (100%)	0,25% (95%) / 0,3% (5%)	0,5% (95%) / 0,6% (5%)	(machines up to 11kV)
<i>Critério Especificação</i>	1% (100%)	0,1% (100%)	0,20%	
<b>VALORES ATINGIDOS</b>	<b>GRAFICO 1</b>	<b>GRÁFICO 2</b>	<b>GRÁFICO 3</b>	
ETAPA DE FABRICAÇÃO	<i>DP Offline</i>	<i>Blackout Test</i>	<i>Surge Test</i>	
<i>Número de Amostras Testadas</i>	100%	100%	100%	
<i>Norma Referenciada</i>	IEEE 1434	IEEE 1434	IEEE 522	
<i>Critério Norma</i>	-	-	3,5*PU (STEPS DE 25%)	
<i>Critério Especificação</i>	50mV	s/ pto a 1,2*Un (9,2kV)	3,5*PU (STEPS DE 25%)	
<b>VALORES ATINGIDOS</b>	<b>GRÁFICO 4</b>	<b>Aprovado e sem pontos</b>	<b>15KV (4)</b>	
ETAPA DE FABRICAÇÃO	<i>Pintura Condutiva</i>	<i>Tensão aplicada (Hipot Vca) - Parte Reta</i>	<i>Tensão aplicada (Hipot Vca) - CB</i>	<i>REPETIÇÃO Voltage Endurance Test</i>
<i>Número de Amostras Testadas</i>	100%	100%	100%	100%
<i>Norma Referenciada</i>	Não normalizado	NEMA MG1	NEMA MG1	IEEE 1043 / 1553
<i>Critério Norma</i>	-	2kV+1 (após montagem)	-	3,75 a 4,4*Un; 90/135°C; 250/400h
<i>Critério Especificação</i>	0,8 a 1,2 kohm/square	3*U (41,4kV) - 1min	2*U (26,4kV)	32kV;120°C; 250h (1a)/400h (3 rest)
<b>VALORES ATINGIDOS</b>	<b>GRÁFICO 5</b>	<b>Aprovado</b>	<b>Aprovado</b>	<b>NOTA 1</b>

### NOTAS

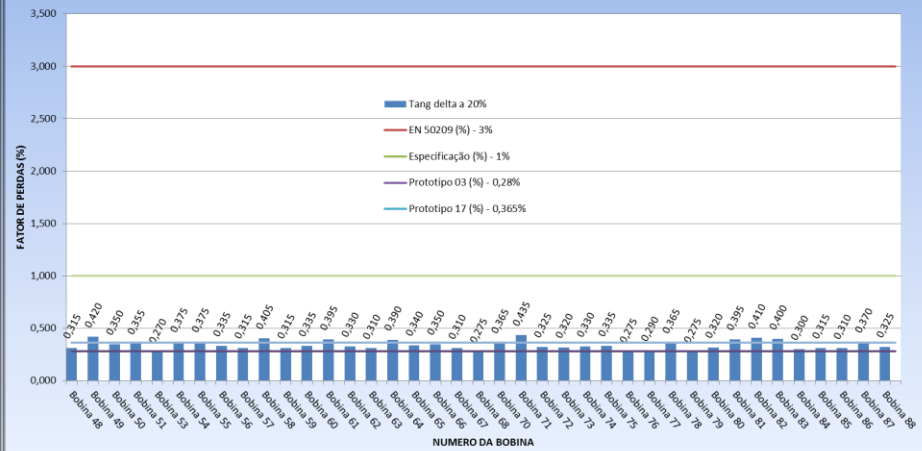
- 1- Seria realizado em 4 amostras retiradas aleatoriamente do lote fabricado, entretanto, prazo de retorno da máquina impactava severamente a produção da planta. Devido aos valores de TIPUP, Δtanδ e Dpoffline foram muito baixos, e semelhantes aos protótipos, optou-se por não realizar o 2º VET.

# Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED

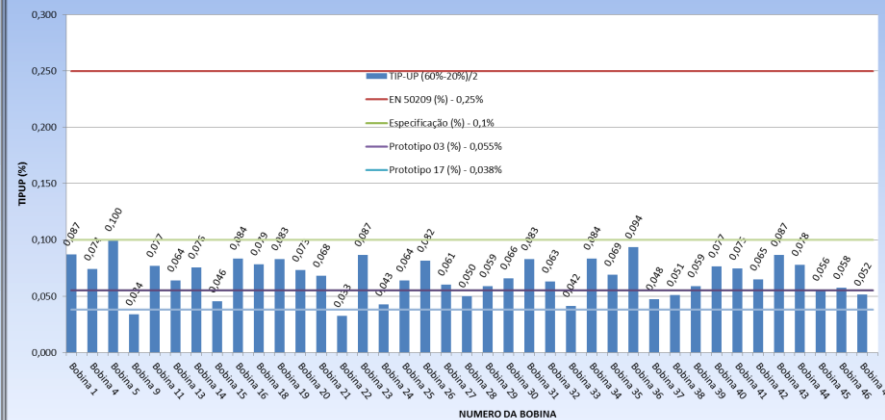
Fator de Perdas (0,2xVff) - Valores médios por parte reta por bobina



