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Control Strategies in Series Voltage Sag Compensator to Mitigate Inrush Current in Transformer

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Abstract - The control strategies used in Series Voltage Sag Compensators (SVSCs) work to reduce the inrush current in transformers by actively managing the flux linkage in the coupling transformer. These methods commonly employ flux-oriented closed-loop control, point-on-wave switching, or fuzzy logic–based decision mechanisms. An inverter-fed series compensator injects a carefully controlled compensating voltage, ensuring smooth flux evolution during sag recovery. As a result, magnetic saturation at the instant of sag clearance is avoided, load voltage is restored seamlessly, and excessive inrush currents that could stress power electronic devices or trigger protection systems are effectively eliminated. This makes SVSCs a reliable solution for dynamic voltage compensation in modern power distribution networks.

Keywords: Flux linkage control, Point on wave switching, Fuzzy logic control, Active inrush current control, coupling transformer design

I. INTRODUCTION

Voltage sag is a common issue in power quality and is one of the most frequently experienced disturbances in electrical systems [10]., characterized by a temporary reduction in supply voltage magnitude. Such events can severely disrupt the operation of sensitive industrial equipment, leading to process interruptions, equipment malfunction, and economic losses. Series Voltage Compensator (DVR) - A Dynamic Voltage Restorer is a device connected in series that adds the necessary voltage to keep the load-side voltage stable at its normal level whenever voltage sags occur.. DVRs are widely adopted due to their fast response and effectiveness in mitigating short-duration voltage disturbances [11],[12]. Transformer Inrush Current Issue -When the DVR restores the supply voltage, the coupling transformer may contain residual magnetic flux from prior operating conditions. The interaction between this residual flux and the newly applied voltage can cause a sudden deviation in flux linkage, driving the transformer core into saturation. This results in a large inrush current. Consequences of Inrush Current-If not properly controlled, the high current may exceed the current-handling capacity of the DVR, triggering protective circuits and potentially causing system shutdown or equipment stress, thereby undermining the reliability of the compensation system [5], [6], [1].

II. PROBLEM FORMULATION AND MATHEMATICAL MODEL

A. Transformer Flux Linkage Model

The instantaneous flux linkage in the coupling transformer refers to the magnetic flux passing through the transformer at any given moment [5]:

where:

$$\lambda(t) = \int v_{inj}(t)\, dt + \lambda_r$$

$$\lambda_r = \text{residual flux}$$

v_{inj} = injected compensation voltage

If compensation begins at an unfavourable phase angle:

$$\lambda_{peak} = \lambda_r + V_m / \omega$$

When: $\lambda_{peak} > \lambda_{sat}$

core saturation occurs.

B. Inrush Current Expression

Magnetizing current

$$im = L\,m / \lambda$$

during saturation: L m ↓⇒ i m ↑
This explains the sudden rise in current during sag restoration.

C. Control Loop Representation

For a VSI-based compensator
G(s) = K + K p i/s
Ls + R
Stability is ensured if adequate phase and gain margins are maintained [9]

III. STRATEGIES FOR INRUSH CURRENT MITIGATION

A. Flux Linkage Control

Concept:- This method involves estimating the leftover flux in the coupling transformer and then injecting a voltage that balances out any resulting changes in the flux.[1],[6].
Implementation: Flux linkage control is usually achieved through feedback controllers like proportional–integral (PI) or fuzzy logic controllers, which operate within the synchronous reference frame. These controllers adjust the injected voltage continuously in real time. These controllers regulate the injected voltage in real time, ensuring smooth flux transition and preventing transformer saturation during voltage restoration.

B. Point On Wave (Pow) Control:

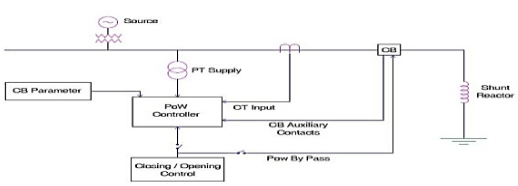

Figure 1. Diagram of Point on Wave Control

Concept:This technique involves powering up the transformer or reconnecting the compensator at the best possible point on the voltage waveform, usually close to the zero-crossing or at a specific phase angle. By carefully choosing the switching instant, the introduction of DC flux offset is minimized, thereby reducing the likelihood of core saturation and limiting the resulting inrush current.

Methods: Uses Phase-Locked Loops (PLL) and precise switching to time the connection [3], [6].

