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Optimized Power Quality and Fast Energy Saving Strategies in Distribution Systems Using Unified Power Quality Conditioner

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ABSTRACT

This thesis addresses voltage issues in power distribution networks with high penetration of Distributed Generation (DG) by introducing a novel Unified Power Quality Conditioner (UPQC) based on fast energy storage. The integration of distributed generation technology, essential for smart grid development, significantly alters power distribution systems. In networks with DG, fluctuations in power output from DGs can cause voltage quality problems such as voltage sags, fluctuations, and interruptions. To enhance the compensation capabilities of the UPQC and reduce grid current fluctuations during power regulation, an improved UPQC topology is proposed. Utilizing super capacitors, which offer high power density, large electrostatic capacity, and long cycle life, in conjunction with a bidirectional DC/DC converter, this energy storage system is connected in parallel with the DC link. This configuration maintains a constant DC voltage and can serve as a backup UPS.

A low-frequency mathematical model of the conditioner is developed using d-q coordinates based on the state-space method, and a non-PLL compensation detection method is employed. Additionally, the thesis provides both voltage and current compensation control strategies and energy management schemes for the super capacitors. The proposed fast energy storage system incorporates low-inductance rail switches and capacitors configured in a low-inductance stage, stacked in series for the required voltage, and parallel units for the needed system inductance and stored energy. This innovation eliminates the necessity for large water transfer capacitors. The structural principles and control strategies are refined using MATLAB/SIMULINK.

INTRODUCTION:

Electrical energy is the most efficient and widely used form of energy, and modern society heavily relies on a consistent electric supply. Life without electricity is unimaginable, and the quality of electric power is crucial for the efficient functioning of end-user equipment. Power quality has become a significant concern for both electric power companies and consumers, as it depends on maintaining the voltage and frequency within standard ranges. Deviations in these parameters can negatively impact power quality.

Advancements in semiconductor technology have significantly improved control over power systems. Semiconductor devices, now prevalent in the power sector, facilitate efficient system management but are non-linear and draw non-linear currents from the source. These devices are also integral to power conversion processes (AC to

DC and DC to AC), involving numerous switching operations that can cause current discontinuities. Such discontinuities and non-linearities introduce harmonics, degrading power quality. Filtering out these harmonics is essential to maintaining power quality.

This thesis explores the concept of Distributed Generation systems, including their introduction, applications, significance, problem formulation, and solutions.

UNIFIED POWER QUALITY CONDITIONER (UPQC)

This paper introduces a UPQC topology designed for applications with non-stiff sources, aimed at resolving various power quality (PQ) issues. Specifically, a Star-Delta supported Three-phase Four Wire (3P-4W) UPQC configuration is proposed for effective PQ mitigation.

The Unified Power Quality Conditioner (UPQC) is a custom power device developed to address voltage and current-related PQ problems in power distribution systems. This thesis suggests a UPQC topology optimized for non-stiff sources, allowing the UPQC to maintain a reduced dc-link voltage without sacrificing its compensation capabilities. The proposed topology aligns the dc-link voltage requirements for both the shunt and series active filters within the UPQC. Key modifications include integrating a capacitor in series with the shunt active filter's interfacing inductor and connecting the system neutral to the negative terminal of the dc-link voltage, eliminating the need for a fourth leg in the voltage source inverter (VSI) of the shunt active filter. This approach reduces the average switching frequency of the VSIs, thereby minimizing switching losses. Furthermore, traditional 3P-4W UPQC topologies use passive elements to mitigate source neutral current, which provides benefits in terms of ruggedness and control simplicity compared to active compensation.