Fator de Perdas (0,2xVff) - Valores médios por parte reta por bobina



TIP-UP [0,6-0,2]/2 - médias por parte reta por bobina

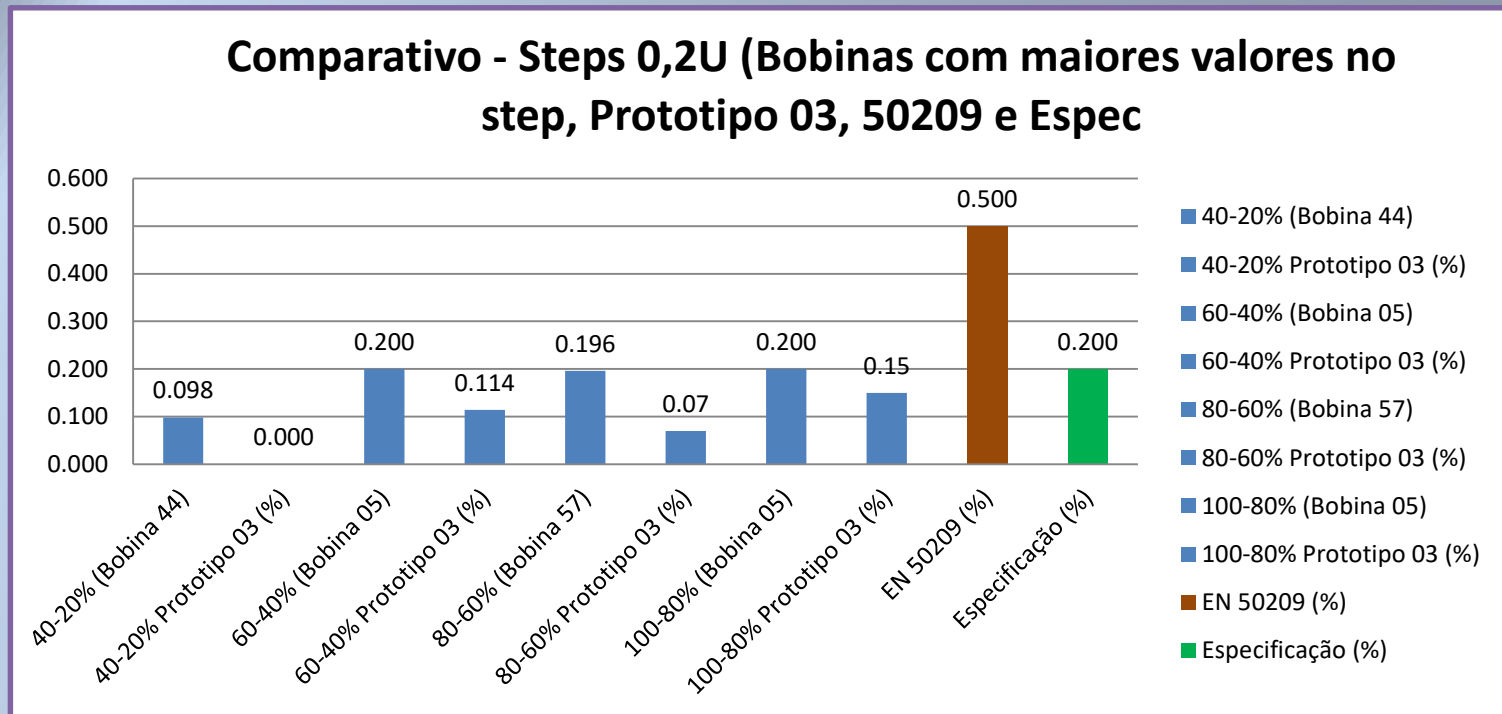


TIP-UP [0,6-0,2]/2 - médias por parte reta por bobina



# Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED

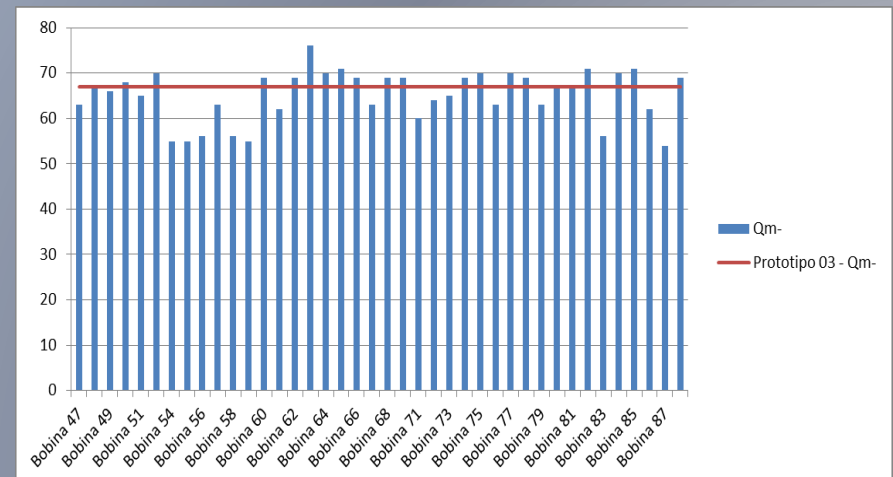
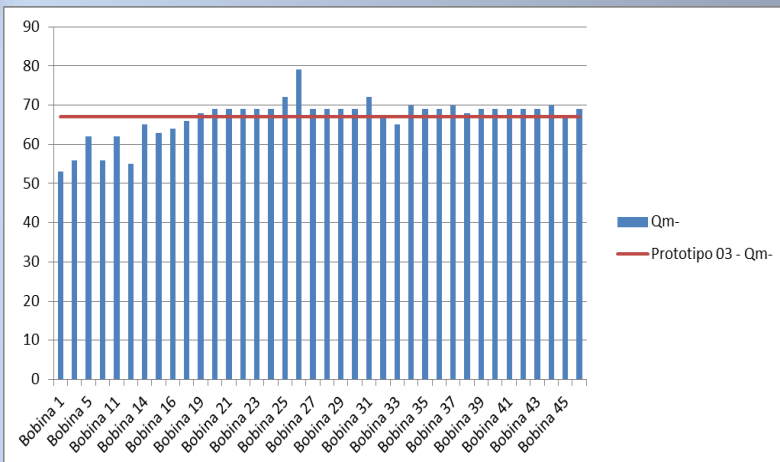
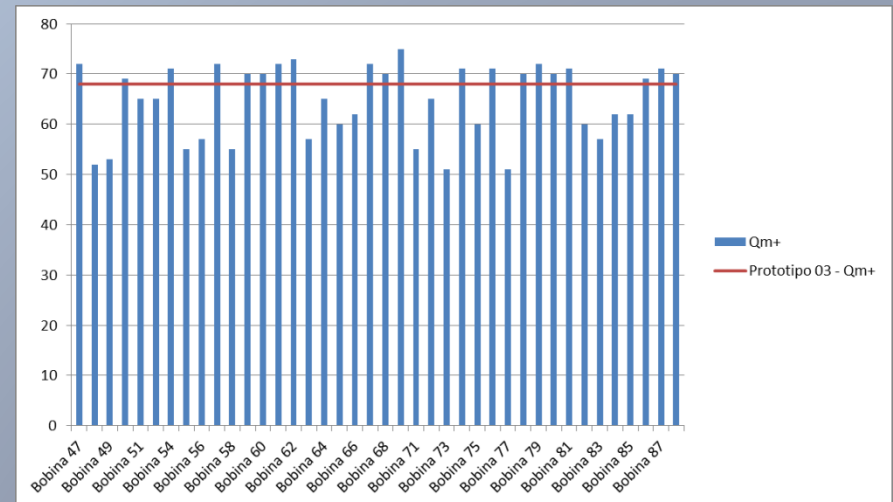
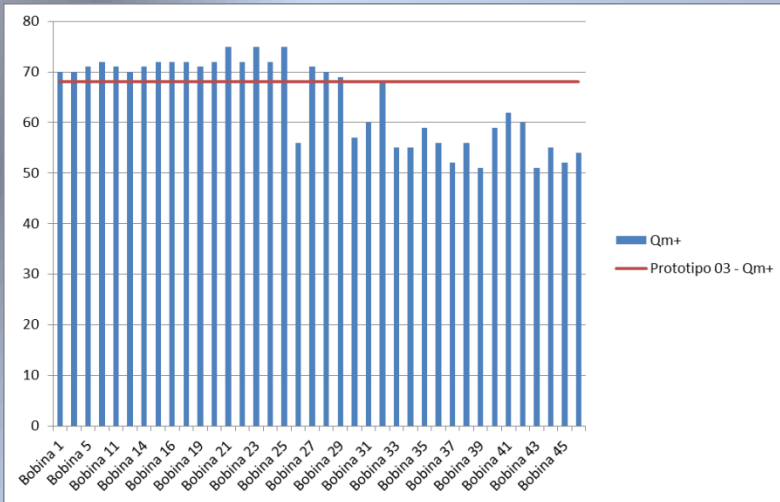
- General Comparison - Delta tangent Delta (steps of 0.2U)



- The coils with higher values in the Step considered remained **within the limit of the specification (0.200)**.

# Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED

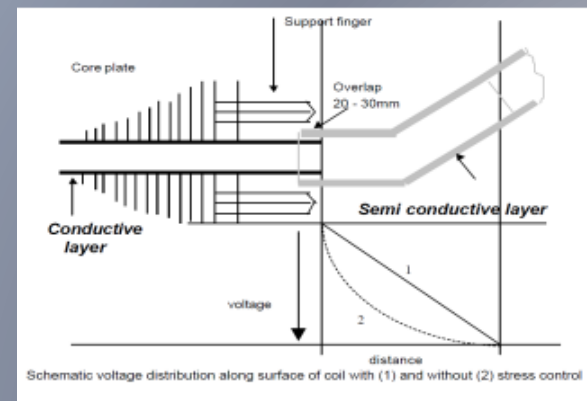
- General Comparison - DPofline



# Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED

## 3 – MOUNTING - Tests and criteria during and after mounting

- Regularity in spacing for endwindings (**minimum 5mm**) - Difficulty encountered due to **the tight design of the machine;**
- Positioning the “**glove**” relative to the **tightening finger** – ok
- **Maximum side clearance of 0.1mm** – ok
- **Endwinding vibration – ok**
- **Coil / core contact resistance** - ok
- Stator Wedge Tap - ok



