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A STATCOM-Control Scheme for Grid Connected Wind Energy System For Power Quality Improvement

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Abstract: This research further explores the potential of integrating advanced STATCOM technology to enhance grid stability under varying operational conditions. The benefits of using STATCOM in high-capacity wind farms are evaluated through extensive simulation and experimental data. Additional insights into harmonic distortion reduction and reactive power management are provided. This paper explores the challenges associated with integrating wind energy into the power grid and the resulting impact on power quality. The paper discusses the use of STATCOM technology to address voltage variations, harmonics, and reactive power compensation. A control scheme based on bang-bang control is introduced to improve grid stability and performance. Simulation results validate the effectiveness of the proposed scheme. harmonics, and reactive power compensation. A control scheme based on bang-bang control is introduced to improve grid stability and performance. Simulation results validate the effectiveness of the proposed scheme.

Keywords – Power Quality, Wind Energy, STATCOM, Reactive Power, Voltage Regulation

1.INTRODUCTION

Sustainable growth and social progress require utilizing renewable energy sources like wind, biomass, hydro, and co-generation. Integrating wind energy into the power system helps minimize the environmental impact of conventional plants but introduces technical challenges like voltage regulation, stability, and power quality issues. Power quality, crucial for customer satisfaction, is affected by fluctuations in wind speed, causing voltage variations and grid disturbances.The rapid growth of wind energy has led to over 28,000 wind turbines operating worldwide, with individual units up to 2 MW. Fixed-speed wind turbines transmit wind speed fluctuations to the grid, causing mechanical and electrical instability. Induction generators, commonly used for wind generation, are cost-effective but require reactive power for magnetization, which affects terminal voltage during power variations.To address these issues, a STATCOM-based control scheme is proposed for grid-connected wind energy systems. It aims to maintain unity power factor at the source, provide reactive power support, and use a bang-bang controller for fast dynamic response. A battery energy storage system is also recommended to stabilize fluctuations. This paper covers power quality standards, grid coordination rules, improvement topology, control scheme, system performance, and conclusions.

II. POWER QUALITY

The container crane industry faces growing challenges related to power quality due to increasing crane performance demands, higher power consumption, and more advanced AC and DC drives. Poor power quality impacts terminal economics, crane reliability, and environmental sustainability. Key power quality issues in container cranes include:

1. **Power Factor**: Low power factor increases kVA demand, leading to higher costs and penalties from utility companies.
2. **Harmonic Distortion**: AC and DC drives generate harmonic currents, which cause voltage distortion and interfere with sensitive electronic equipment.
3. **Voltage Transients:** Created by SCR commutation and AC drive chopping, transients can reach 3 to 4 times nominal line voltage, damaging equipment.
4. Voltage Sags and Swells: These disturbances are caused by fluctuating crane loads, affecting equipment stability and performance.

2.1 Power Quality Solutions

To address these issues, power quality can be improved through:

- Power factor correction
- Harmonic filtering
- Line notch filtering
- Transient voltage suppression
- Proper grounding systems

2.2 Economic Impact

Poor power quality leads to penalties for low power factor and increased system losses. Correcting power factor on a modern quay crane can reduce utility costs by 6% to 10% monthly. Terminal operators should consider future utility regulations and deregulation impacts when planning for growth.

2.3 Initial Capital Investment

Designing power distribution systems for container cranes is costly due to high kVA demand. Poor power factor increases equipment size requirements for transformers, switchgear, cables, and collector bars. Investing in power quality correction reduces these costs.

2.4 Equipment Reliability

Harmonics, voltage transients, and poor power factor reduce equipment life and reliability. Installing harmonic filters and transient suppression systems can mitigate these issues.

2.5 Power System Adequacy

Before adding new cranes, a power system analysis should assess the existing system's capacity to handle increased loads. Corrective measures may be required to avoid disruptions.

2.6 Environmental Impact

Improved power quality reduces power losses, lowering overall energy consumption and emissions. This contributes to better environmental sustainability.