Thus, a Star-Delta supported 3P-4W UPQC configuration is proposed for comprehensive PQ problem mitigation. The delta-connected secondary of a star-delta transformer offers a circulating path for zero sequence current (io) during load imbalance, effectively reducing the supply neutral current to zero. This configuration can be implemented using standard three-leg VSIs. In the context of a deregulated power market and stringent PQ standards, utilities prioritize effective PQ management. Three-phase four-wire distribution systems face significant PQ challenges, such as high reactive power demand, harmonic currents, voltage fluctuations, and unbalanced loads. Various UPQC topologies have been proposed in literature to address these issues, including three-leg VSI with split capacitors, three single-phase VSIs, four-leg VSIs, and current source inverters. However, selecting a common DC-link voltage suitable for both shunt and series active filters remains challenging, often leading to overrating the series active filter due to higher DC-link voltage requirements for the shunt active filter. Efforts to reduce DC-link voltage storage capacity, such as using hybrid filters in motor drive applications, have been made, yet PQ issues persist in three-phase, four-wire distribution systems, affecting voltage regulation, power factor, efficiency, and causing transformer overheating. Consequently, Custom Power Devices (CPDs) have become vital for enhancing power supply reliability and quality. Among CPDs, UPQC is notable for its ability to simultaneously mitigate voltage and current-related PQ problems. By integrating series and shunt active power filters, UPQC offers comprehensive PQ improvement capabilities. Various control strategies have been proposed for UPQC, including p-q theory, Synchronous Reference Frame (SRF) theory, and symmetrical component transformation, each with specific advantages and applications. Advanced control systems using techniques like one-cycle control further enhance UPQC performance.

System Description:

The system configuration considered for the three-phase, four-wire distribution system is depicted in Figure 1. The UPQC is connected upstream of the load to ensure that both source and load voltages remain distortion-free. Reactive current drawn from the source is adjusted to ensure that source currents are in phase with utility voltages. Voltage harmonics can be introduced into the source voltage by controlling the three-phase diode bridge rectifier. The UPQC setup, employing two VSIs, is illustrated in Figure 3.2, with one VSI acting as the shunt APF and the other as the series APF. The shunt APF uses a three-phase, four-leg VSI, while the series APF employs a three-phase, three-leg VSI. Both APFs share a common DC link, allowing coordinated compensation. The four-leg VSI-based shunt active filter effectively suppresses source current harmonics, negative sequence currents, balances loads, and corrects power factor. The implemented control algorithm primarily involves computing the reference voltages and currents for load and source, respectively.

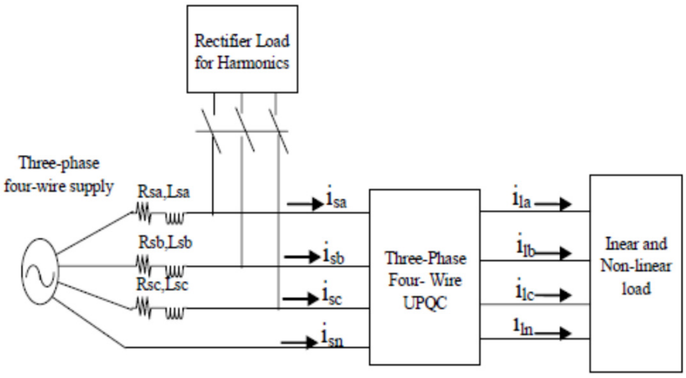

Fig 1 The system of UPQC

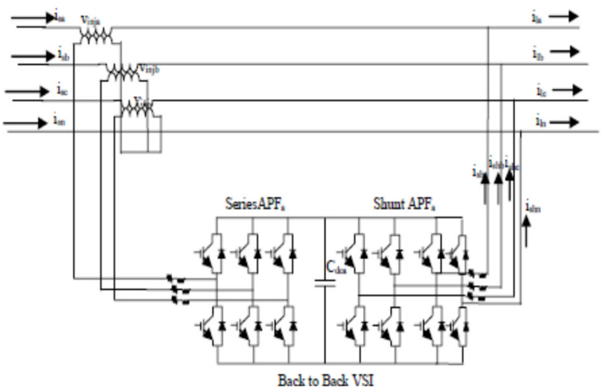

Fig 2 UPQC block diagram

Before implementing the UPQC, the voltage on the source side is denoted as Vs, the load voltage is represented by vL, the voltage injected by the series APF is termed v, and the DC link voltage between the two inverters is labeled \(V_{dc} \). Similarly, the current on the source side is denoted as \(i_s \), the current drawn by the loads is represented by \(i_L \), the neutral current on the source side is \(i_{\text{sn}} \), the load neutral current is labeled \(i_{\text{ln}} \), and the current injected by the shunt APF is \(i_{\text{sh}} \).