Pre-Insertion Resistors (PIRs): Concept: In this approach, resistors are temporarily added in series with the transformer during startup to limit the initial surge of current.. Once the system reaches steady operating conditions, these resistors are bypassed, allowing normal operation while preventing excessive inrush current..

C. State-Feedback Control:

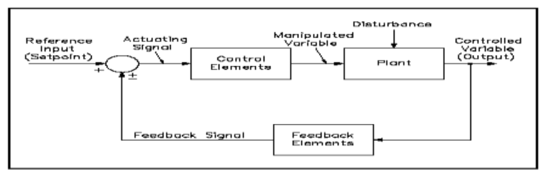

Figure 2. State Feedback Control

Concept**:** This technique employs a robust feedback control scheme that monitors both the filter capacitor voltage and inductor current to accurately regulate the compensator output. By doing so, it enhances disturbance rejection capability and ensures stable operation under varying system conditions [1], [6].

IV. LITERATURE SURVEY

A review of existing research shows that significant efforts have been made to develop control strategies for series voltage sag compensators, also known as Dynamic Voltage Restorers (DVRs). A major focus has been on reducing transformer inrush current. These strategies mainly work by controlling the magnetic flux linkage in the coupling transformer during voltage compensation, which helps avoid core saturation and large transient currents. The main challenge in controlling inrush current with series compensators comes from traditional sag compensation methods. While these methods aim to restore the load voltage precisely—often at a specific point on the voltage waveform—they can inadvertently cause an imbalance in the transformer's magnetic flux. This imbalance can push the transformer core into saturation, leading to strong inrush currents that risk damaging the compensator. From the literature, several important strategies have been identified to address and reduce inrush current effectively.

1) Direct Flux Linkage Control -This advanced active control approach explicitly models the magnetizing characteristics of the transformer and treats flux linkage as a controlled state variable [1], [6].

Mechanism: An additional flux linkage control loop, typically implemented using a proportional–integral (PI) regulator in conjunction with a flux estimator, is incorporated into the control architecture. This loop directly tracks and regulates the transformer's magnetic flux, preventing excessive deviation during voltage restoration.

Advantage: Because this approach addresses the core cause of saturation directly, it proves to be very effective and doesn't require any prior information about the transformer's parameters, leftover flux, or the precise timing of switching..

1. **Integrated State**- Feedback Control—this approach integrates inrush current reduction into a unified state-feedback control system for the voltage sag compensator..

Mechanism: The control system includes flux linkage deviation as part of its design, enabling it to regulate both the load voltage and the transformer's flux at the same time.. Full-state feedback, often complemented by feed forward and decoupling control actions, is employed to enhance dynamic performance and tracking accuracy [1].

1. **Controlled Voltage Injection and Interruption Timing** -Certain techniques focus on modifying the timing and waveform of the injected compensation voltage.

Mechanism: These methods either delay the injection of compensating voltage for a brief, optimized interval or shape the injected waveform such that the transformer's residual flux aligns with the prospective supply flux. This alignment minimizes DC flux offset and avoids saturation [3], [4].

Trade-off: Although effective in limiting inrush current, these strategies may introduce a short-duration voltage dip or waveform distortion at the load, which can be undesirable for highly sensitive equipment requiring continuous point-on-wave voltage restoration.

Passive (Hardware-Based) Techniques **-**In addition to active control methods, passive mitigation approaches are also reported in the literature as part of the overall system design.

Pre-insertion resistors: Temporary series resistors are inserted during energization to restrict the initial current surge and are bypassed once steady-state conditions are reached.

Transformer design optimization: Employing transformer cores with higher saturation limits, increasing the number of turns, or oversizing the transformer can reduce inrush current, although these solutions significantly increase system cost and physical size.

V. SYSTEM DESCRIPTION

A Series Voltage Sag Compensator (VSC) mitigates voltage sag events by rapidly injecting a compensating voltage to restore the load-side voltage. However, this fast voltage restoration can unintentionally lead to magnetic saturation of the coupling transformer, resulting in high inrush current. To address this issue, modern control strategies emphasize flux-oriented approaches that regulate the transformer's magnetic flux linkage. These methods typically involve injecting a controlled voltage offset, managing residual magnetic flux, and employing feedback-based controllers such as proportional–integral (PI) or state-feedback schemes. The compensator uses a voltage source inverter (VSI) along with a filter and a coupling transformer to control the injected voltage. This helps reduce peak inrush current and supports a smooth and stable recovery during transient events..

