

2.3	Effects of ageing in insulation systems of power transformers	43
2.3.1	Thermal stress	43
2.3.2	Mechanical stress	45
2.3.3	Electrical stress	46
2.3.4	Ambient stress	48
2.4	Condition monitoring techniques in power transformers	49
2.4.1	Electrical measurements	49
2.4.2	Apparent charge estimation: quasi-integration and calibration	51
2.4.3	PD detection in transformers	54
2.4.4	Unconventional methods of partial discharge measurements in power transformers	58
2.4.5	Methods of partial discharge analysis	63
2.5	Conclusions	77
	Acknowledgements	78
	References	79
<b>3</b>	<b>Moisture analysis for power transformers</b>	<b>87</b>
	<i>Belén García, Alexander Céspedes and Diego García</i>	
3.1	Introduction	87
3.2	Moisture in transformer insulation	88
3.2.1	Risks associated to the presence of high levels of moisture in transformers	88
3.2.2	Sources of moisture contamination in transformers	89
3.3	Moisture dynamics in transformers	90
3.3.1	Adsorption and desorption of moisture in cellulosic insulation	92
3.3.2	Moisture distribution within transformer solid insulation	94
3.3.3	Solubility of water in oil	95
3.3.4	Moisture equilibrium between paper and oil	96
3.3.5	Moisture equilibrium in alternative fluids	98
3.3.6	Moisture dynamics in a transformer under operation	100
3.4	Monitoring of moisture content in oil	101
3.4.1	Periodical sampling of oil	101
3.4.2	On-line measure of oil moisture with capacitive sensors	102
3.4.3	Interpretation of the moisture content of oil	104
3.5	Estimation of the moisture content of solid insulation from moisture in oil measures	106
3.5.1	Determination of moisture content of paper using the equilibrium charts	106
3.5.2	Improved methodologies to estimate the moisture content of paper from the measures of moisture content of oil	107

3.6	Dielectric response methods for the estimation of moisture in solid insulation	108
3.6.1	Theoretical principles	108
3.6.2	Frequency dielectric spectroscopy	110
3.6.3	Recovery voltage method	115
3.6.4	Polarisation and depolarisation currents	117
3.7	Conclusions, future trends and challenges	119
	References	120
<b>4</b>	<b>Assessing DP value of a power transformer considering thermal ageing and paper moisture</b>	<b>125</b>
	<i>Ricardo David Medina Velecela, Andres Arturo Romero Quete, Enrique Esteban Mombello, Giuseppe Rattá and Diego Xavier Morales Jadán</i>	
	Abstract	125
4.1	Introduction and preliminary issues	126
4.2	State of the art	126
4.3	Theoretical framework	127
4.3.1	Paper as power transformer solid insulation system	127
4.3.2	Paper degradation process	127
4.3.3	Degradation accelerators	129
4.3.4	Paper humidity	129
4.3.5	Assessing of depolymerization process	131
4.4	Proposed method	133
4.4.1	Problem description	133
4.4.2	Oil moisture estimation	133
4.4.3	New approach for degree of polymerization assessing	134
4.5	Casestudy	135
4.5.1	Results	136
4.6	Conclusions	139
	References	140
<b>5</b>	<b>Frequency response analysis</b>	<b>143</b>
	<i>Mehdi Bagheri and Toan Phung</i>	
	Abstract	143
5.1	Introduction	143
5.2	Transformer winding deformation	144
5.2.1	Deformation types and short-circuit current	144
5.2.2	Transformer transportation causing active part displacement	146

5.3	Methods to recognize winding deformation	148
5.3.1	Short-circuit impedance	148
5.3.2	Transfer function	151
5.4	Sweep frequency response analysis	152
5.5	Standard connection methods	153
5.5.1	End-to-end measurement	153
5.5.2	Inductive interwinding measurements	153
5.5.3	Capacitive interwinding measurements	153
5.5.4	End-to-end short-circuit measurements	153
5.6	FRA signature assessment	155
5.6.1	Visual assessment of FRA signature	155
5.6.2	Statistical assessment of FRA signature	162
5.7	Factors affecting frequency response signature	166
5.7.1	Winding inductance, capacitance	166
5.7.2	Series capacitance under buckling	178
5.7.3	Shunt capacitance under buckling	178
5.7.4	Tap-changer	178
5.7.5	Paper insulation deterioration	183
5.7.6	Temperature and moisture content	187
5.8	Online transformer winding deformation diagnosis	199
5.8.1	Methods for online transformer active part assessment	199
5.8.2	Online FRA setup	203
5.8.3	Online FRA (OFRA) progress and influence of bushing tap	205
	References	207

## **6 Monitoring of power transformers by mechanical oscillations** **211**

*Michael Beltle*

6.1	Introduction	211
6.2	Physics of mechanical oscillations	212
6.2.1	Oscillations of the core	212
6.2.2	Oscillations of the windings	213
6.3	Measurement of vibrations	214
6.3.1	Comparison of tank wall and in-oil measurement	216
6.4	Sensitivity of surface tank measurements	217
6.4.1	Laboratory setup	217
6.4.2	Field test: sensor positions	219
6.5	Superimposing effects on tank wall measurements	220
6.5.1	Effects of on-load tap-changer position	220
6.5.2	Effects of transformer load and operating temperature	221
6.6	Practical case studies	223
6.6.1	Mechanical oscillations over time	223

6.7	Behaviour of mechanical oscillations at DC superimposition	225
6.7.1	DC-coupling path into power transformers	225
6.7.2	Saturation and its effect on magnetostriction	226
6.7.3	Test setup for DC superimposed effects	227
6.7.4	DC-detection using vibration measurement	229
6.7.5	Dependency of DC-driven vibration and transformer noise	231
6.7.6	Case study on transformers impacted by DC	233
6.8	Conclusion	234
	References	235
<b>7</b>	<b>Lifecycle management of power transformers in a new energy era</b>	<b>239</b>
	<i>Carlos Gamez</i>	
7.1	Introduction	239
7.2	A changing landscape	240
7.2.1	Renewable energy sources	243
7.2.2	Energy storage	246
7.3	Impact on asset management strategies	246
7.3.1	Operation, maintenance and replacement of ageing assets	247
7.4	The advent of artificial intelligence	248
7.5	Analysis automation as an aid to lifecycle management	251
7.5.1	Condition attributes	252
7.5.2	Measurements	253
7.5.3	Analysis rules	253
7.5.4	Implementation tool	254
7.6	The digital substation	254
7.6.1	Value proposition	254
7.6.2	Technical standards	255
7.6.3	Hardware and software technologies	255
7.6.4	Business processes	256
7.7	Summary	256
	References	257
<b>8</b>	<b>Power transformer asset management and remnant life</b>	<b>259</b>
	<i>Norazhar Abu Bakar</i>	
	Abstract	259
8.1	Introduction	259
8.2	Transformer health condition	261
8.3	Proposed approach	263
8.4	Fuzzy-logic model development	264
8.4.1	Furan criticality	265
8.4.2	CO ratio criticality	267

8.4.3	Paper ageing criticality	270
8.4.4	Relative accelerating ageing criticality	271
8.4.5	Thermal fault criticality	274
8.4.6	Electrical fault criticality	275
8.4.7	Overall thermal–electrical fault criticality	276
8.4.8	IFT criticality	277
8.4.9	Remnant life estimation	281
8.4.10	Asset management model	282
8.5	Case study on pre-known condition of power transformer	284
8.6	Conclusion	289
	Acknowledgement	291
	References	291

<b>Index</b>	<b>295</b>
--------------	------------