POWER QUALITY IMPROVEMENT BY DYNAMIC VOLTAGE RESTORER AND UNIFIED POWER QUALITY CONDITIONER USING FUZZY LOGIC

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I dedicate this thesis to my friend Abdul RehmanAl-Najjar (deceased), my wife and my sons, Shamsher Ali Khan and Altamash Ali Khan

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ABSTRACT

Voltage sag and harmonics have significant negative impact on power quality. Propagation of distorted waveform in the system ultimately instigates a range of power quality issues. Protection against this situation is necessary because it adversely affects reliability and quality of power supply. Custom Power Devices (CPD) such as Dynamic Voltage Restorer (DVR) and Unified Power Quality Conditioner (UPQC) provide a level of reliability and power quality that is urgently required. The basic purpose of this thesis is to implement new control strategies to mitigate voltage sag/swell and to suppress harmonics to evaluate CPD performance. The CPD system is controlled by Fuzzy Logic Controllers (FLCs) with 49 rules and 25 rules, respectively and their performances are compared with Proportional Integral (PI) controller. This thesis focuses on FLC with fewer rules to avoid complexity, reduce computation time and consume less memory space. The proposed strategy depends on d-q transformation, phase-locked loop synchronization and constant DC link voltage. Simulation results depict better reliability of fuzzy logic techniques with non-linear loads when compared with PI technique. The capability of DVR and UPQC using FLC especially with fewer rules is demonstrated using test models built in Matlab/Simulink software. Both equipments potentially restore sags and improve overall harmonic profile while reducing total harmonic distortion to values within the prescribed criterion set by IEEE standards. The proposed FLC approach with reduced rule base, is superior to PI and FLC with 49 rules, assures effective performance, with normalization and tuning of parameters especially the membership functions and scaling factors. It yielded excellent voltage profile with best possible compensation during system contingencies, conforming to the IEEE standards that affirm FLC as an effective solution for power quality problems.

ABSTRAK

Voltan lendut dan harmonik mempunyai kesan negatif yang signifikan terhadap kualiti kuasa. Perambatan gelombang terherot dalam sistem peda akhirnaya menyebabkan pelbagai isu kualiti kuasa yang lain. Perlindungan terhadap keadaan ini adalah perlu kerana ia memberi kesan buruk terhadap kebolehpercayaan dan kualiti bekalan kuasa. Peranti Kuasa Langganan (CPD) seperti Pemulih Voltan Dinamik (DVR) dan Penyesuai Kualiti Kuasa Disatukan (UPQC) menyediakan tahap kebolehpercayaan dan kualiti kuasa yang amat diperlukan. Tujuan asas tesis ini adalah untuk melaksanakan strategi kawalan baru untuk mengurangkan voltan lendut dan menyekat harmonik bagi menilai prestasi CPD. Sistem CPD dikawal oleh pengawal logik kabur (FLC) dengan 49 peraturan dan 25 peraturan, dan prestasi mereka dibandingkan dengan pengawal kamiran berkadaran (PI). Tesis ini menumpukan kepada FLC dengan peraturan yang sedikit untuk mengelakkan kekompleksan, mengurangkan masa pengiraan dan menggunakan ruang memori yarg kecil. Strategi yang dicadangkan bergantung kepada transformasi d-q, penyegerakan Gelung Terkunci Fasa dan voltan pautan DC malar. Keputusan simulasi menunjukkan kebolehpercayaan yang lebih baik dengan teknik logik kabur dengan beban tidak linear berbanding teknik PI. Keupayaan DVR dan UPQC menggunakan FLC khususnya dengan bilangan peraturan yang rendah ditunjukkan menggunakan model ujian dibina dalam perisian Matlab / Simulink. Kedua-dua peralatan berpotensi menghilangkan lendut dan meningkatkan keseluruhan profil harmonik di samping mengurangkan Jumlah Herotan Harmonik kepada nilai-nilai dalam kriteria yang ditetapkan oleh piawaian IEEE. Pendekatan FLC yang dicadangkan dengan asas peraturan yang dikurangkan, PI dan FLC yang baik dengan 49 peraturan akan memastikan prestasi yang berkesan, dengan penormalan dan penalaan parameter terutama rangkap keahlian dan faktor penskalaan, menghasilkan pengaturan voltan yang sangat baik dan meningkatkan profil voltan sewaktu kesilapan diluar jangkaan sistem, yang mematuhi piawaian IEEE dan mengesahkan FLC sebagai penyelesaian yang berkesan untuk masalah kualiti kuasa.

