

Contents

- 1 Introduction 1**
 - 1.1 Basic terms 3
 - 1.1.1 Time series definition and properties 3
 - 1.1.2 Time series forecasting 5
 - 1.1.3 Feature vector and classifier pipeline 6
 - 1.2 Problem statement 7
 - 1.2.1 Load forecasting in power systems 7
 - 1.2.2 Forecasting horizons 8
 - 1.2.3 Challenges in load forecasting in modern power grids . . 9
 - 1.2.4 Aims of the thesis 12
 - 1.3 Scientific contribution 13
 - 1.3.1 Training data clustering: similar day versus sliding win-
dow approach 13
 - 1.3.2 Training for load forecasting based on Hidden Markov
Models (HMMs) 14
 - 1.3.3 Optimized Viterbi algorithm 15
 - 1.3.4 Simplified geometric integration for transition and ob-
servation densities 16
 - 1.3.5 Evaluation of different Deep Neural Network (DNN)
architectures 17
 - 1.3.6 Encoder-decoder with modified attention function 17
 - 1.3.7 Adaptive learning of the function approximation 18
 - 1.4 Overview 18

2	Literature overview	21
2.1	Hidden Markov Models (HMMs) for load forecasting	22
2.2	Deep Neural Networks (DNNs) for load forecasting	24
2.2.1	Multilayer Perceptron Networks (MLPs)	25
2.2.2	Convolutional Neural Networks (CNNs)	26
2.2.3	Recurrent Neural Networks (RNNs)	27
2.2.4	Encoder-Decoder architectures	29
3	Data description and modeling	33
3.1	Raw data	36
3.1.1	Load data	36
3.1.2	Weather data	38
3.1.3	Location-based marginal pricing (LBMP) data	42
3.2	Data preprocessing and cleaning	43
3.2.1	Load data	44
3.2.2	Weather data	45
3.2.3	Location-based marginal pricing (LBMP) data	47
3.2.4	Data normalization	49
3.3	Feature selection	51
3.4	Data set clustering	55
4	Finite Hidden Markov Models (HMMs)	63
4.1	Finite First-Order Markov Chains (MCs)	63
4.2	Finite Hidden Markov Models (HMMs) with discrete states . . .	65
4.3	State, state transitions and observation functions	68
4.3.1	Calculation of the state-dependent observation density .	69
4.3.2	Calculation of state transition density	73
4.4	Optimized Viterbi algorithm	75
4.5	Hidden Markov Model (HMM)-based algorithm for load fore- casting	77
5	Artificial Neural Networks (ANNs)	81
5.1	Multilayer Perceptron Network (MLP)	82

5.1.1	Gradient descent	83
5.1.2	Gradient calculation using backpropagation	84
5.1.3	Different strategies for the calculation of the parameter update	85
5.2	Nonlinear Autoregressive Network with Exogenous Inputs (NARX)	86
5.3	Deep Neural Networks (DNNs)	87
5.3.1	Elman Network	88
5.3.2	Long short-term memory cells (LSTM)	89
5.3.3	Sequential encoder-decoder with attention	90
5.3.4	Sequential encoder and stacked decoder with multi- layer attention and convolution	93
5.3.5	Attention function	96
5.3.6	Adaptive learning of the approximation function	97
5.3.7	Data selection for the training	99
5.3.8	Local over-fitting and global generalization	101
5.3.9	Deep neural network (DNN) based algorithm for load forecasting	102
6	Experiments	105
6.1	Load forecasting with Hidden Markov Models (HMMs)	106
6.1.1	Default parameters	106
6.1.2	Evaluation of Hidden Markov Model (HMM)-based load forecasting with benchmark methods	107
6.1.3	Numerical integration versus geometric approximation of area and volume	113
6.1.4	Performance improvement through the optimized Viterbi algorithm	115
6.1.5	Batch sizes	116
6.1.6	The superiority of data preselection over the sliding window approach	118
6.2	Deep Neural Networks (DNNs)	123

6.2.1	NARX	124
6.2.2	RNN and LSTM	128
6.2.3	Sequential encoder-decoder with LSTM	132
6.2.4	Sequential encoder-decoder with LSTM and a single at- tention layer	135
6.2.5	Sequential encoder and stacked decoder	138
6.2.6	Sequential encoder stacked decoder with multiple at- tention layers	142
6.2.7	Improved attention function	143
6.2.8	Weighting the inputs with a convolutional layer	146
6.2.9	The superiority of data preselection over sliding win- dow approach	149
6.2.10	Adaptive learning using Transfer Learning	152
6.2.11	SESTDAC - parameter variation	155
6.2.12	Summary of the results of the different DNN architectures	162
6.2.13	SESTDAC evaluation using benchmark methods	164
6.3	Comparison of results for NYISO data from the literature	167
7	Summary	169
8	Future Work	173
	List of Figures	174
	List of Tables	177
	Bibliography	179