2.7 International Standards

The International Electro-technical Commission (IEC) provides guidelines for wind turbine power quality, including IEC 61400-21 for measuring grid-connected wind turbines' power quality and IEC 61400-12 for turbine performance. Adhering to these standards ensures acceptable harmonic levels and voltage stability.

Addressing power quality issues in container crane operations improves operational efficiency, lowers costs, enhances equipment reliability, and supports environmental goals.

III. FACTS

FACTS devices enhance power system controllability using power electronics, improving operational efficiency without costly infrastructure upgrades. They enable better power flow control, increased transmission capacity, voltage regulation, reactive power compensation, and stability enhancement. FACTS devices include shunt and series compensation and phase shift controllers, acting as fast current, voltage, or impedance controllers with response times under a second. They optimize power transmission, reduce flicker, and support renewable integration, making them essential for managing long transmission lines and improving overall grid performance.

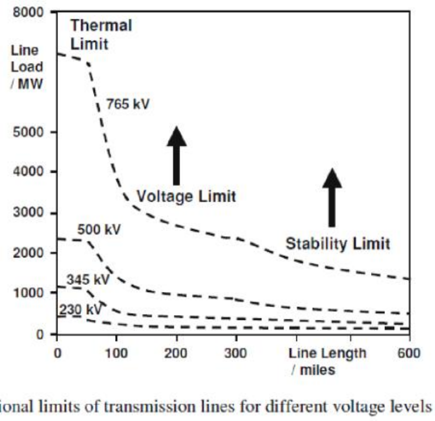

Fig. 1.1. Operational limits of transmission lines for different voltage levels

3.1 FACTS Devices and Configurations

FACTS devices enhance power systems using advanced power electronics like Thyristor valves, IGBTs, and IGCTs. They enable fast and precise control of current, voltage, and impedance, improving stability and efficiency. FACTS are categorized as static (no moving parts) and dynamic (fast response).

3.2 Shunt Devices:

Shunt devices, such as SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator), act as reactive power compensators, reducing losses, improving power quality, and stabilizing voltage. SVCs rapidly adjust reactive power to control voltage fluctuations, preventing issues like voltage collapse. STATCOMs, using voltage source converters, provide faster and more precise compensation, making them ideal for industrial and transportation systems.

3.3 SVC and Its Applications

SVC (Static Var Compensator) improves power system stability by increasing transfer capacity, damping power oscillations, and controlling voltage. It's widely used in transmission systems, traction systems, HVDC systems, and arc furnaces to reduce voltage variations and improve power quality.

3.4 SVC Components:

SVC includes Thyristor Switched Capacitors (TSC) and Thyristor Controlled Reactors (TCR) for reactive power control. The first SVC for arc furnaces was installed in 1972, and for transmission systems in 1979.

3.5 TSC-TCR SVC:

TSC-TCR combinations reduce operating losses and improve performance under large disturbances. Rapid switching prevents transients and enhances system stability, though increased complexity raises capital costs.

IV.STATCOM AND SERIES DEVICES

4.1 STATCOM:

STATCOM (Static Compensator), introduced in 1999, is an advanced SVC using Voltage Source Converters (VSC) with GTO, IGCT, or IGBT. It offers better dynamics, lower cost, and faster response than synchronous condensers. STATCOM maintains reactive power provision even under low voltage, enhancing grid stability. Combining it with energy storage improves power quality.

4.2 STATCOM Control:

STATCOMs use 6-pulse and multi-pulse configurations to minimize harmonics. Techniques like Pulse Width Modulation (PWM) allow better control at the cost of higher switching losses. Multi-level configurations reduce harmonics by generating a staircase voltage.

4.3 Series Devices:

Series devices, like Thyristor Controlled Series Compensation (TCSC), improve transmission capacity and stability by adjusting line impedance. Voltage Source Converter-based series devices offer better control and faster response

V.TCSC, DFC, AND UPFC OVERVIEW

5.1 TCSC (Thyristor Controlled Series Capacitors):

TCSC addresses dynamic issues in transmission systems by increasing damping, overcoming Sub Synchronous Resonance (SSR), and regulating steady-state power flow.

