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Comparative Analysis of PWM and Svpwm Techniques for Transformer Transient Mitigation in Series Voltage Compensation Systems

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ABSTRACT

The increasing integration of power electronic devices in electrical power systems has intensified the need for effective control techniques capable of minimizing transformer transient disturbances in series voltage compensation applications. This study investigates and compares the performance of Pulse Width Modulation (PWM) and Space Vector Pulse Width Modulation (SVPWM) techniques in controlling transformer transients and improving overall compensation system performance. The analysis focuses on critical parameters such as transient response characteristics, harmonic distortion, voltage stability, switching efficiency, and power quality enhancement.

A detailed simulation model of a transformer-based series voltage compensator is developed using MATLAB/Simulink to evaluate the operational behaviour of both modulation strategies under different loading and disturbance conditions. The comparative results indicate that the SVPWM technique achieves improved voltage utilization, faster dynamic response, and reduced Total Harmonic Distortion (THD) when compared with conventional PWM methods. In contrast, PWM demonstrates easier implementation and reduced computational requirements, which may be advantageous in less complex applications. The research further highlights the influence of modulation strategies on transformer stress reduction and transient mitigation within modern compensation systems.

The outcomes of this work provide a useful reference for the design and optimization of efficient series voltage compensation systems aimed at enhancing power system reliability, stability, and power quality.

Keywords: Pulse Width Modulation (PWM), Space Vector Pulse Width Modulation (SVPWM), Transformer Transients, Series Voltage Compensation, Total Harmonic Distortion (THD), Power Quality, Voltage Stability, Power Electronics, MATLAB/Simulink, Dynamic Response.

INTRODUCTION

Voltage sag is one of the most common power quality problems affecting modern electrical power systems and is responsible for significant equipment malfunction, transformer losses, and reduced system reliability. During voltage sag conditions, transformers may experience magnetic flux distortion and core saturation, resulting in high inrush currents that can trigger over-current protection and cause compensation failure. In series voltage compensation systems, a short delay in sag detection and voltage injection further increases the risk of transformer transient disturbances.

To minimize these effects, effective control techniques are required for fast and stable voltage compensation. Pulse Width Modulation (PWM) and Space Vector Pulse Width Modulation (SVPWM) are widely used switching techniques in power electronic compensation systems due to their ability to regulate voltage and improve system performance. While PWM offers simple implementation, SVPWM provides better voltage utilization and reduced harmonic distortion.

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LITERATURE REVIEW

Series voltage compensation techniques, particularly Dynamic Voltage Restorer (DVR)-based systems, have been widely investigated for mitigating voltage sag disturbances and improving power quality. Previous studies have demonstrated that the effectiveness of DVR systems depends strongly on the detection speed, compensation strategy, and converter control method employed. [4]

Transformer transient behaviour during voltage disturbances has also been studied extensively, with researchers identifying core saturation and magnetic flux imbalance as major causes of excessive inrush currents during transient conditions. These effects can reduce compensation effectiveness and increase stress on power system components. [2], [3]

PWM remains one of the most commonly applied modulation techniques due to its simple structure and ease of implementation. However, conventional PWM methods may experience limitations in harmonic performance and voltage utilization. Recent studies have demonstrated that SVPWM provides improved DC-link voltage utilization, optimized switching patterns, and lower harmonic distortion compared with traditional PWM approaches. [1], [5]

Although several studies have investigated PWM and SVPWM separately, limited attention has been given to their comparative influence on transformer transient mitigation during series voltage compensation. Therefore, this study evaluates both techniques using MATLAB/Simulink simulations under voltage sag and varying load conditions.

METHODOLOGY

This research adopted a simulation-based approach to investigate the performance of PWM and SVPWM techniques in controlling transformer transients during series voltage compensation. The methodology consisted of system modelling, component selection, simulation, and comparative performance analysis using MATLAB/Simulink.

Initially, an extensive review of journals, textbooks, research papers, and technical articles was conducted to understand voltage sag disturbances, transformer inrush currents, and existing voltage compensation techniques. The study focused on the effects of voltage sag on transformer operation and the role of inverter-based compensation methods in minimizing transient disturbances. PWM and SVPWM control methods were also studied to understand their switching characteristics and suitability for voltage sag compensation applications.

Following the research phase, the required system components were selected and modelled in MATLAB/Simulink. The developed system included a three-phase programmable AC source, multi-winding transformer, voltage source inverter (VSI), rectifier units, anti-parallel thyristor-diode switches, capacitor filters, and series RLC loads. A delta-star transformer rated at 220V/220V was incorporated to improve system protection and reduce harmonic distortion. A six-IGBT universal bridge inverter with a DC-link capacitor was used to generate the compensation voltage required during sag conditions.

