Electrical Power and Energy Systems 84 (2017) 153–167

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Power quality enhancement using fuzzy sliding mode based pulse width modulation control strategy for unified power quality conditioner

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ARTICLE INFO

Article history:
Received 4 January 2016
Received in revised form 3 March 2016
Accepted 13 May 2016

Keywords:
FSMPWM
Power quality
Sliding surface
Mamdani based fuzzy
Chattering effects
Fixed switching

ABSTRACT

This paper proposes a fixed switching methodology based on fuzzy sliding mode pulse width modulation (FSMPWM) control strategy for three-phase three-wire unified power quality conditioner (UPQC). The proposed FSMPWM control technique eliminates numerous power quality (PQ) problems such as current harmonics, load unbalance, voltage sag/swell, voltage unbalance, voltage distortion and phase-angle jump existing in the power distribution network. Initially, the design of FSMPWM is based on the implementation of sliding surface by proper extraction of reference current and voltage signals for UPQC. Subsequently, the equivalent control law is formulated for both shunt and series converter. With this consideration, Mamdani fuzzy rule base is designed at the sliding surface for generation of switching pulse. Moreover, the proposed method eliminates the chattering effects by smoothing the control law in a narrow boundary layer for generating fixed switching pulse for both shunt and series converter. The performance of proposed UPQC system has been simulated and analyzed by MATLAB/SIMULINK followed by real-time experimental studies accomplished with a real-time-hardware-in the loop (HIL) system in OPAL-RT simulator. Additionally, the efficacy of this proposed technique is compared with a conventional sliding mode controller (CSMC).

Introduction

UPQC is a custom power device (CPD) utilized for eliminating the PQ problems such as harmonics [1] unbalance, sag and swell and phase-angle jump due to the extensive usage of electronically switched devices and non-linear load [2,3]. This CPD comprises of both shunt and series converters coupled through a common DC-link voltage and deals with harmonics in load current and also imperfections in source voltage [4]. The shunt converter can eliminate current harmonics and unbalances from the nonlinear load so that perfect sinusoidal current flows through the power network, however series converter can compensate voltage sag/swell, voltage unbalance, voltage distortion and phase-angle jump present on the source side, so that perfect voltage regulation is maintained across the load [5].

Therefore, UPQC draws the consideration of power engineers to create active and adaptable solutions to PQ issues, which leads to the development of novel topologies and advanced control systems for UPQC. Control system plays an important part in the overall performance of a power conditioner. The quick detection of disturbance signal and fast extraction of reference signal are the main requirements for perfect compensation. Some advanced control techniques have been reported for UPQC in the literature, which include neural networks, SRF and PSO based controller [6–8]. However, these controllers are mainly used for reference signal generation and not so much useful in generation of pulse width modulation (PWM) signal. PWM controllers such as Hysteresis, triangular carrier and space vector modulation (SVM) [9–11] are failed to track the reference signal properly during load and supply side perturbations, therefore compensation capability of UPQC is degraded.

Recently, many control techniques like deadbeat control, repetitive controller and Fuzzy PWM controller [12–14] have been investigated to accomplish the aforementioned demands. Additionally, harmonics elimination method and nonlinear observer strategy are employed to improve the transient response. However, these control techniques utilize average modeling technique of the converter [15]. As the state space equations of converter vary with switching states, power converters suffer from discontinuous control [16]. The inherent switching nature of power converters is compatible with sliding mode controller (SMC) [17,18]. Moreover, the SMC is popular for its stability, robustness, good regulation and frequent switching action under all operating conditions of load and supply voltage.

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http://dx.doi.org/10.1016/j.ijepes.2016.05.007
0142-0615/

Irrespective of excellent performance, SMC suffers from chattering problem, which leads to generate a variable switching frequency causing switching and power losses, as well as electromagnetic compatibility (EMC) noise. To avoid this drawback, a fuzzy logic controller is considered in conjunction with SMC to generate a fixed switching methodology. This Fuzzy-logic SMC [19–21] is one of the promising solutions to handle power systems uncertainty, as well as nonlinearity situations. Power system uncertainty arises due to random variation of system loads, irregular fluctuations of system parameter such as capacity of distribution line and sudden failure of system component of the power line. To operate UPQC in the above uncertainty conditions, a fuzzy SMC based PWM technique is proposed for accurately tracking the reference signal, which provides better compensation capability of UPQC.

