

Contents

Foreword.....	5
1 Introduction to ferroresonance oscillations.....	11
1.1 Scope.....	11
1.2 Forced oscillations in non-linear resonance circuits, general considerations.....	13
1.2.1 Definitions of system stabilities.....	14
1.3 Excitation of steady state and non-steady state ferroresonance oscillations.....	15
1.4 Inductive voltage transformer.....	18
1.5 Non-linear magnetization characteristic.....	20
1.5.1 Introduction.....	20
1.5.2 Measuring of the magnetization curves.....	23
1.5.2.1 Measuring of magnetization curves with an analog measuring circuit.....	23
1.5.2.2 Digital measuring setup for the hysteresis loop and the magnetization curve of silicon-iron cores.....	27
1.5.3 Magnetic core design.....	31
2 Theoretical considerations of non-linear oscillations.....	35
2.1 The first solution by <i>Rüdenberg</i> , graphical treatment for power frequency ferroresonance oscillations.....	35
2.1.1 Preliminary remarks.....	35
2.1.2 Ferroresonance circuit without energy losses.....	35
2.2 Voltage and current during a single period of ferroresonance oscillation at power frequency.....	40
2.3 Analytical description of oscillations in non-linear circuits.....	43
2.3.1 Introduction: Developments in the theory of ferroresonance oscillations.....	43
2.3.2 Analytical model.....	43
2.3.3 The differential equation for ferroresonance oscillations.....	48
2.3.4 Oscillation frequencies in ferroresonance systems.....	50
2.3.5 Solution of the differential equation for the network frequency $f_0 = 50$ Hz or 60 Hz; $\omega_0 = 2\pi f_0$ [1/s].....	51

2.3.6	Solution of the non-linear differential (2.22) for the second subharmonic $f_0/2$	53
2.3.7	Solution of the non-linear differential equation (2.22) for the third subharmonic frequency $f_0/3$	54
3	Single-phase ferroresonance oscillation.	59
3.1	Introduction.	59
3.2	General schematic diagram for single-phase ferroresonance	59
3.3	Practical cases of ferroresonance configurations	61
3.4	Parameters relevant ferroresonance	63
3.5	Ferroresonance in CVTs	64
3.6	The simplification of non-linear electrical circuits with the theorem of <i>Thévenin</i>	65
4	Three-phase ferroresonance oscillations	67
4.1	Introduction.	67
4.2	Resulting Waveform of three-phase Ferroresonance Oscillations	68
4.3	Physical explanation for the beat	72
4.4	Practical example.	72
4.5	Results of field tests	74
4.5.1	Example 1	75
4.5.2	Example 2	77
4.5.3	Example 3	80
4.5.4	Example 4	82
5	Simulation of ferroresonance oscillations	83
5.1	Schematic circuit and circuit elements of single phase ferroresonance configuration.	84
5.2	Circuit losses	86
5.3	Magnetization curve	87
5.3.1	Analytical approximation of the magnetization curve.	88
5.3.2	Iron losses	89
5.3.3	Representation of hysteresis curve	90
5.4	Characterization of ferroresonance oscillations	91
5.4.1	Non-steady-state (transient) ferroresonance oscillations.	93
5.4.2	Steady-state ferroresonance oscillation at power frequency	95
5.4.3	Steady-state subharmonic ferroresonance oscillation.	97
5.4.4	Steady-state chaotic ferroresonance oscillation	97
5.5	Discussion of single phase ferroresonance behavior.	99
5.5.1	Dependence on switching phase angle	99

5.5.2	Limits of ferroresonance regimes	103
5.5.3	Detailed analysis of simulated signals.....	107
5.5.4	Ferroresonance behavior with damping device	109
5.5.5	Comparison between experiment and simulation	112
5.6	Simulation of three phase ferroresonance oscillations.....	114
6	Detection and measurement of ferroresonance oscillations	117
6.1	Introduction.....	117
6.2	Detection of ferroresonance oscillations.....	118
6.2.1	Detection of single-phase ferroresonance oscillations	118
6.2.2	Detection of three-phase ferroresonance oscillations	118
6.2.3	Power quality measurements	119
6.3	Measurement of ferroresonance oscillations	121
6.3.1	Single-phase ferroresonance.....	122
6.3.2	Three-phase ferroresonance	125
7	Prevention and measures against ferroresonance oscillations.....	127
7.1	Overview of measures to avoid ferroresonance oscillations.....	127
7.2	Definition of switching procedures to avoid ferroresonance oscillations.....	130
7.3	Measures in new substation projects	134
7.3.1	Design of inductive voltage transformers.....	135
7.4	Existing substations	135
7.4.1	Damping in case of single-phase ferroresonance.....	136
7.4.2	Damping in case of three-phase ferroresonance.....	138
7.5	Overview and conclusions.....	140
8	List of symbols	145
	Literature	149
	Subject Index.....	155