The complete simulation model was designed to include both voltage sag compensation and transformer inrush current mitigation circuits. Voltage and current measurement units were connected throughout the system to monitor performance parameters. PWM and SVPWM pulse generation techniques were implemented separately using a discrete synchronous six-pulse generator to control the switching operation of the VSI and compensation units.

The system was simulated under different load conditions using both PWM and SVPWM control methods. Performance analysis was carried out by observing parameters such as transient response, voltage stability, harmonic distortion, and compensation effectiveness. The outputs obtained from the simulations were then

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compared to determine the most effective modulation technique for minimizing transformer transients and improving the performance of the series voltage compensation system.

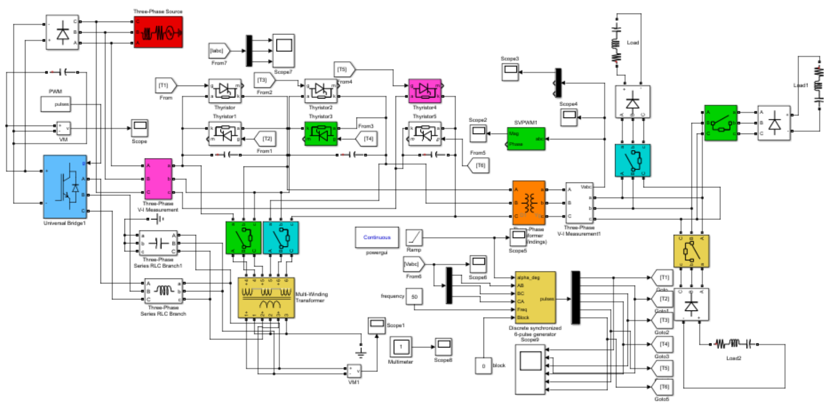

Figure 1: Simulation model with PWM technique

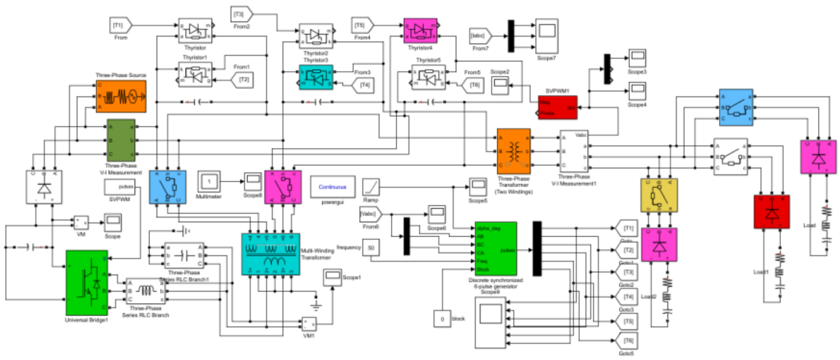

Figure 2: Simulation model with SVPWM technique

RESULTS AND DISCUSSION

The transient performance of the PWM and SVPWM controlled series voltage compensation system was evaluated during transformer energization and dynamic load variation conditions. The analysis considered transformer magnetic flux behaviour, inrush current characteristics, harmonic distortion, and transient recovery capability.

Figure 12 illustrates the transient response comparison between SPWM and SVPWM during transformer energization and a subsequent dynamic load step applied at (t = 40) ms. During the initial energization period (t < 20) ms, the transformer core enters the magnetic saturation region as the flux trajectories exceed the allowable operating limit of ±0.9 Wb. Under the SPWM control strategy, the maximum flux excursion reached approximately 1.20 Wb. This increased magnetic flux deviation resulted in reduced effective core inductance and produced a high asymmetric inrush current peak of 89.3 A.

In comparison, the SVPWM technique demonstrated improved transient control due to its optimized space-vector switching sequence and improved volt-second balance. The maximum flux excursion was limited to approximately 1.10 Wb, reducing transformer magnetic stress during energization. As a result, the peak inrush current was reduced to 66.9 A, representing a 25.1% reduction in transient current stress compared with SPWM operation.

Following the application of the dynamic load step at (t = 40) ms, both control strategies successfully tracked the new operating condition. However, the SPWM response exhibited a higher DC-offset component, larger current oscillations, and slower attenuation before reaching steady state. The SVPWM-controlled system

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achieved faster stabilization with improved current symmetry and reduced transient deviation, demonstrating superior dynamic response and improved volt-second equilibrium.

The harmonic performance of both modulation strategies was further evaluated and results shown on Figure 11 using Total Harmonic Distortion (THD) analysis. The measured current THD values were 44.74% for SPWM and 34.01% for SVPWM. The reduction in THD represents approximately a 24% improvement in waveform quality when using SVPWM.