The control strategy for the UPQC aims to generate reference signals for both the shunt and series APFs. This approach effectively mitigates most of the load current and source voltage distortions. The series APF is regulated to eliminate supply voltage harmonics, while the shunt APF is managed to alleviate harmonics and negative sequence currents in the supply current.

In terms of Instantaneous Power Theory, the PQ Theory stands out as one of the most common and widely used methods. This section provides a concise overview of the PQ method. The considered nonlinear load is a three-phase diode bridge rectifier. Figure 3 illustrates the basic configuration of the p-q theory. The load current signals are transformed into the conventional rotating frame d-q, defined by the transformation angle.

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad \ldots. (3.1)$$

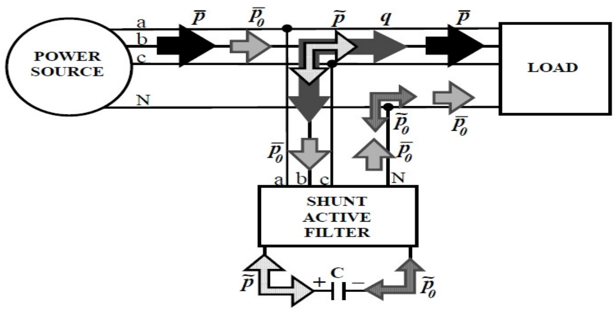

Fig 3 Basic principle of p-q theory

PROPOSED CONCEPT

This paper explores various issues associated with Distributed Generations (DGs), such as voltage sag, fluctuation, and interruption. To mitigate these issues, a Flexible AC Transmission System (FACTS) device called EUPQC is proposed.

The rapid evolution of distributed generation technology, which supports smart grids, has led to power distribution networks with DGs experiencing fluctuations in power output. These fluctuations can cause voltage quality problems like sagging, fluctuation, and interruption, exacerbated by inherent network defects. As a result, there is a pressing need for effective measures to enhance power quality. The impact of DGs on voltage quality in local power distribution networks has become a significant focus for scholars worldwide.

To address voltage quality issues in distribution networks with high DG penetration, Distributed FACTS (DFACTS) systems emphasize user-side flexibility and power quality control. Among DFACTS devices, the Unified Power Quality Conditioner (UPQC) is considered the most comprehensive and effective.

It is widely acknowledged in academia that integrating energy storage units enhances the stability and power quality of DG systems. Extensive research has analyzed the role of energy storage in improving voltage quality, including its working principles and mathematical models.

Various energy storage technologies, such as Superconducting Magnetic Energy Storage (SMES) and Flywheel Energy Storage (FES), have proven effective in providing active and reactive power compensation, thereby enhancing AC transmission system stability.

Given the voltage quality challenges stemming from interconnected DGs in MV/LV distribution networks and inherent network defects, this thesis proposes a novel UPQC structure based on supercapacitor fast energy storage. The efficacy and reliability of the control strategy for this device are validated through experimental results and detailed simulations. The practical application of such a UPQC in distribution networks effectively improves voltage quality.

In distribution networks with high DG penetration, ensuring sufficient power support is crucial to mitigate output power fluctuations. Energy storage technologies play a vital role in achieving this by offering efficient mass storage and fast, efficient energy conversion. Supercapacitor storage, known for its ability to smooth short-duration, high-power loads, is particularly suitable for addressing power quality issues in such networks, including voltage sags and instantaneous disturbances.

Custom power technology, grounded in power electronics, offers the reliability and stability required in MV/LV distribution networks. UPQC, with its integrated series and parallel compensation features, emerges as the most comprehensive and effective DFACTS technology. Developing custom power technology based on UPQC, capable of injecting active power during voltage regulation and integrating reactive compensation, presents a feasible strategy for enhancing power quality in distribution networks with high DG penetration.

