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Effect of switching angle on transformer inrush current

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A B S T R A C T :

This project investigates the effect of switching angle on transformer inrush current using MATLAB/Simulink simulation. Transformer inrush current is a transient phenomenon that occurs when a transformer is energized, often reaching values several times higher than the rated current. One of the key factors influencing inrush current magnitude is the switching angle—i.e., the point on the AC waveform at which the transformer is switched on. In this study, a single-phase transformer model is developed in MATLAB/Simulink, and various switching angles (ranging from 0° to 180°) are analyzed to observe their impact on peak inrush current. The results demonstrate that switching at voltage zero-crossing (0° or 180°) leads to maximum inrush, while switching near peak voltage significantly reduces the inrush current. These findings are critical for the design of protection schemes and optimizing transformer energization processes in power systems. The simulation results are validated through waveform analysis and are presented to support the theoretical framework. This work offers insights into controlling inrush current by selecting optimal switching instants, contributing to more reliable and efficient transformer operation.

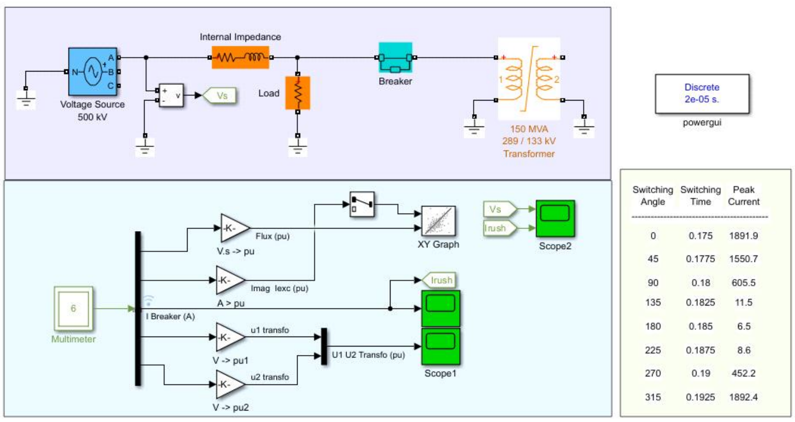
Introduction

Transformer inrush current is a significant transient phenomenon that occurs when a power transformer is energized. This sudden surge of current, which can be several times higher than the rated current, is mainly due to the residual flux and magnetizing characteristics of the transformer core. If not properly controlled, inrush current can lead to protection malfunctions, insulation stress, and even damage to transformer windings.

In this project, a MATLAB/Simulink model is developed to analyze how the switching angle at the moment of transformer energization affects the magnitude of inrush current. The system consists of a 150 MVA, 289/133 kV transformer connected to a 500 kV voltage source through internal impedance and a breaker. By varying the switching angle from 0° to 315°, the peak inrush current is recorded and analyzed for each case.

The simulation results clearly show that energizing the transformer at the zero-crossing of the voltage waveform (0° and 315°) leads to the highest inrush currents, reaching nearly 1900 A. On the other hand, switching near the voltage peak (around 135° to 225°) results in minimal inrush. These findings demonstrate the critical role of controlled switching in reducing transient stress and improving transformer lifespan.

Block Diagram



Switching Angle	Switching Time	Peak Current
0	0.175	1891.9
45	0.1775	1550.7
90	0.18	605.5
135	0.1825	11.5
180	0.185	6.5
225	0.1875	8.6
270	0.19	452.2
315	0.1925	1892.4

Construction and Working

- In this project, a MATLAB/Simulink model is designed to analyze the inrush current behavior of a power transformer when energized at different switching angles. The main components of the simulated power system include:
- Voltage Source (500 kV, 50 Hz): A three-phase AC voltage source represents the high-voltage transmission network supplying power to the transformer.
- Internal Impedance and Load: These blocks represent the source impedance and load conditions, respectively, contributing to realistic system behavior during switching.
- Circuit Breaker: A key element in this simulation, the breaker is used to energize the transformer at predefined points on the voltage waveform. The switching time is controlled to simulate different angles (0°, 45°, 90°, …, 315°).
- Power Transformer (150 MVA, 289/133 kV): The core component under study, the transformer is modeled with nonlinear magnetization characteristics to capture inrush phenomena accurately.
- Measurement Blocks: Current and voltage measuring devices are included to monitor inrush current, flux, and other signals, which are then displayed using scopes and XY graphs.

Working

- The simulation begins with the circuit breaker open, disconnecting the transformer from the high-voltage source. At a predetermined time (corresponding to a specific switching angle), the breaker closes, allowing current to flow into the transformer. Due to the nonlinearity of the transformer's magnetic core and the possible mismatch between the instantaneous supply voltage and residual flux, a large transient current (inrush current) flows.
- The circuit breaker is configured to close at various time instants (e.g., 0.175s, 0.1775s, etc.), each corresponding to a different point on the AC waveform (0°, 45°, …, 315°). The simulation measures the resulting peak inrush current for each case. As observed in the results, energizing the transformer near the voltage peak minimizes inrush current, while switching near voltage zero leads to a significantly higher current due to core saturation.
- This approach demonstrates how point-on-wave switching significantly affects transformer energization behavior and highlights the importance of choosing the right switching instant to reduce transient stress on power system equipment.