Performance Parameter	**SPWM**	**SVPWM**
Maximum flux excursion (Wb)	1.20	1.10
Peak inrush current (A)	89.3	66.9
Inrush current reduction (%)	—	25.1
Current THD (%)	44.74	34.01
THD improvement (%)	—	24
Transient response	Slower attenuation	Faster stabilization
Magnetic stress	Higher	Reduced

Table 1: Quantitative Performance Comparison of SPWM and SVPWM

The results confirm that both PWM and SVPWM methods can control transformer transients during series voltage compensation. However, SVPWM provides superior performance through reduced inrush current, improved harmonic characteristics, lower magnetic flux deviation, and enhanced transient stability. Therefore, SVPWM is a more effective modulation strategy for advanced power quality improvement and transformer transient mitigation applications.

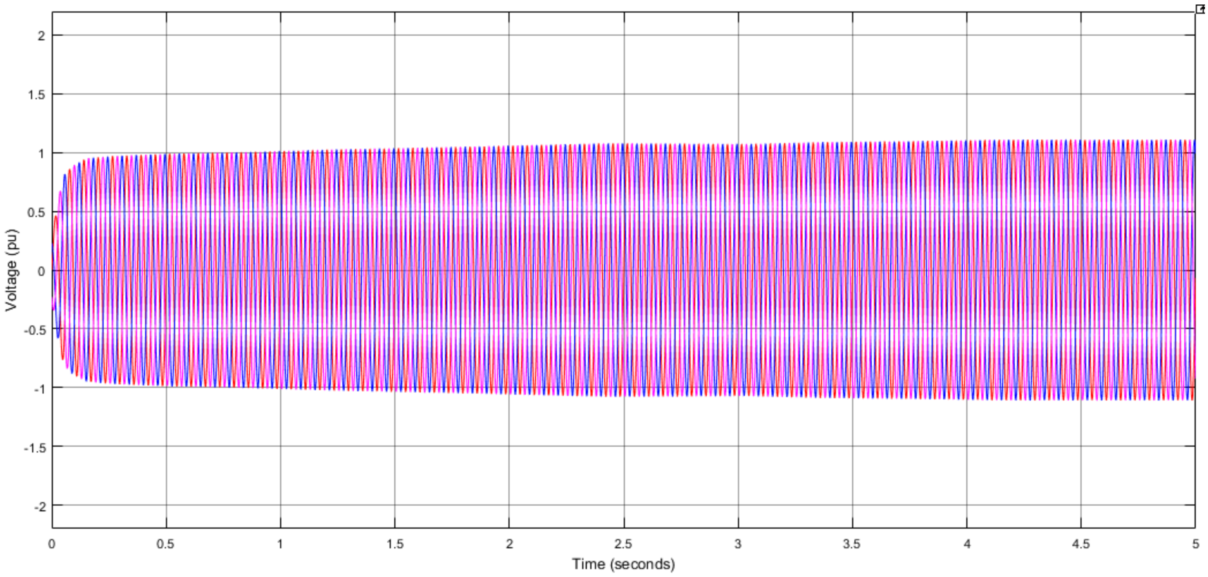

Figure 3: Source voltage (PWM technique)

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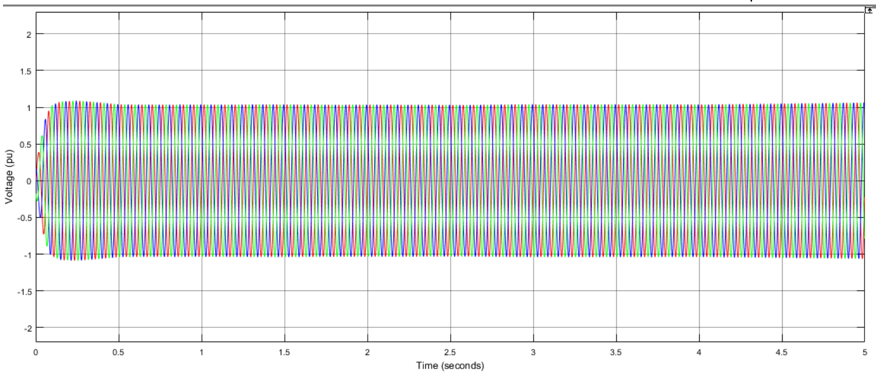

Figure 4: Load voltage (PWM technique)