# ***Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED***

## **3 – MOUNTING - Tests and criteria during and after mounting**

- Hi-Pot AC After installation and before interconnections between coils: Value of  $1.2x (2U + 3)$  kV (37.2 kV) for 1min - ok - last coil after inserted failed in this applied voltage test, due to the placement process.
- Hi-pot AC, After coil interconnections, with Vca application of  $(2U + 3)$  kV (30.6 kV) for 1min in the phases against the ground, before the final curing – ok
- Hi-pot AC, After coil interconnections, with Vca application of  $(2U + 1)$  kV (27.4 kV) for 1min in the phases against the ground, after final cure – ok
- BLACKOUT TEST, After interconnection of coils in a dark room, voltage Vca up to  $1.2xU / \sqrt{3}$  (9.57 kV) – ok
- DON'T paint stator



# ***Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED***

## **3 – MOUNTING - Tests and criteria during and after mounting**

Factory Signature Essays (for future trends). Tests after final assembly. No minimum acceptance values were required

- Insulation Resistance
- **Off-line partial discharges - a maximum value of 200mV per phase was suggested**
- **Dielectric Losses -  $[\text{Tan}\delta (0.6xU) - \text{Tan}\delta (0.2xU)] / 2$**
- **Dielectric Losses ( $\Delta\text{Tan}\delta$ )**
- **Capacitance**
- Resistance ohmic
- **Partial discharges On-line** in the field, machine at full load (load variations were suggested to observe variations of DP as a function of temperature)

# ***Practical Case - Rewinding a 13.2 kV motor – SPECIFICATION / VALUES REQUIRED / ACHIEVED***

## **4 - OTHER IMPORTANT POINTS.**

- During the reform of the machine, other very important points that must be observed:
  - Magnetic core (IEEE 432)
  - Registration of all information, dimensions and materials of the machine
  - Welding procedure and acceptance criterion of damper windings (penetrating liquid and ultrasound);
  - Insulation system for the poles;
  - Rotor balancing at high speed (recommended) - avoid refining in the field;

# ***CONCLUSIONS AND RECOMMENDATIONS***

- **Monitoring via PD** allowed the identification and monitoring of the **degradation of the insulation system in advance**, which enabled the elaboration of a more rigorous and careful specification, as well as **optimization of the stopping time**;
- The **life expectancy** of a winding will depend heavily on aspects of **design, fabrication and assembly (SPECIFICATION)** and other **stresses (electrical, thermal, mechanical and environmental)**;
- Despite being a weak link of the machine, **many users still can not specify the purchase of a new winding**;
- **Specification** of purchase of new winding for critical machine must be **strict** and based on **standards and objective criteria "pass-fail"**.
- **Standards are not always objective** in the criteria. **The user must specify acceptance values, if not present**.
- The specification must have a balance between **CRITERIA AND COSTS**, otherwise, **exaggerated encumbrance** may occur without the actual need;

# ***CONCLUSIONS AND RECOMMENDATIONS***

- We **believe** that **existing and standardized criteria may be more stringent**;
- Some standards need to adopt quantitative acceptance criteria.
- **Even with the high demands** of a rewinding specification (in addition to manufacturing follow-up), **critical AT** machines should **be monitored** minimally through **online PD, winding and bearing temperature, endwinding vibration (2 and 4 pole) and rotor magnetic flux (Synchronous machines)**, in addition to predictive tests and periodic visual inspections;
- All **records of tests and results** must be archived, as they will be **fundamental for future trendings and evaluation of eventual failures**;
- **The practical case presented shows that it is possible to provide more stringent criteria** than those provided for in the standard;