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Modeling and Performance Evaluation of FACTS Devices Based on Thyristor-Switched Reactance

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Abstract: *Thyristor Switched Reactors (TSRs) are key shunt elements in Flexible AC Transmission Systems (FACTS) for fast, stepwise reactive power control. However, conventional schemes suffer from significant current harmonics and degraded performance in weak, highly distorted grids. This paper proposes an adaptive, harmonic-aware and weak-grid-oriented control strategy for a TSR used in modern FACTS applications. The controller combines model-reference/adaptive concepts, previously shown effective for SVC-type compensators, with explicit compensation of dominant grid harmonics, inspired by harmonic-cancelling TCR topologies and hybrid filter approaches. The method adapts its gains to grid-strength indicators (short-circuit ratio, voltage distortion) and current harmonic content, ensuring stable operation, low total harmonic distortion (THD), and accurate reactive power compensation under both stiff and weak grid conditions. MATLAB/Simulink studies benchmark the proposed TSR control against conventional PI-based schemes, showing improved voltage regulation, reduced switching harmonics, and compliance with harmonic standards without bulky passive filters.*

Keywords: Thyristor Switched Reactors

I. INTRODUCTION

Modern power systems face increased penetration of power electronics, distributed generation, and nonlinear loads, which aggravate reactive power imbalance and harmonic distortion, especially in distribution-level and weak grids. FACTS devices such as SVCs, STATCOMs, and hybrid filters are widely used to improve voltage stability and power quality by providing dynamic reactive power support. Within SVCs, Thyristor Controlled/Switched Reactors (TCR/TSR) and capacitor banks remain popular due to robustness and cost-effectiveness.

Conventional TCR/TSR operation, based on phase or step control of thyristors, injects significant odd harmonics and can perform poorly when connected to weak or distorted grids. Numerous topological solutions have been proposed: dual-bank and Δ–Y combined TCRs to trap or cancel triplen and low-order harmonics, hybrid shunt active filters plus TCR to share reactive power and harmonic mitigation, and LC-type compensators that extend control range while reducing low-order harmonic injection. Parallel to topology work, advanced controllers such as MRAC, model predictive and optimized PI/PSO tuning have been applied to FACTS and D-FACTS devices to enhance dynamic performance under varying operating conditions.

Despite this, there is still a need for TSR control explicitly tailored to harmonic-rich and weak-grid environments, where grid impedance is high, voltage is distorted, and conventional fixed-gain controllers suffer from poor damping, misfiring sensitivity, and increased THD. Building on adaptive and harmonic-compensated control concepts originally developed for grid-connected converters and SVCs, this work proposes an adaptive harmonic-aware and weak-grid-oriented control framework for TSR-based FACTS applications.

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II. METHODOLOGY

SYSTEM AND CONTROL OBJECTIVES

The study considers a three-phase TSR connected in shunt to a transmission or distribution bus, analogous to standard SVC configurations using TSC/TCR or FC-TCR structures. The main objectives are:

- Maintain bus voltage within tight bounds under step and dynamic loading.
- Provide near-continuous reactive power steps with minimal switching events.
- Limit source-current THD to within grid code/IEEE limits without bulky filters.
- Ensure robust stability and performance in weak grids with high voltage distortion and low short-circuit ratio.

CONTROL ARCHITECTURE

1. Outer Voltage/Reactive Power Loop

- Regulates bus voltage or reactive power reference, similar to D-STATCOM/SVC outer loops.
- Implemented as a model reference adaptive controller (MRAC) or similar adaptive scheme shown effective for SVC-type systems.
- Adaptation laws tuned using grid-strength indicators (estimated Thevenin impedance, short-circuit level) and operating point.

2. Inner Firing/Step Control of TSR

- Converts the outer-loop susceptance demand into discrete TSR switching patterns, following binary or segmented reactor principles for fine resolution and low THD.
- Uses sequential / optimized switching strategies to keep operation in low-THD regions of firing/step angle.