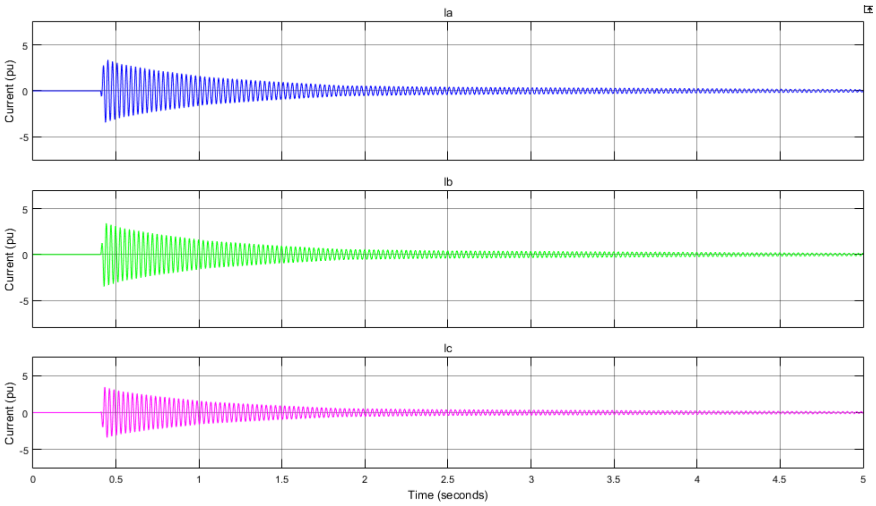

Figure 5: Load current (PWM technique)

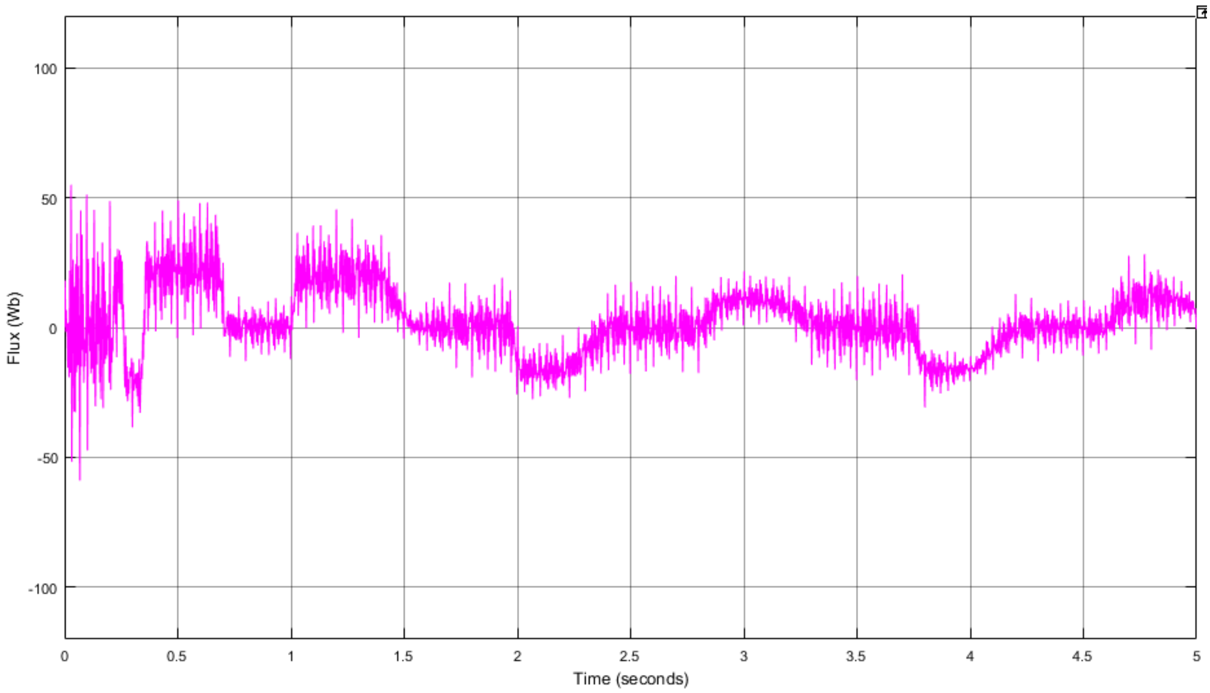

Figure 6: Transformer magnetic flux (PWM technique)

