ASSESSMENT AND MITIGATION OF POWER QUALITY DISTURBANCES

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by

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CERTIFICATE

It is certified that the thesis entitled "**Assessment and Mitigation of Power Quality Disturbances,**" being submitted by **Mr. Raj Kumar** for award of the degree of **Doctor of Philosophy** in the **Instrument Design Development Centre, Indian Institute of Technology Delhi**, is a record of the student work carried out by him under our supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

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ABSTRACT

Power quality problems are arising due to the proliferation of the sensitive electronic loads in industrial and commercial power systems which are the sources of many power quality distortions and disturbances in the distribution system as well as mostly affected by these disturbances. Power quality disturbances generated by these loads propagate on the electrical network to affect the distribution system equipments and causing malfunction of some of the electronic equipments of others. Therefore, due to these power quality issues, the customers are focussing attention on the quality of power necessary for the successful operation of these loads. Ensuring good power quality requires good initial design, effective mitigation equipment, and cooperation with the supplier, frequent monitoring and good maintenance. A high level of power quality is understood as low level of disturbance and agreement on the acceptable levels of disturbance. The limits on power quality are set by certain international standards such as IEEE-1159, IEC 61000 and EN 50160 to maintain the power quality to an acceptable benchmark. When these limits are exceeded, it is not certain that the equipment is no longer to operate or work without any malfunction.

Power quality disturbances like voltage sag, swell, interruption, flicker, notches and spikes commonly occur in a distribution system. Voltage sags are mostly caused by the switching on loads with heavy starting currents and utility fault clearing while the swells are mainly due to the sudden load reduction and a single phase fault on a three phase system. An interruption which is the complete loss of supply voltage is mainly due to any supply grid equipment failure or the operation of the utility protective devices. The flicker which is a symptom of voltage variation is usually caused by large fluctuating loads such as arc furnaces, rolling mill drives and main winders etc. The notching is due to the electronic devices such as variable speed drives, light dimmers and arc welders under normal conditions. The spikes are caused by the lightening, grounding and switching of the inductive

loads. Nonlinear loads are main cause for the origin of the harmonics in the power system. The power system parameters -frequency, voltage and current amplitude, waveform and symmetry can serve as the frames of reference to classify these power quality disturbances according to the impact on the quality of the available power. Disturbances like voltage sag, swell and interruptions are called as events while disturbances like harmonics and flicker are called as power quality variations as these continuously exist in the distribution system. Multistage and multiple power quality disturbances also occur due to the complexity of the power system.

Therefore, the continuous monitoring of power quality is essential today for understanding the causes and the characteristics of various power quality distortions and disturbances so that electrical environment at that location is evaluated to diagnose the incompatibilities between the source and the load. Digital signal processing techniques are used in these instruments for the recognition and the assessment of these power quality disturbances. Power quality disturbances recognition helps the power engineers to solve the power quality issues between the utilities and the consumers and to find the optimum solution for the mitigation of these power quality disturbances. Therefore, the power quality improvements are needed in the form of mitigating devices for the longevity of the electronic equipments. Several measures can be taken at the various levels of the distribution system to make the end use devices less sensitive and to provide the clean and consistent power to the consumers to minimize the equipments failures and operational upsets.

PQ monitoring basically involves the measurements of the voltage and current signals to quantify the performance of the supply, identification of the disturbances and to find the cause of the equipment malfunction. The process of PQ monitoring requires signal processing of the sensed signals for the analysis and the extraction of the relevant features. The main features are extracted from the transformed signals and are used for the classification of these

disturbances so that these techniques can be effectively used for the development of the intelligent PQ monitoring equipments. The selection of the suitable features is extremely important as these features decide the computation time and the precision of the classification. The practical signal processing techniques have been the discrete Fourier transform and the root mean square but these are not suitable for the stationary measurement data. As most of the PQ disturbances are nonstationary in nature so the joint time-frequency domain analysis is needed with the signal processing techniques in order to track the time evolving characteristics of the disturbances.

This research work is aimed towards the development and investigation of signal processing techniques for the assessment and mitigation of various power quality disturbances originating in a distribution system. The simulation to the real acquisition of power quality disturbances are presented in this work. The disturbances are generated in the laboratory by switching a number of linear and nonlinear loads. However, due to the non availability of the practical data and rating constraints, numerical models are used to generate the synthetic data of common power quality disturbances such as voltage sag, swell, interruption, flicker, harmonics, spikes and notches as per IEEE 1159 standard. These are analysed with a number of signal processing techniques like instantaneous symmetrical components, complex wavelet transform, Stockwell-transform, Hilbert Huang transform for the assessment. All the single stage power PQ disturbances are detected and classified using symmetrical components in time domain. The multiple PQ disturbances along with the single stage are detected and assessed with the complex wavelet transform. Stockwell-transform based artificial neural network classifier and rule-based decision tree are proposed for the recognition and the classification of single stage and a number of multiple disturbances. Hilbert Huang transform along with the probabilistic neural network is proposed for the recognition and the classification of the single stage and multiple disturbances.