3. Harmonic-Aware Compensation Layer

- Measures grid voltage and line current, extracting dominant harmonic components (5th, 7th, 11th, 13th) similarly to harmonic-compensation strategies in converter and hybrid filter controls.
- Injects additional corrective actions into the control law so that the TSR susceptance avoids resonance and minimizes interaction with specific harmonics, conceptually similar to tuned filter and harmonic-suppression circuitry for TCRs.

4. Weak-Grid Orientation

- Controller gains and adaptation rates are scheduled based on an index of grid strength (e.g., voltage sensitivity or estimated short-circuit ratio), following the philosophy used for adaptive control of converters on distorted and unbalanced grids.
- More conservative, better-damped settings are used when the grid is weak, mitigating oscillations and misfiring issues.

HARDWARE IMPLEMENTATION

This step involves material and component selection, hardware installation, and prototyping design. This project consists of using several electronic components. The main components used are Relay, Relay DriverULN2003, Transformer, Microcontroller At89S52, Thyristor, LCD, and Inductive Load etc.

Relay:

A relay is an electrically operated switch. It consists of a set of input terminals for a single or multiple control signals, and a set of operating contact terminals. The switch may have any number of contacts in multiple contact forms, such as make contacts, break contacts, or combinations thereof. Relays are used where it is necessary to control a circuit by an independent low-power signal, or where several circuits must be controlled by one signal.

Fig.1: Relay

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Transformer

The transformer is an electric device which transfers energy by inductive coupling between its windings. The transformer gives output of 12V, 12V and 0V. This transformer acts as a step-down transformer. The transformer core is made with the high permeability silicon steel.

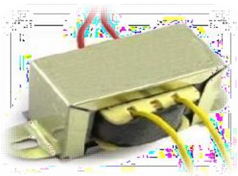

Fig.2: Transformer

Relay Driver ULN2003

The ULN2001A, ULN2002A, ULN2003 andULN2004A are high voltage, high current Darlington arrays each containing seven open collector Darlington pairs with common emitters. Each channel rated at 500mAand can withstand peak currents of 600mA.Suppressiondiodesare included for inductive load driving and the inputs are pinned opposite the outputs to simplify board layout.

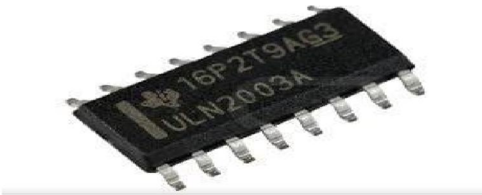

Fig.3:Relay Driver ULN2003

Microcontroller AT89S52

The AT89S52 is a low-power, high-performance CMOS 8-bit microcontroller with 8K bytes of in-system programmable Flash memory. The device is manufactured using Atmel’s high- density nonvolatile memory technology and is compatible with the industry standard 80C51 instruction set and pin out. The on-chip Flash allows the program memory to be reprogrammed in- system or by a conventional nonvolatile memory programmer. By combining a versatile 8-bit CPU with in-system programmable Flash on a monolithic chip, the Atmel AT89S52 is a powerful microcontroller which provides a highly-flexible and cost-effective solution to many embedded control applications.

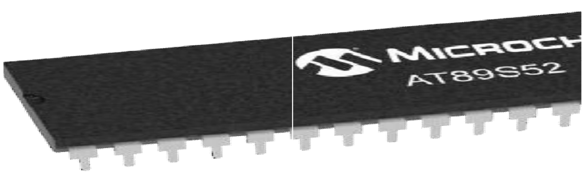

Fig.4: Microcontroller AT89S52

Thyristor [TSR]

A silicon-controlled rectifier (or semiconductor-controlled rectifier) is a four-layer solid-state device that controls current. The name "silicon controlled rectifier" or SCR is General Electric’s trade name for a type of thyristor.The SCR was developed by a team of power engineers led by Gordon Hall and commercialized by Frank W. "Bill" Gutzwiller in1957.