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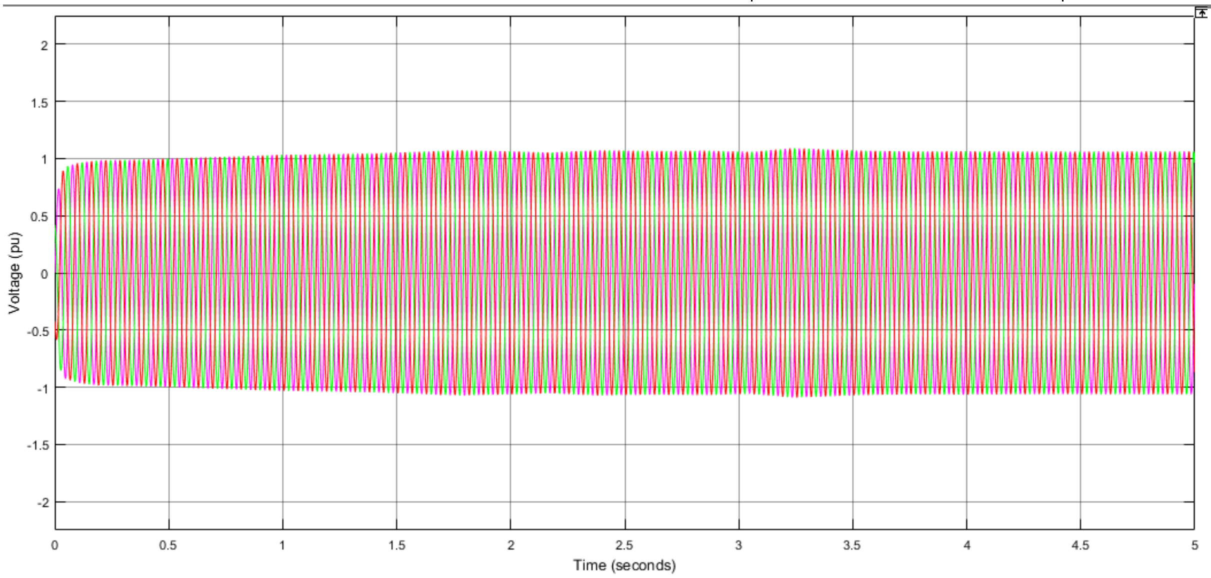

Figure 7: Source voltage (SVPWM technique)

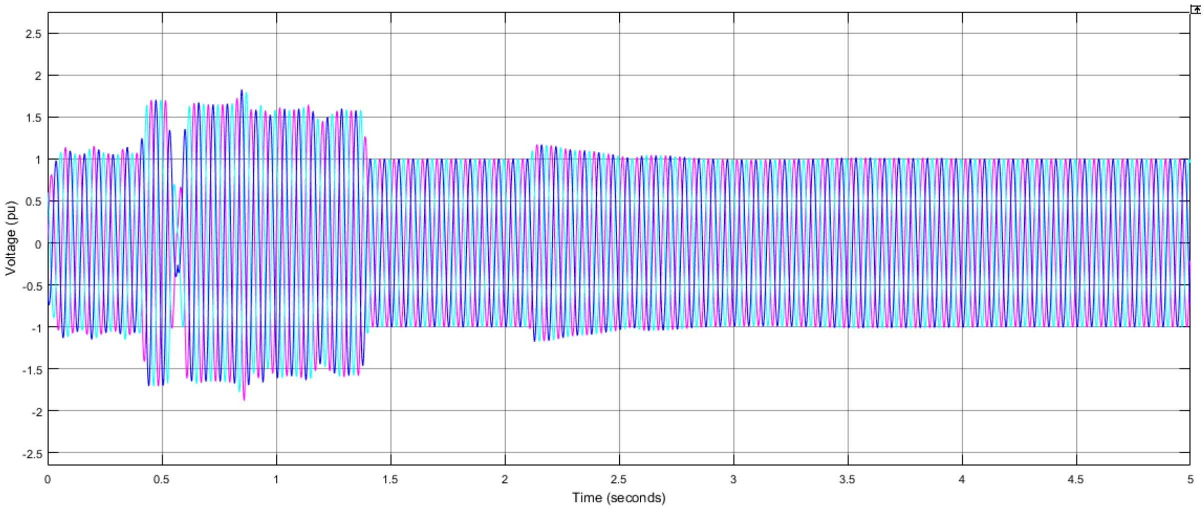

Figure 8: Load voltage (SVPWM technique)