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LIST OF ABREVIATIONS

ANFIS	-	Adaptive Neuro-Fuzzy Inference System
ANN	-	Artificial Neural Netwok
APF	-	Active Power Filters
CPD	-	Custom Power Devices
SCD	-	Synchronous Current Detection
CSI	-	Current Source Inverter
d	-	direct or real
DC	-	Direct Current
DFT	-	Discrete Fourier Transform
DOL	-	Direct-On-Line
d-q-0	-	transformation direct-quadrature-zero transformation
DSTATCOM	-	Distribution STATic COMpensator
DVR	-	Dynamic Voltage Restorer
DWT	-	Discrete Wavelet Transform
EMI	-	Electro-Magnetic Interference filter
FACTS	-	Flexible AC Transmission Systems
FFT	-	Fast Fourier Transformer
FL	-	Fuzzy Logic
FLC	-	Fuzzy Logic Controller
FOC-IM	-	Field-Oriented Control Induction Motor
FORTRAN	-	FORula TRANslating System programming language
FT	-	Fourier Transform
GTO	-	Gate Turn Off thyristor
ICC	-	Indirect Current Control
IEEE	-	Institute of Electrical and Electronic Engineers
IGBT	-	Insulated-Gate Bipolar Transistor
IGCT	-	Integrated Gate-Commutated Thyristor
Ki	-	integral
Kp	-	proportional
LLG	-	Double Line-to-Ground fault
LLLG	-	Triple Line-to-Ground fault
LPF	-	Low Pass Filter
LQR	-	Linear Quadratic Regulator

max-min	-	maximum-minimum
MC-DVR	-	Multi Converter DVR
MRA	-	Multi-Resolution Analysis
MSPWM	-	Multiple Sinusoidal Pulse Width Modulation
MVAr	-	Mega Volt Ampere reactive
NB	-	Negative Big
NM	-	Negative Medium
NS	-	Negative Small
OCC	-	One Cycle Control
OCCC	-	One Cycle Current Control
OPC	-	Optimal Predictive Control
PBT	-	Power Balance Theory
PCC	-	Point of Common Coupling
PI	-	Proportional Integral
PID	-	Proportional Integral Derivative
PL	-	Positive Large
PLL	-	Phase-Locked Loop
PM	-	Positive Medium
PQ	-	Power Quality
PR	-	Proportional Resonant
PS	-	Positive Small
PSCAD	-	Power System Computer Aided Design
PS-SPWM	-	Phase-Shifted Sinusoidal Pulse Width Modulation
PV	-	Photo-Voltaic
PWM	-	Pulse Width Modulation
Ref	-	Reference
RMS	-	Root Mean Square
SLG	-	Single Line-to-Ground fault
SPWM	-	Sinusoidal Pulse Width Modulation
SRF	-	Synchronous Reference Frame
SVM	-	Space Vector Modulation
THD	-	Total Harmonic Distortion
UCES	-	Ultra-Capacitor Energy Storage

UPQC	-	Unified Power Quality Conditioner
UVT	-	Unit Vector Template generation
VAr	-	Volt Ampere reactive
VSC	-	Voltage Source Converter
VSI	-	Voltage Source Inverter
Z	-	Zero
ZSI	-	Z-Source Inverter