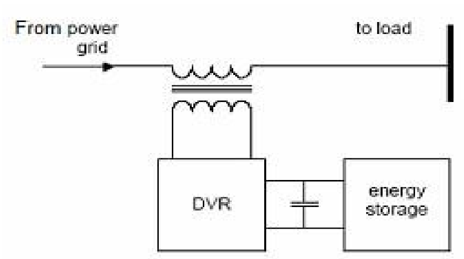

Figure Diagram of the Basic Setup for a Series Voltage Sag Compensator

A. Components

A typical VSC configuration consists of a three-phase voltage source inverter (VSI), a passive output filter comprising inductive and capacitive elements, and a series-connected coupling injection transformer interfacing the compensator with the load.

B. Operating Modes

Normal Operation: Under steady-state conditions, the compensator is bypassed using thyristors or bypass switches to minimize losses and improve system efficiency.Sag Compensation Mode: When a voltage sag occurs, the VSI produces a compensating voltage that is sent through the coupling transformer to bring the load voltage back to its normal level. Inrush Current Initiation: During voltage restoration—particularly if the sag occurs near the voltage peak—the sudden application of compensation voltage can introduce a DC flux offset in the transformer core. This offset may drive the core into deep saturation, causing a large inrush current [11], [9].

C. Control Strategies For Inrush Current Mitigation

Flux-Based Control (Core Strategy)

Objective: To regulate the transformer's magnetic flux linkage (λ) and prevent core saturation during voltage recovery.
Approach: Flux Linkage Offset Control: A controlled voltage offset is intentionally introduced, or the phase and magnitude of the injected voltage are adjusted, to counteract residual magnetic flux. This action steers the net flux toward a safe operating region.
Residual Flux Management: The residual flux present in the transformer is estimated, and compensation commands are modified accordingly to avoid excessive flux peaks during transient conditions.

Feedback Control (Implementation Layer)

State-Feedback Control: -Measured system states, such as filter capacitor voltage and inductor current, are used to implement a robust state-feedback controller. This enhances control accuracy, dynamic response, and disturbance rejection.
PI Control Structure:A cascaded control architecture is commonly adopted, where an outer voltage control loop ensures accurate load voltage regulation, and an inner current loop governs the inverter current dynamics. This structure enables fast and precise voltage restoration.
Advanced and Combined Techniques: Controlled Switching: The VSI is energized at an optimal instant, typically near the zero-crossing of the source voltage, to minimize DC flux components.
Integrated Control: Flux-based logic is combined with fast feedback controllers to provide real-time adaptation during sag recovery and transformer energization.
Effectiveness of the Approach -By precisely regulating the voltage injected by the VSI, these control strategies directly influence the magnetic flux trajectory of the coupling transformer. This prevents flux excursions beyond saturation limits, significantly reduces transient inrush current, and safeguards the compensator's protection circuitry. As a result, reliable voltage sag mitigation is achieved without compromising system stability or equipment integrity.

VI. METHODOLOGY

In a Series Voltage Sag Compensator (SVSC), reducing transformer inrush current mainly depends on how the voltage is injected into the system. Control strategies focus on carefully managing both the timing and the speed of voltage injection, while also ensuring that the magnetic flux in the coupling transformer remains within safe and controlled limit. Although rapid voltage recovery is essential for protecting sensitive loads, an abrupt application of compensating voltage can cause sudden flux variations, pushing the transformer core into saturation. To avoid this condition, modern solutions emphasize controlled voltage injection, point-on-wave (PoW) switching, and advanced control techniques such as state-feedback and feed forward control. These methods are typically implemented using a voltage source inverter (VSI) controlled by space vector pulse width modulation (SVPWM). This approach allows the injected voltage to be generated with high accuracy and flexibility, making it well-suited for precise control applications [4]..

The overall operating principle involves detecting the occurrence of voltage sag, determining the required magnitude and phase of the compensating voltage, and injecting this voltage either progressively or at an optimal phase angle of the supply waveform. By avoiding sudden changes in magnetic flux within the coupling transformer, these methods help reduce inrush current and keep the system stable during transient conditions..