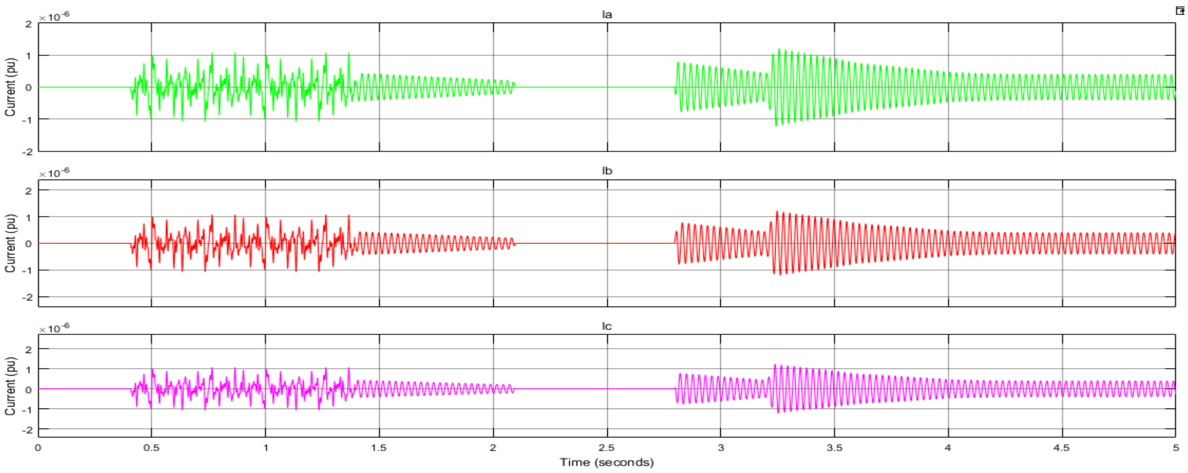

Figure 9: Load current (SVPWM technique)

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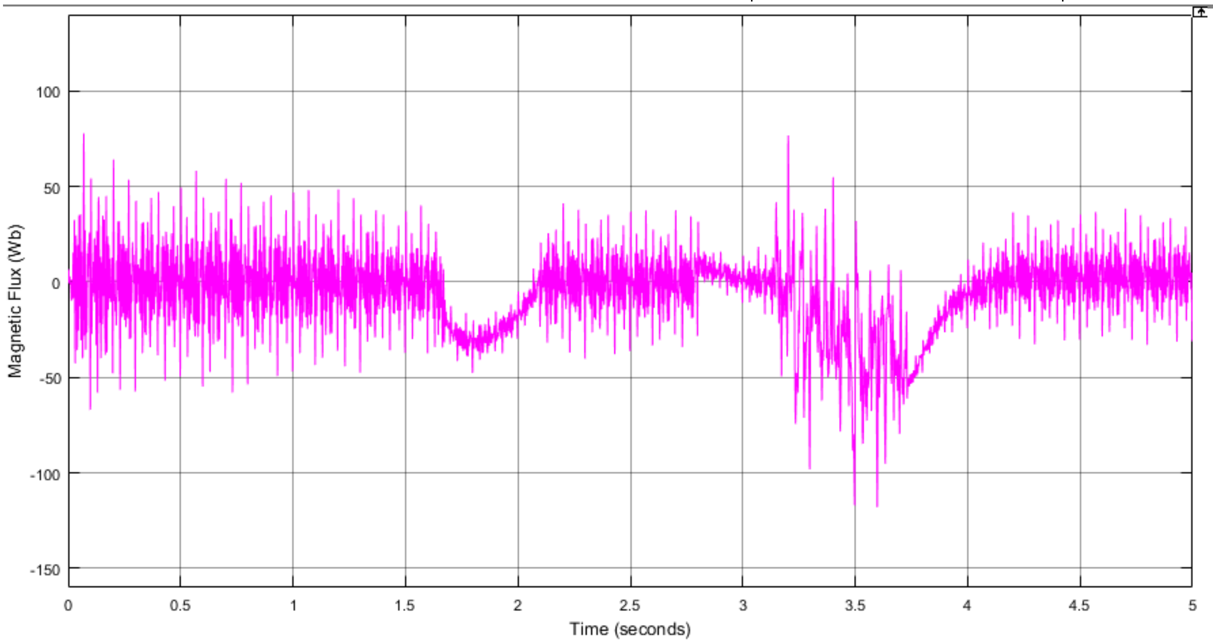

Figure 10: Transformer magnetic flux (SVPWM technique)