- *Advantages:*
    1. Smooth control of compensation level
    2. Direct power flow control
    3. Improved capacitor protection

4. Damping of power oscillations (0.5–2 Hz)

5.2 DFC (Dynamic Power Flow Controller):

DFC combines a Phase Shifting Transformer (PST) and Thyristor Switched Capacitors/Reactors (TSC/TSR) for advanced power flow control.

- **Components:**
    1. Phase Shifting Transformer (PST)
    2. TSC/TSR for fast response
    3. Optional Mechanically Switched Shunt Capacitor (MSC)
- **Control Principles:**
    1. Fast response with TSC/TSR switching
    2. PST tap-changer minimizes switching under high loads
    3. Optimized reactive power consumption

5.3UPFC (Unified Power Flow Controller):

UPFC combines shunt compensation and phase shifting for full voltage and power flow control.

- **Components:**
    - Two Voltage Source Inverters (VSIs)
    - Common DC storage capacitor
    - Shunt and series transformers
- **Operation:**
    - Series inverter injects symmetrical three-phase voltage
    - Controls active and reactive power flow
    - High cost limits practical applications

5.4 UPFC (Unified Power Flow Controller):

The UPFC regulates active and reactive power flows on a transmission line by injecting a controlled magnitude and phase angle voltage in series with the line.

Operating Principle:

- The UPFC consists of two Voltage Source Inverters (VSIs) connected through a common DC capacitor.
- The series inverter injects voltage into the line to regulate active and reactive power flow.
- The shunt inverter regulates the DC capacitor voltage and provides reactive power compensation.

Operating Modes:

1. **VAR Control Mode:**
    - The shunt inverter injects a specific reactive current based on a reference value.

- ○ The control adjusts the inverter's gating to maintain the desired reactive current.

2. **Automatic Voltage Control Mode:**
   - ○ The shunt inverter automatically adjusts reactive current to maintain a target bus voltage.
3. **Direct Voltage Injection Mode:**
   - ○ Series inverter injects voltage with direct reference to magnitude and phase angle.
4. **Phase Angle Shifter Emulation Mode:**
   - ○ Controls phase displacement between sending and receiving end voltages.
5. **Line Impedance Emulation Mode**:
   - ○ Controls injected impedance to regulate line impedance.
6. **Automatic Power Flow Control Mode**:
   - ○ Directly regulates active and reactive power flow (P and Q) despite system variations.

VI.STATCOM (Static Synchronous Compensator):

STATCOM is a solid-state power converter version of the SVC, providing faster response and better dynamic performance.

Structure:

1. Voltage Source Converter (VSC): Converts DC to AC and regulates output.
2. Step-up Coupling Transformer: Matches STATCOM voltage to the grid.
3. Controller: Adjusts output based on system requirements. Operating Principle:
4. If the STATCOM voltage (VsV_sVs) is higher than the bus voltage (EsE_sEs), it injects reactive power (capacitive).
5. If the STATCOM voltage (VsV_sVs) is lower than the bus voltage (EsE_sEs), it absorbs reactive power (inductive).
6. Provides continuous and precise reactive power control with fast response.

VIII.STATCOM-BASED CONTROL SCHEME FOR POWER QUALITY IMPROVEMENT IN GRID-CONNECTED WIND SYSTEMS

7.1 INTRODUCTION.

The American Wind Energy Association (AWEA) led efforts to develop grid codes for wind plant interconnection in the U.S., especially after the 2003 blackout. The grid code, based on IEC-61400-21, defines rules for wind system operation at the distribution level and sets limits for voltage rise, voltage dips, flicker, harmonics, and grid frequency.

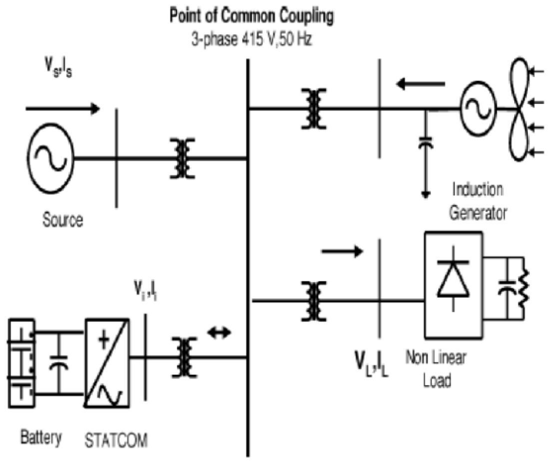

Fig. 1. Grid connected system for power quality improvement.