These signal processing techniques are further investigated for the mitigation of PQ disturbances. Control algorithms based on these techniques for distribution static compensator (DSTATCOM) are proposed for the PQ improvements in a distribution system. A model of a DSTATCOM involving a three leg voltage source converter for a three phase distribution system is developed with the help of Simulink and SimPower toolboxes of MATLAB. The steady state and the dynamic performances are evaluated for both the linear and nonlinear loads under the balanced and unbalanced load conditions simultaneously. The simulated results are validated on a developed laboratory prototype of DSTATCOM. A comparison table of the different algorithms under a nonlinear load in the balanced and unbalanced conditions has been presented. The distortion in the grid current is least at a nonlinear load in the balanced condition with instantaneous symmetrical component technique. The S-transform based control algorithm is providing the least distortion in the grid current during the unbalanced load conditions in the system. PQ indices with these control algorithms are found to within the acceptable limits of international PQ IEEE-519 standard.

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LIST OF ABBREVIATIONS

ACO	Ant Colony Optimization
AF	Active Filter
ANN	Artificial Neural Network
ASD	Adjustable Speed Drives
BNT	Balanced Neural Tree
CAIFI	Customer Average Interruption Frequency Index
CBEMA	Computer Business Equipment Manufacturer Association
CENELEC	European Committee for Electrotechnical Standardization
CF	Crest Factor
CPD	Custom Power Device
CWT	Complex Wavelet Transform
DAQ	Data Acquisition
DSTATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
DWT	Discrete Wavelet Transform
EKF	Extended Kalman Filter
EMC	Electromagnetic Compatibility
EMD	Empirical Mode Decomposition
EN	European Norms
ES	Expert System
ESD	Electrostatic Discharge
FES	Fuzzy Expert System
FL	Fuzzy Rule
GA	Genetic Algorithm
HHT	Hilbert Haung Transform
HMM	Hidden Markov Model
HSA	Hilbert Spectral Analysis
IA	Instantaneous Amplitude
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IF	Instantaneous Frequency
IGBT	Insulated Gate Bipolar Transistor
IMF	Intrinsic Mode Function
IP	Instantaneous Phase
IRP	Instantaneous Reactive Power
ISC	Instantaneous Symmetrical Component

ITI	Information Technology Industry Council
ITIC	Information Technology Industry Council
KF	Kalman Filter
MAV	Moving Average Filter
MIF	Mean Instantaneous Frequency
ML	Maximum Likelihood
NEMP	Nuclear Electromagnetic Pulses
NI	National Instruments
NN	Neural Network
PCC	Point of Common Coupling
PLC	Programmable Logic Controller
PLL	Phase Locked Loop
PNN	Probabilistic Neural Network
PQ	Power Quality
PSO	Particle Swarm Optimization
RBF	Radial Basis Function
RMS	Root Mean Square
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SLG	Single Line to Ground
SNR	Signal to Noise Ratio
SRF	Synchronous Reference Frame
ST	Stockwell Transform
STFT	Short Time Fourier Transform
SVM	Support Vector Machine
THD	Total Harmonic Distortion
UPQC	Unified Power Quality Conditioner
VSC	Voltage Source Converter
WT	Wavelet Transform

LIST OF SYMBOLS

a	Overloading factor
C_{dc}	DC link Capacitances
C_f	Ripple filter capacitance
D	Second norm of the supply voltage
f_S	Sampling frequency
i_{AfLa},i_{AfLb},i_{AfLc}	Three phase active power components of load currents
i_{ApLg}	Average active power component of load currents
i_{ca},i_{cb},i_{cc}	Three phase instantaneous compensating currents
I_{crpp}	Current ripples
i_{fLa},i_{fLb},i_{fLc}	Three phase fundamental load components
i_{La},i_{Lb},i_{Lc}	Three phase instantaneous load currents
I_{nApLg}	Net active power component of supply currents
I_{peak}	Peak value of current
I_{pdc}	DC link voltage controller output
i_{sa},i_{sb},i_{sc}	Three phase instantaneous supply currents
i_{aref}, i_{bref}, i_{cref}	Three phase reference supply currents
K_i	Integral gain
K_p	Proportional gain
L_f	Interfacing inductance
m	Modulation index
p_{lavg}	Average active power of load
p_{loss}	Losses of DSTATCOM
p_s	Instantaneous three phase power of load
p_{st}	Total power from source
R_f	Ripple filter resistance
S_1 *to* S_6	Gating signals
T_s	Sampling time
u_{ap},$u_{bp,}$ u_{cp}	In-phase unit voltage templates
u_{aq},$u_{bq,}$ u_{cq}	Quadrature phase unit voltage templates
v_a, v_b, v_c	three phase instantaneous voltages
i_a, i_b, i_c	three phase instantaneous currents
v_a^+, v_b^+, v_c^+	Positive sequence components of the three phases
v_a^-, v_b^-, v_c^-	Negative sequence components of the three phases
v_a^0, v_b^0, v_c^0	Zero sequence components of the three phases
V_{dc}	DC link voltage
V_{dce}	DC link voltage error

V_{dc1}	Minimum DC link voltage
V_{LL}	Line to line voltage
V_p	Peak value of PCC voltage
v_p^+	Peak value of the positive sequence components
v_p^-	Peak value of the negative sequence components
v_{sa}, v_{sb}, v_{sc}	Three phase instantaneous supply voltages
$v_{sab}, v_{sbc}, v_{sca}$	Three phase instantaneous line voltages
Vsw	Voltage rating
Z_{sa}, Z_{sb}, Z_{sc}	Three phase source impedance
α	Fortescue operator
Φ	Phase angle
ε	Hysteresis band
ω	Angular frequency
τ	Shifting operator