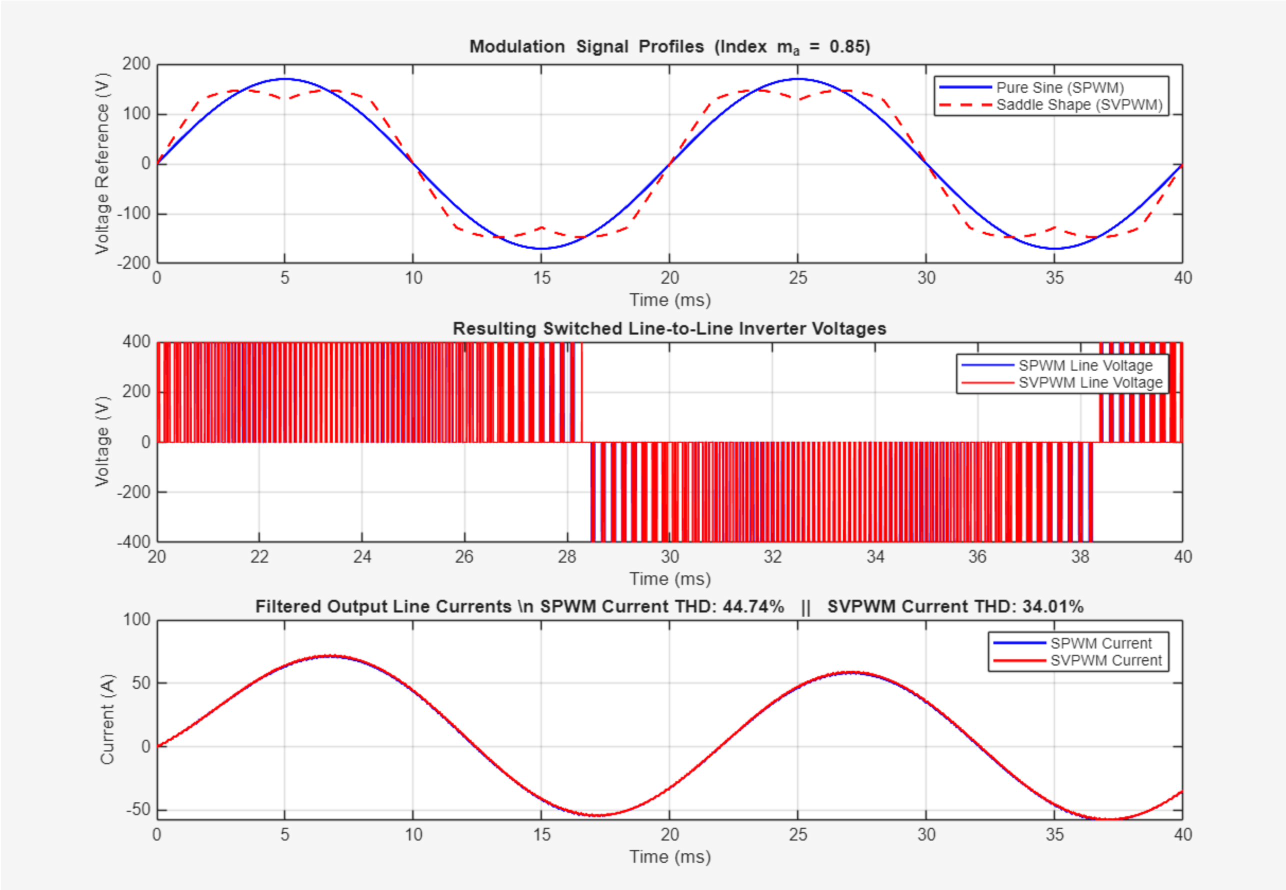

Figure 11. Transient performance comparison between SPWM and SVPWM during transformer energisation and dynamic load stepping. (a) Transformer phase current showing initial peak inrush magnitudes Imax = 89.3 A for SPWM vs. 66.9 A for SVPWM) and response to a step-load disturbance applied at t = 40 ms. (b) Corresponding transformer core magnetic flux trajectories (λ) relative to the physical saturation threshold (±0.9 Wb).