LIST OF SYMBOLS

A	-	Ampere
ce	-	Change in error
H	-	Henry
e	-	error
I	-	Current
I_L	-	Load Current
kV	-	kiloVolt
kW	-	kiloWatt
L	-	Inductance
p.u	-	Per unit
R	-	Resistance
V	-	Voltage
V_L	-	Load voltage
V_{th}	-	Thevenin equivalent system voltage during fault
X	-	Inductance
X/R	-	ratio of total inductive reactance to its total resistance
Y	-	Star
Z	-	Impedance
Z_{th}	-	Thevenin equivalent load Impedance
α	-	Alpha
β	-	Beta
Δ	-	Delta
δ	-	Sigma
μ	-	Micro
π	-	Pi
ω	-	Omega

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Contemporary power system is an arrangement of composite networks involving various generating stations and load centers integrated through extensive transmission and distribution networks. Power supply interruptions and outages are a nuisance affecting domestic, commercial and in particular industrial customers. This results in considerable financial losses with high impact on production costs. In the present competitive world market, dispersed generation trends and general awareness of the people towards better quality of power have forced the restructuring of power systems. Expectations on improved quality and reliability of power supply to the customers have increased.Power Quality (PQ) is defined in IEEE Std book Electrical Power System Quality (Dugan, *et al.,* 1996) as “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment” (Reid, 1996). This phenomenon incorporates all possible situations in which power system supply voltage (voltage quality) or load current (current quality) waveforms deviate from sinusoidal waveform. PQ is a criterion for proper electrical system to function efficiently without compromising the performance (Singh and Dwivedi, 2012).

PQ problems encompass severe disturbances such as voltage sag, voltage swell, current and voltage harmonics, and unbalanced load. Inferior PQ leads to low power factor and low efficiency, generating large current unbalance. PQ disturbances may be either caused by the quality of the supply voltage (source) or by the quality of the current drawn by the load. Advanced power electronic devices and equipments widely employed nowadays draw harmonic currents and reactive power from AC mains due to their inherent non-linear V-I characteristics. Such non-linear loads pollute the network by injecting current harmonics. This consequently deteriorates utility voltage and causes a drop in supply voltage and amplifies losses.

Considerable attention has been given to PQ due tomodern industrial shift towards mechanized automation. This inclination trend relies heavily on sensitive power electronic devices. These devices are much more susceptible to distortion in supply voltage than their previous generation counterparts. This has caused complications not only for the utilities but also for the end-users themselves. Modern power semiconductor devices are in all likelihood not only the prime source of harmonic insertion but also augment reactive power in the system. Rigorous utilization of power converters as rectifiers creates non-sinusoidal current thus polluting the supply. Consequently, the harmonic components will contaminate voltage at the point of common coupling. Besides, these polluted voltages and currents proliferate into the supply system, amplify losses, cause measurement imprecision and create severe electromagnetic compatibility problems. Introduction of system harmonics have brought PQ issues to the fore-front and compelled suffering utilities to provide distortion-free sinusoidal power supply. At the same time customers are also bound by regulations through proper standards to curb the quantity of harmonic currents and unbalance in all the three phases due to different loading conditions which augments harmonic distortions that a load may produce.

The situation calls for alleviation of PQ issues in the shape of “Custom Power Devices (CPD)” which are capable enough to present customized resolution to PQ problems. CPD improve the quality and reliability of power delivered to customers and are based on electronic power converters and provide the ability to make quick adjustments to control the electrical system. The strength and benefits of these devices become diverse, when they are combined and this concept leads to the evolution of multi-type CPD. The function of CPD is not only to minimize the effects of voltage sag and swell, but also to limit the harmonic distortion caused by the presence of non- linear loads in the network (Ghosh and Ledwich, 2001; Khadkikar and Chandra, 2008; Renuga, *et al*., 2013).

Current harmonics are considered as the most frequent PQ issues while voltage sag is the most detrimental. These problems incur huge financial losses. Research reveals that voltage sag/swells and harmonic distortions at the Point of Common Coupling (PCC) are mainly liable to severe impact on sensitive loads. Even worse case scenario is the malfunctioning of system equipments (Kolhatkar and Das, 2007; Hari, *et al*., 2011; Khadkikar, 2013).