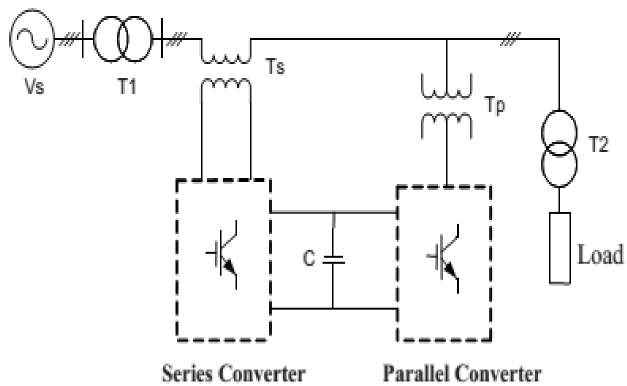

Fig 4 Structure scheme of UPQC

RESULTS AND ANALYSIS

In this paper, the simulation results are analyzed by simulating the proposed model in the environment of MATLAB/SIMULINK.

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include:

1. Math and computation
2. Algorithm development
3. Data acquisition
4. Modeling, simulation, and prototyping
5. Data analysis, exploration, and visualization
6. Scientific and engineering graphics

MATLAB/SIMULINK RESULTS:

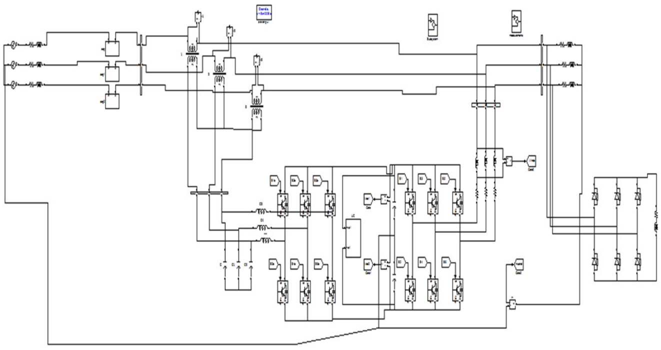

Fig 5 Simulink diagram of distributed generation system with EUPQC

Fig 5.a Simulation waveforms of distribution system with EUPQC

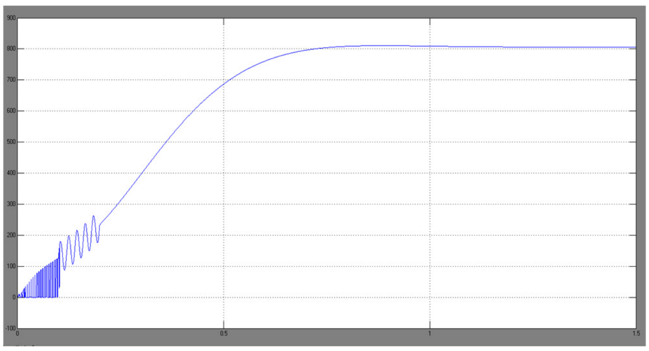

Fig 5.b Simulation waveform of super capacitor DC bus voltage

Figure 5.2a presents the simulation waveforms of the distribution system with EUPQC, showing the three-phase source voltage, load voltage, and compensation voltage. Figure 5.2b depicts the simulation waveform of the supercapacitor DC bus voltage, illustrating the voltage changes during the sampling time from 0.8 to 1 second.

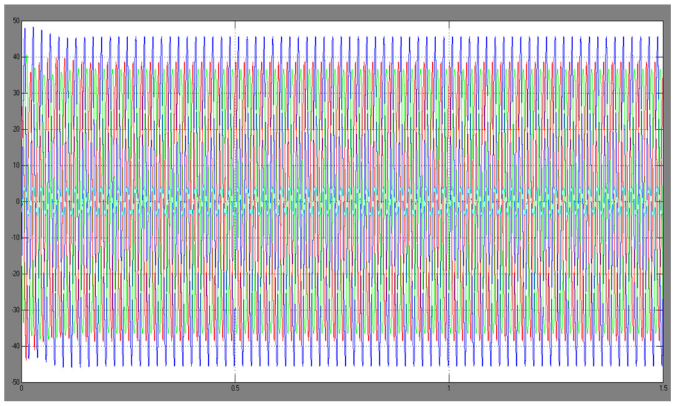

Fig 5. c Three phase source current and neutral current distribution system with EUPQC