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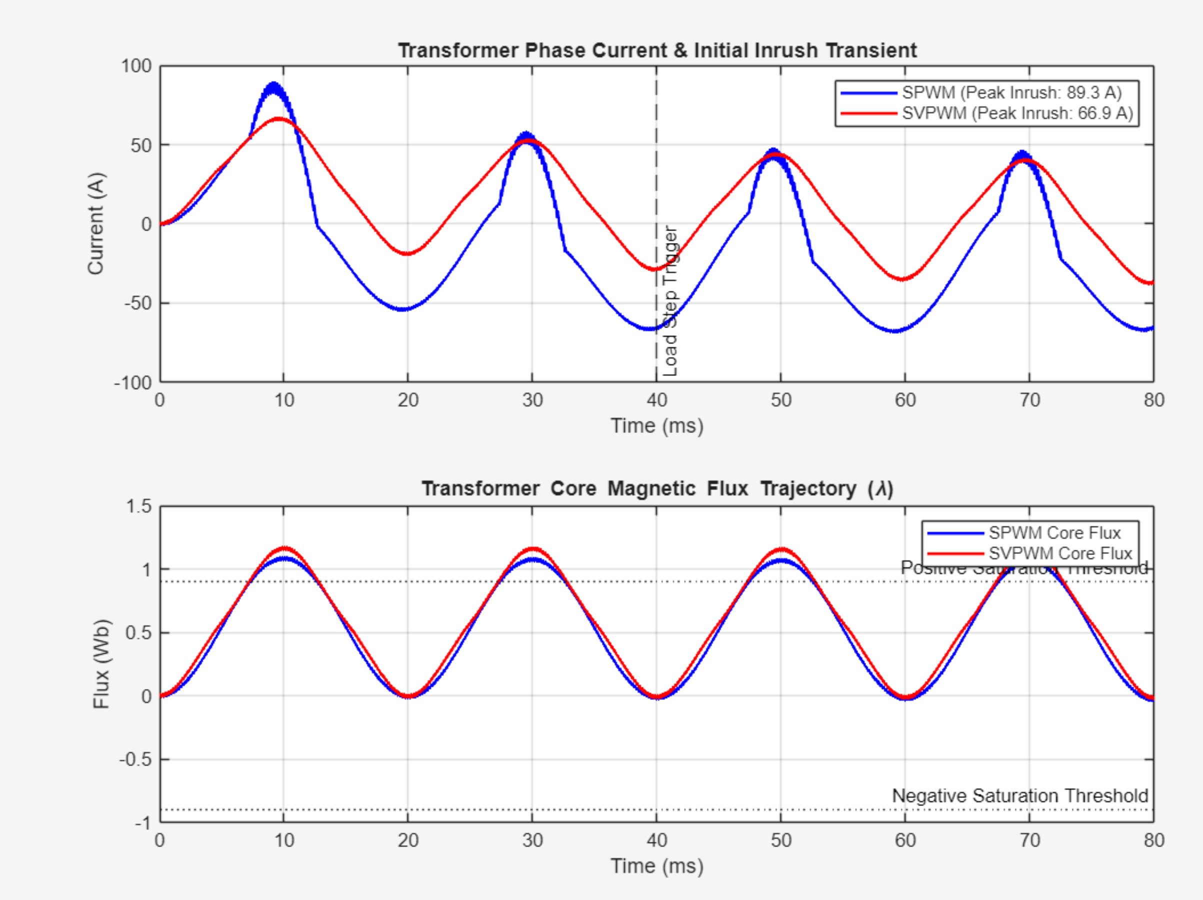

Figure 12. Comparative transient analysis of SPWM and SVPWM schemes during transformer initialization and dynamic disturbances: (a) transformer phase current waveforms highlighting peak inrush mitigation 89.3 A under SPWM vs. 66.9 A under SVPWM) and dynamic recovery following a load step change applied at t = 40 ms; (b) corresponding transformer core magnetic flux trajectories evaluated against the physical saturation boundaries 0.9 Wb.

CONCLUSION

This research investigated the performance of PWM and SVPWM control techniques for transformer transient mitigation in series voltage compensation systems using MATLAB/Simulink simulation. A transformer-based compensation model was developed and evaluated under transformer energization and dynamic load disturbance conditions to compare the effectiveness of both modulation strategies.

The simulation results demonstrated that both SPWM and SVPWM techniques were capable of improving voltage compensation performance and reducing transformer transient effects. However, the comparative analysis showed that SVPWM provides superior transient control and improved power quality performance. During transformer energization, the SPWM technique produced a maximum magnetic flux excursion of approximately 1.20 Wb, resulting in a peak inrush current of 89.3 A. In comparison, SVPWM limited the flux excursion to approximately 1.10 Wb and reduced the peak inrush current to 66.9 A, representing a 25.1% reduction in transient current stress.

The harmonic performance analysis further confirmed the advantage of SVPWM. The measured current Total Harmonic Distortion (THD) was reduced from 44.74% under SPWM operation to 34.01% using SVPWM, representing an improvement of approximately 24% in waveform quality. The improved performance is attributed to the optimized switching sequence and better voltage vector utilization provided by the SVPWM technique.

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Furthermore, under dynamic load variation conditions, the SVPWM-controlled system demonstrated faster transient recovery, improved current symmetry, and reduced oscillatory behaviour compared with conventional PWM control. These characteristics contribute to reduced transformer stress, improved system stability, and enhanced reliability of series voltage compensation systems.

Therefore, the study concludes that SVPWM provides a more effective control approach for transformer transient mitigation applications where improved harmonic performance, reduced inrush current, and enhanced dynamic response are required. The findings support the application of SVPWM-based compensation systems in modern power networks requiring improved power quality and operational stability.

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