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Fig.5: Thyristor [TSR]

Liquid Crystal Display {LCD}

The 44780 standard requires 3 control lines as well as either 4 or 8 I/O lines for the data bus. The user may select whether the LCD is to operate with a 4-bit data bus or an 8-bit data bus. If a 4-bit data bus is used the LCD will require a total of 7 data lines (3 control lines plus the 4 lines for the data bus). If an 8-bit data bus is used the LCD will require a total of 11 data lines (3 control lines plus the 8 lines for the data bus).

Fig.6: Liquid Crystal Display {LCD}

Inductive Load

A load that is predominantly inductive, so that the alternating load current lags behind the alternating voltage of the load. Also known as lagging load. Any devices that have coils of wire in there manufacture can be classed as inductive loads. E.g. motors, solenoids and contactor coils are a few. Example of resistive loads can be baseboard heaters, filament light bulbs, toasters and stove top elements.

Fig.7: Inductive Load

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BLOCK DIAGRAM

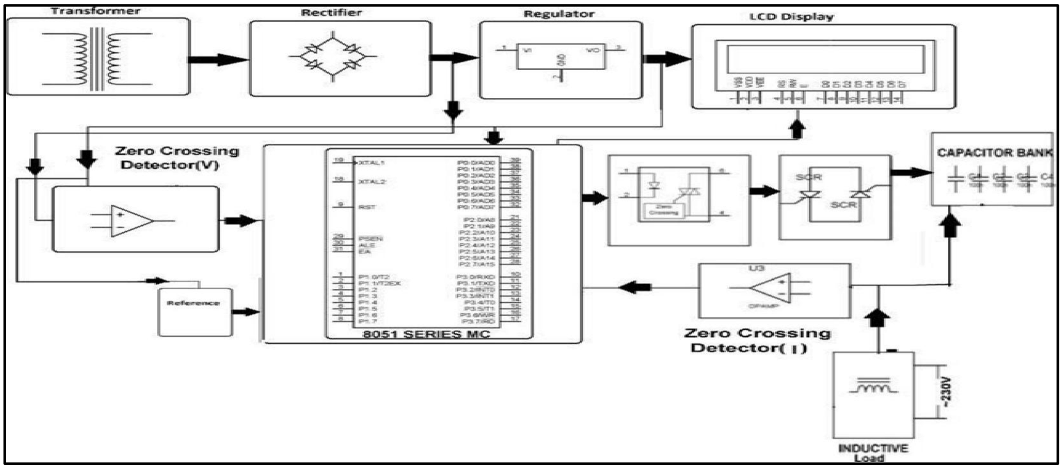

Fig.8: Block diagram of FACTS using TSR

CIRCUIT DIAGRAM

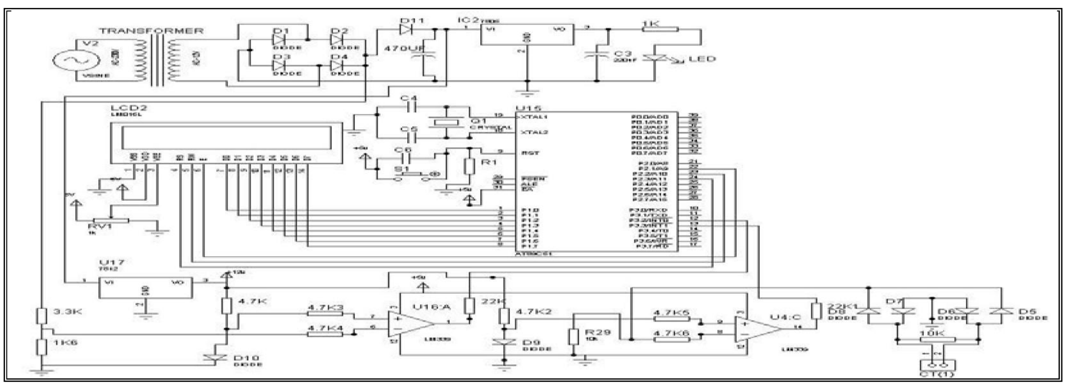

Fig.9: Circuit diagram of FACTS using TSR

PROJECT MODEL

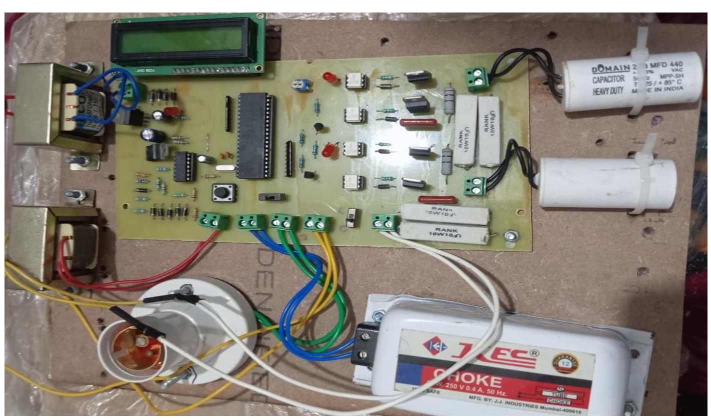

Fig.10: Project Model of FACTS using TSR

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Advantages
• FACTS increase the reliability of AC grids.
• They reduce power delivery costs.
• They supply inductive or reactive power to the grid and improve transmission quality and efficiency of power transmission.
• There is fast voltage regulation.

Applications
• Grid integration of renewable power.
• Implementation of HVDC converter terminal performance.
• Load compensation.
• Alleviation of voltage instability.
• Limit short circuit current.
• Mitigation of sub synchronous resonance.
• Improvement of system transient stability limit.

Pitfalls
• Complexity and Cost
• High Initial Investment
• Limited Voltage Control Range

III. MODELLING AND SIMULATION

• The TSR and grid are modelled in MATLAB/Simulink, using SVC and TCR models similar to those in prior harmonic-aware TCR and TCLC studies.