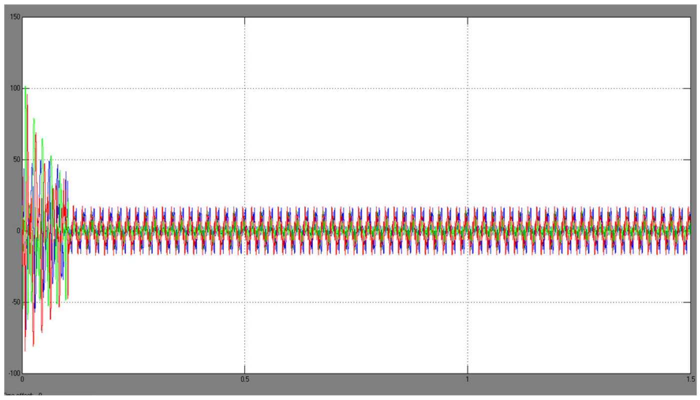

Fig 5.d Three phase compensation current and neutral current distribution system with EUPQC

Fig 5.2c Three phase source current and neutral current distribution system with EUPQC in this fig source current and load current as same, fig 5.2d Three phase compensation current and neutral current distribution system with EUPQC.

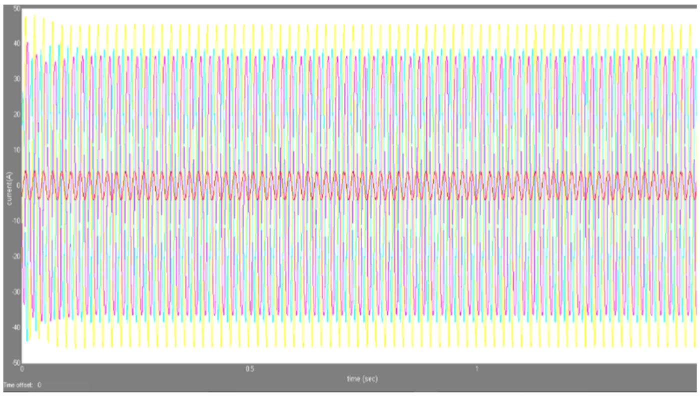

Fig 5.e Three phase load and neutral current distribution system with EUPQC

Figure 5.e shows the three-phase load and neutral current distribution system with EUPQC, where the source current is identical to the load current. The three-phase source voltage peaks are normally 311V, but they change in sequence to 311V, 200V, and 100V from 0.05s to 0.15s. The three-phase balanced loads are each 6.28 Ω/20mH. The three-phase nonlinear load is composed of a three-phase rectifier with 20 Ω/20mH. The series converter compensates for voltage sags, while the parallel converter mitigates harmonic and reactive currents. The switching frequency is $f_{\text{PWM}} = 10$ kHz, and the sampling time is from 0.8 to 1 second.

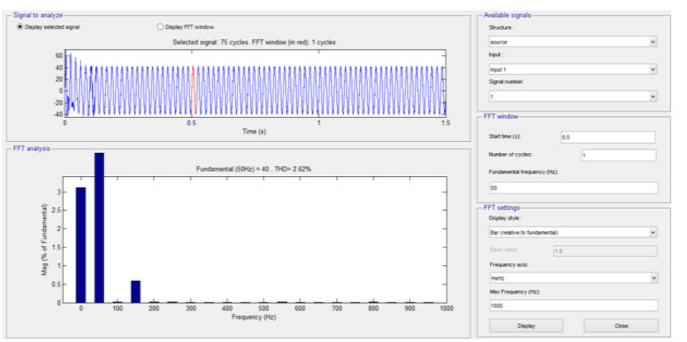

Fig 5.f THD calculation of distribution system with EUPQC

CONCLUSION

This thesis examines the structural principles and control strategies of EUPQC, leading to several key conclusions. Integrating supercapacitor energy storage with a DC/DC converter effectively buffers reactive power, facilitates energy exchange, and supports voltage compensation. This integration enables decoupling between the series converter and the parallel converter. Additionally, EUPQC can now address voltage quality issues, such as power interruptions, that were previously beyond the capabilities of traditional UPQC. Implementing EUPQC can alleviate power quality challenges in distribution networks with high DG penetration. Control strategies for the three main components of EUPQC are proposed based on feedback control principles. Simulation analyses are conducted to evaluate performance under scenarios such as source voltage sag and balanced load operation.

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