The objective of this study is to improve the power quality in power distribution network by employing novel FSMPWM technique. This control method generates a fixed switching PWM signal, which reduces the excessive power losses and EMC noise generated by UPQC and also simplifies the series LC filter design. As a consequence, it is efficient in elimination of PQ issues such as current harmonics, load unbalance, voltage distortion, voltage sag/swell, voltage unbalance and phase-angle jump present in the power distribution network. The proposed FSMPWM based control scheme considers $s, \dot{s}$ as input fuzzy variables and the fuzzy rule base table is constructed by using two-dimensional spaces. This table will have 49 rules with s and $\dot{s}$ having seven triangular membership functions each. A singleton output membership function is used for the defuzzification purpose for generating switching pulse for both shunt and series converters. Moreover, reduction of mathematical operands, insensitiveness to the system uncertainty and external disturbance are the main advantages of this proposed method, which facilitates a simpler hardware control circuit. The performance of the proposed control strategy was simulated, analyzed and investigated using MATLAB/SIMULINK followed by real-time experimental studies accomplished by using hardware-in-loop (HIL) system in OPAL-RT simulator and also a comparative study has been pursued employing CSMC [22] and the proposed one.

UPQC power circuit configuration

The power circuit configuration of UPQC is shown in Fig. 1. It comprises of series converter and shunt converter. The series converter is a three phase PWM voltage source inverter, which mitigates voltage sag, swell, voltage distortion and voltage unbalance existing in the supply voltage. Subsequently, the *LC* filter consists of inductor L_{sef} and capacitor C_{ef} connected in output of series converter to prevent the flow of switching ripples. Similarly, the transformers are connected at the output of the *LC* filter to provide isolation between series converter and the power line and also prevent the DC-link capacitor from being short circuited due to the operation of various switches. The power circuit of shunt converter consists of a three phase PWM voltage source inverter, which is connected through an interfacing inductor L_{shf} to provide isolation between the shunt converter and power line. The purpose of shunt converter is to restrain the load current harmonics and to control the DC-link voltage. However, insulated gate bipolar transistors (IGBTs) with anti-parallel diodes are used as PWM voltage source inverter and a 3-phase diode-bridge rectifier employed with resistive R_L as well as inductive L_L are used as a nonlinear load.

Reference current generation for shunt converter

The proposed control strategy shown in Fig. 2 is employed to generate a reference current signal as well as PWM signal for shunt converter of UPQC. At first reference current signal is generated by considering the peak amplitude of source current I_{max} generated from the PI-controller (Proportional constants: $k_p = 0.2475$ and Integral constant: $k_i = 8.7500$). This peak value of the reference current is produced by regulating DC-link capacitor voltage V_{dc} of UPQC [23]. Commonly, a PI-controller is utilized for determining the magnitude of this I_{max} from the error between the average voltage across the DC-link capacitor V_{dc} and the reference voltage V^*_{dc}. Thus, reference source currents described in Eq. (1) are generated by multiplying I_{max} with the unit vector (U_{sa}, U_{sb}, U_{sc}) signal generated from the phase locked loop (PLL) [24] block that is shown in Fig. 3.

$$\begin{aligned} I^*_{Sa} &= I_{max} \times U_{sa} \\ I^*_{Sb} &= I_{max} \times U_{sb} \\ I^*_{Sc} &= I_{max} \times U_{sc} \end{aligned} \tag{1}$$

Fuzzy sliding mode control of shunt converter

To apply the fuzzy sliding mode control (FSMC) theory to the shunt converter, sliding surfaces are developed and based on which equivalent control laws are designed. Then, PWM signals are generated by utilizing Mamdani based fuzzy system at the sliding surface.

For designing sliding surface, the equivalent circuit for one leg of shunt converter is considered, which is illustrated in Fig. 4. Sliding mode control law depending upon switching function '*u*' is considered here. When either S1 or D1 conducts, then $u = 1$, and when either S2 or D2 conducts, then $u = -1$. The inductor current is given by the following expression,

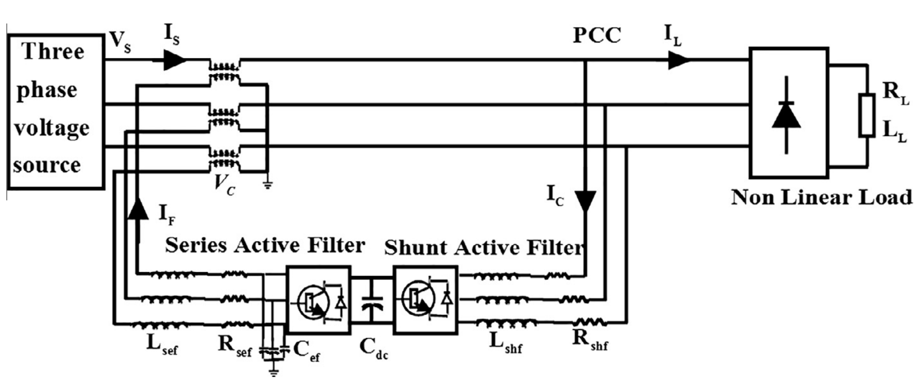

Fig. 1. Power circuit configuration for UPQC.