To reduce such unwanted nuisances, passive power filters were primarily used. Well-designed passive filters can be implemented in large sizes of MVAr ratings and provide almost maintenance free service due to absence of rotating parts. These filters are more economical to implement than their rotating counterparts i.e., synchronous condensers. A fast response time of the order of one cycle or less can be obtained. These compensation equipments have some drawbacks as they are not suitable for variable loads, since, they are designed for a specific reactive power as well as variation of the load impedance can detune the filter. To overcome passive power filters characteristic limitations such as producing superfluous resonance and augmenting harmonic currents, a step further in fruitful research efforts bore the development and manifestation of more advanced Active Power Filters (APF) technology. These however are presently very uneconomical but their installation proves indispensable for solving PQ problems in distribution networks such as compensation of harmonic current, reactive current and voltage sag. Ultimately, this would ensure a pollution free system with increased reliability and quality. APF family include different devices commonly called CPD. The concept of custom power was introduced by (N.G. Hingorani) in 1995. This term illustrates the value-added power that electric utilities will present to their customers. The enhanced level of power consistency with minimal interruptions and less discrepancy will be guaranteed by the application of power electronic controllers either to the utility distribution systems or at the supply end of industrial and commercial customers. CPD are the proficiently progressive face of APF family and are pertinent to power distribution systems for accomplishing stability and reliability of power supply to a large extent. Fundamentally, APF inject harmonic currents of the same magnitude but opposite polarity to cancel harmonics. Nevertheless harmonic distortions are only part of the problem, while fault or load variations may cause voltage sag. CPD comprise of DSTATCOM (Distribution STAtic COMpensator), DVR (Dynamic voltage restorer) and Unified Power Quality Conditioner (UPQC) etc. DSTATCOM is connected in shunt with the power system whereas DVR is a series connected device that injects series voltage to recompense supply voltage.DVR is recognized as the most appropriate to protect sensitive loads against PQ disturbances. DVR role is not only voltage sag mitigation but also harmonic distortion reduction caused by non-linear loads in the network.

UPQC is the more advanced type of CPD combining two APFs. It’s good control methods with precise recognition of the disturbance signal, swift processing of reference signal and high dynamic response facilitates in preferred compensation. It charters two voltage source inverters (VSI): one act as a series APF (DVR) and the other as shunt APF (D-STATCOM), connected back to back through common DC-link capacitor. The former is regarded as the most fitting to prevail over voltage related problems while the latter as the most promising to manage current related problems. Practical implementation of such devices emerges feasible, given that superior quality supply voltage and drawn current is stressed profoundly. Nevertheless, simultaneous installation of both DVR and DSTATCOM may not be a worthwhile solution. Their combined configuration with back-to-back inverter system called UPQC was proposed by Fujita and Akagi (Fujita and Akagi, 1995). UPQC is ever since popularly used enormously and regarded as the ultimate solution for inferior PQ predicament by several researches (Sadaiappan, *et al*., 2010; Hari, *et al*., 2011).

UPQC is probably the best CPD dealing with both load current and supply voltage imperfections. It consists of two VSI sharing the same capacitive DC-link. It is a very versatile device that can perform both the functions of load compensation and voltage control simultaneously.

1.2 Problem Statement

Inadequacy of conventional PQ improvement equipment has necessitated vibrant and adaptable resolution to PQ problems. This has propelled the development of CPD. The contemporary and promising CPD that deals with voltage related issues is DVR, while the more flexible CPD is UPQC which deals mutually with load current and supply voltage imperfections. Various researches have been performed in relation to their performances under a variety of fault conditions with different conventional linear and non-linear control systems with the application of linear, non-linear and heavy loads. To be regarded as established equipments their performances ought to be scrutinized further with different control strategies for frequently utilized load conditions under frequently occurring fault conditions in the distribution system. This needs modelling and development of both the equipments along with their control schemes and algorithms for PQ improvement. Fuzzy Logic Control (FLC) has gained momentum during the last decade or so especially in power systems because it neither requires precise mathematical formulations nor fast processors. Besides it needs less data storage in the form of knowledge base which includes Membership Functions (MF's) and rules.