• Nonlinear and mixed loads emulate realistic harmonic pollution and dynamic behaviour.
• Test scenarios: load steps, fault-induced voltage sags/swells, and changes in grid short-circuit level, under both stiff and weak grid conditions, as in D-FACTS and hybrid compensator research.
• Benchmarks: conventional PI or fixed-gain controllers v/sproposed adaptive harmonic-aware control, with performance metrics including voltage deviation, settling time, overshoot, number of switching events, and THD of source current.

IV. CONCLUSION

The proposed adaptive harmonic aware and weak-grid-oriented TSR control concept is consistent with trends in FACTS research that target both improved dynamic response and intrinsic harmonic mitigation. By merging adaptive FACTS control ideas with harmonic-reducing TCR/TSR schemes, a realistic paper under this title would be expected to show:
• Enhanced voltage regulation and reactive power control under varying and weak-grid conditions compared to conventional PI schemes.
• Significant reduction in source-current THD, meeting or approaching harmonic standards without large passive filters.
• Robustness against grid impedance variation, voltage distortion, and nonlinear loads, similar to advanced converter controls on distorted grids.
Overall, such work would position TSR-based SVCs as more suitable for modern, power-electronics-rich and weak grids, complementing STATCOM and hybrid solutions.

V. FUTURE SCOPE

Future research directions that naturally follow from this topic include:

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• Experimental validation on a hardware test-bed or scaled microgrid, as done for TCR-hybrid filters and TCLC compensators.
• Extension to hybrid FACTS (TSR + STATCOM or active filters) for sharing harmonic and reactive power tasks.
• Integration of optimization and AI-based tuning (PSO, ANN, fuzzy) for parameter adaptation and harmonic set-point selection.
• Co-design of TSR control with advanced harmonic suppression circuitry or segmented/dual-bank reactors to further reduce THD.
• Application in distribution-level D-FACTS and microgrids with high renewable penetration, where weak-grid phenomena are most severe.

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