7.2 Power Quality Issues

- **Voltage Rise (u):** Caused by maximum apparent power, grid impedance, and phase angle. Limit: <2%.
- **Voltage Dips (d):** Caused by wind turbine startup. Limit: ≤3%.
- **Flicker:** Due to switching operations. Long-term flicker coefficient limit: ≤0.4.
- **Harmonics:** Total harmonic distortion (THD) for 132 kV systems: Voltage <3%, Current <2.5%.
- **Grid Frequency:** Wind farm must withstand frequency changes from 47.5–51.5 Hz and up to 0.5 Hz/s.

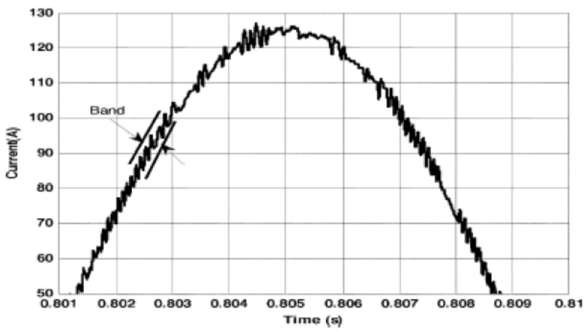

Fig. 4. Switching signal within a control hysteresis band.

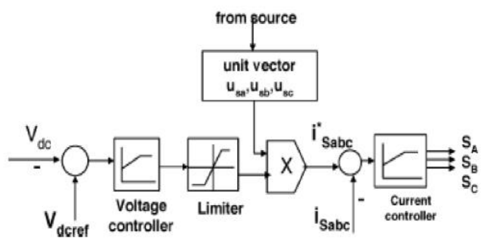

Fig. 3. Control system scheme.

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7.3 Topology for Power Quality Improvement

A STATCOM-based current-controlled voltage source inverter injects current to cancel reactive and harmonic components, improving power factor and grid quality.

A. Wind Energy Generating System

- Uses a constant-speed pitch control turbine with an induction generator.

- Captures wind power based on air density, turbine blade area, and wind speed.

B. BESS-STATCOM

- Battery Energy Storage System (BESS) regulates voltage by injecting/absorbing reactive power.
- Connected in parallel to the STATCOM's DC capacitor for rapid power fluctuation control.

7.4 Control Scheme

Bang-Bang Controller:

- Uses a hysteresis-based method to keep current within set limits.
- Synchronizes reference currents with grid voltage for sinusoidal source current.

7.5 System Performance

- STATCOM starts operation at t = 0.7 s, improving power factor and reducing harmonic distortion.
- DC link voltage remains stable during load changes.
- THD reduced from 4.71% to within standard limits.

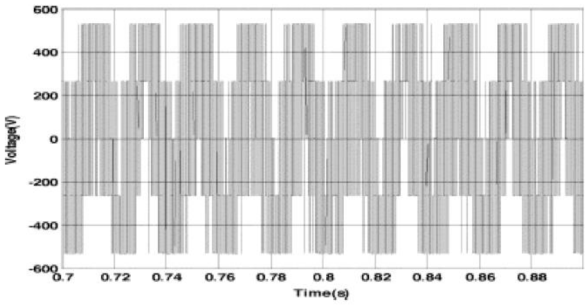

Fig. 8. STATCOM output voltage.

VIII.CONCLUSION

The proposed STATCOM-BESS control scheme effectively improves power quality in grid-connected wind systems, meeting IEC-61400-21 standards. It maintains source voltage and current in-phase, cancels harmonics, and supports reactive power demands, enhancing grid stability. This version is more concise but retains the essential information. Let me know if you'd like to adjust anything!

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