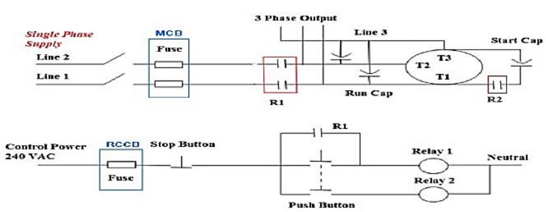

Figure 4. Control Circuit Wiring Diagram

A. Point-On-Wave Voltage Injection

Concept: Instead of immediately restoring the full compensation voltage, the SVSC applies the injected voltage at a carefully chosen point on the supply voltage waveform, typically close to the voltage peak where the rate of change of magnetic flux is minimal. This strategy minimizes the introduction of DC flux components and reduces the risk of transformer saturation [9].
Implementation: Following sag detection, the control system synchronizes with the supply waveform and initiates voltage injection at the optimal phase angle. Space vector PWM is widely used to generate the required voltage waveform with high precision and fast dynamic response.

B. Open Loop Control

Concept: Open Loop Control improves transient performance by introducing a precompiled voltage reference alongside the feedback loop. This enables the compensator to respond instantly to sag events without waiting for voltage error accumulation.
Implementation: The needed compensation voltage is adjusted by adding an estimate of the voltage drop across the filter inductor. This helps create smoother voltage changes, reduces overshoot, and lowers the electrical stress on the transformer [3].

C. State-Feedback Control

Concept: This approach uses feedback from key system variables—such as transformer current, filter inductor current, or estimated magnetic flux—to continuously adjust the injected voltage. Direct observation of system states allows effective suppression of flux deviation and inrush current.
Implementation: A state-feedback controller regulates the VSI operation, ensuring fast stabilization of the load voltage while preventing excessive current that could activate protection mechanisms.

D. Series Resistance Insertion (Hybrid Approach)

Concept: A temporary series resistor is introduced during transformer energization or sag recovery to restrict the initial current surge. Once steady-state conditions are achieved, the resistor is bypassed.
Implementation: This method provides a simple and economical means of limiting current and is often combined with equally phase energization to further reduce peak current levels.
Overall Process Flow-

1. **Sag Detection:** The SVSC continuously monitors the supply voltage to identify sag conditions.
2. **Compensation Calculation:** The magnitude and phase angle of the required compensating voltage are calculated.
3. **Inrush Mitigation Activation:** Appropriate mitigation techniques, such as point-on-wave switching or feed forward control, are activated to regulate voltage injection.

4. **Inverter Control:** The VSI generates a precisely controlled voltage waveform using SVPWM.
5. **Flux Management:** Transformer magnetic flux is maintained in operating limits to avoid saturation.

Smooth Voltage Restoration**:** The applied voltage is restored gradually and reliably to its nominal level, effectively preventing inrush current.

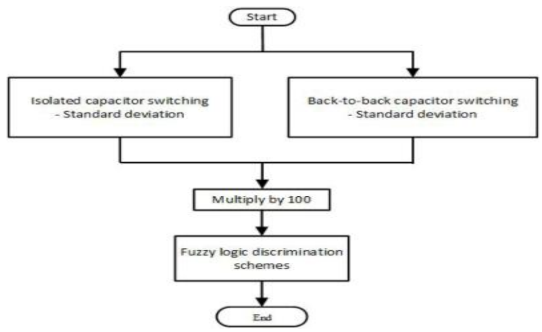

Figure 5. flow chart diagram transient inrush current discrimination

VII. CONCLUSION

To effectively reduce transformer inrush current in a Series Voltage Sag Compensator (SVSC), control strategies focus on carefully managing the timing and speed of voltage injection, while ensuring the magnetic flux within the coupling transformer remains well controlled.. Although fast voltage restoration is essential for protecting sensitive loads, abrupt application of the compensating voltage can introduce sudden flux variations, driving the transformer core into saturation. To avoid this condition, contemporary approaches emphasize controlled voltage application, point-on-wave (PoW) switching, and advanced control schemes such as feed forward and state-feedback control. These techniques are commonly realized using a voltage source inverter (VSI) operated with space vector pulse width modulation (SVPWM), which enables accurate and flexible synthesis of the injected voltage. The overall operating principle involves early detection of voltage sag, precise computation of the required compensating voltage, and controlled injection of this voltage either gradually or at an optimal phase angle of the supply waveform. By minimizing abrupt flux transitions in the coupling transformer, these strategies effectively limit inrush current and preserve system stability during transient recovery.

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