Conventionally, the more advanced non-linear FLC system has been utilized with 49 rules which are computationally demanding and time consuming. As the number of the linguistic variables increases, the computational time and required memory increase. This is because the implementation of FLC require a large computational time for processing each step time in order to compute the appropriate control value to be applied to the system. Therefore, a reduction of the large fuzzy rule base is required. Although some studies have tried lesser rules (even 9 rules) but they cannot come up with conclusive performance of the equipments. An effort is needed to come up with the best possible number of rules for FLC system so that both DVR and UPQC can perform satisfactorily, conforming to IEEE laid standards for both harmonic compensation and voltage sag minimization and hence results in enhanced PQ. Studies showed that FLC with 49 rules takes double computational time as compared to FL with 25 rules (Karakose and Akin, 2010). Rule reduction will definitely lessen computation effort and reduce time consumption for processing. Performance analysis and comparison of this reduced rule control strategy with classical PI and FLC with 49 rules for further evidence is necessitated under harmonic generating loads including Field Oriented Control-Induction Motor (FOC-IM) under frequently occurring fault conditions.

1.3 Objectives of the Research

The objectives of this research are as follows:

i) To develop simulation models of DVR and UPQC in distribution system subject to the presence of voltage sag and harmonics with various load and fault conditions.

ii) To design PI, FLC (49 rules) and FLC (25 rules) systems for DVR and UPQC to tackle voltage sag and harmonic problems in distribution network.

iii) To investigate effectiveness of PI, FLC (49 rules) and FLC (25 rules) based DVR and UPQC and tuning and normalization of FLC (25 rules) to get similar or better performance in accordance with the IEEE 519-1159 standards.

1.4 Scopes of the Research

The scopes of this research are shown below:

i) The system is a distribution network comprising of two 11 kV adjacent feeders

ii) Performance of the designed models of DVR and UPQC is evaluated for mitigating PQ issues such as voltage sag/swell and harmonic distortions.

iii) Performance of DVR and UPQC is investigated using PI control and FLC under linear, non-linear and FOC-IM load conditions.

1.5 Significances of the Research

Significances of this research are:

i) Develop FLC knowledge base which includes MF's and rules suitable for proper functioning of DVR and UPQC. The increasing need is to design highly reliable, efficient and low complexity controllers. FLC's are able to make effective decisions on the basis of linguistic information. The application of FLC will definitely not only minimize computation efforts but also improve performance of these equipments in relation to voltage sag and harmonic mitigation.

ii) Formulate the best possible control strategy for DVR and UPQC which will help improve PQ of the system with different load and fault conditions. Amongst the three control strategies which are PI, FLC with 49 rules and reduced25 rules the focus will be on FLC method with 25 rules. Although, many works have been reported in literature regarding reduction of rules at the expense of enhanced complexities. The easier approach of tuning of parameters as well as scaling factors and normalization help excel the performance of this strategy as compared to PI control method. As compared to FLC 49 rules its performance will be improved as well as reduction in the computation time and memory space with the exception of a few results.

1.6 Organization of Thesis

Contents of the thesis are arranged as follows.

Chapter 2 defines the different terms and concepts associated with PQ and CPD. Literature survey is also included in this chapter.

Chapter 3 explains in detail the methodology adopted in this work. Various control strategies employed for both DVR and UPQC are taken into consideration to improve PQ.

Chapter 4 presents discussion of the results of PI, FLC (49 rules) and FLC (25 rules) control strategies for DVR and UPQC Matlab / Simulink test models.

Chapter 5 summarizes the conclusion of this work and future work of this research.

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