Simulation Results

To observe the effect of switching angle on transformer inrush current, the circuit breaker was configured to energize the transformer at specific angles: 0°, 90°, and 180°. The corresponding inrush current waveforms were recorded and analyzed.

• At 0° Switching Angle

The transformer was energized at the zero-crossing of the voltage waveform. The inrush current reached a peak value of approximately 1891.9 A. This high value is due to the mismatch between the instantaneous flux requirement and the residual flux in the transformer core, resulting in deep core saturation.

• At 90° Switching Angle

The transformer was energized near the peak of the voltage waveform. The resulting inrush current was significantly lower, with a peak value around 605.5 A. This demonstrates that energizing near voltage peaks minimizes the flux jump and hence reduces core saturation and inrush current.

• At 180° Switching Angle

Similar to the 0° case, the transformer was switched on at the negative zero-crossing. The peak inrush current again increased sharply to approximately 1892.4 A, confirming that switching at zero-voltage instants leads to maximum inrush.

These results are consistent with theoretical expectations and confirm that switching angle is a critical factor in controlling transformer energization transients.

Graphs and Figures

Figure 1: Inrush Current at 0° Switching Angle

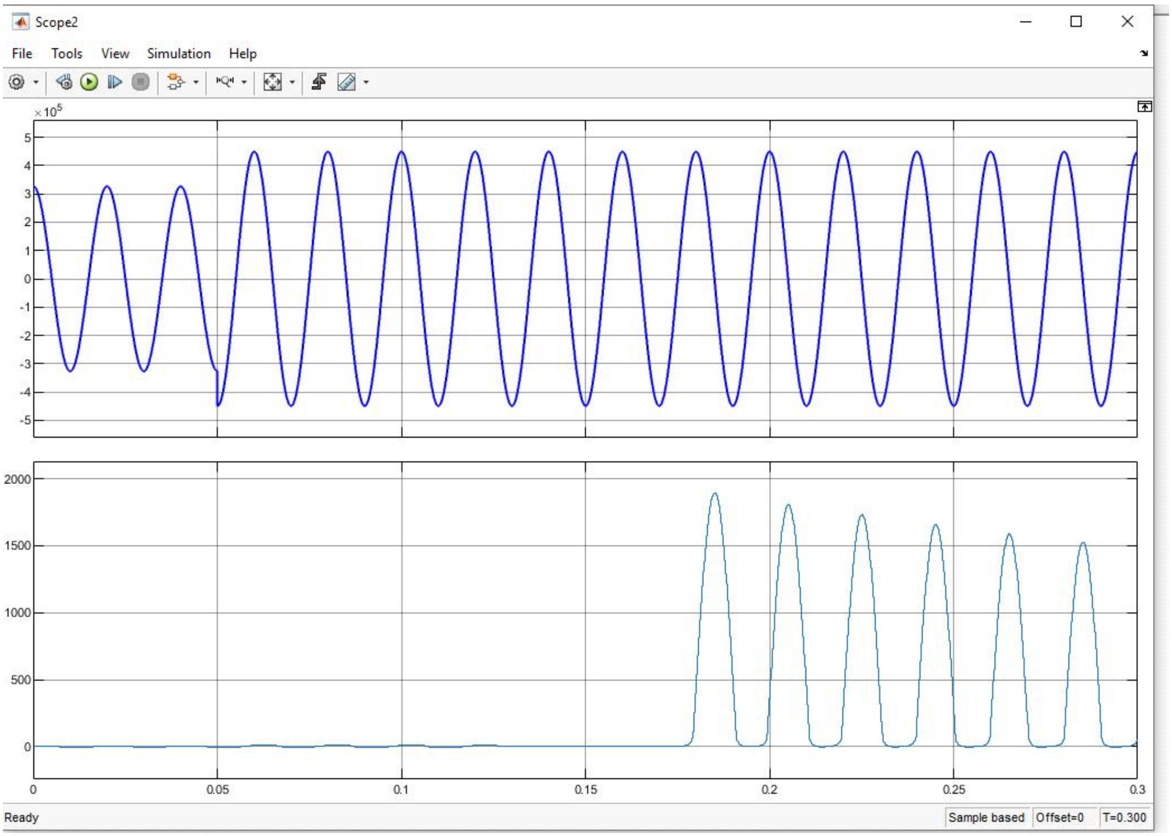


Figure 2: Inrush Current at 90° Switching Angle

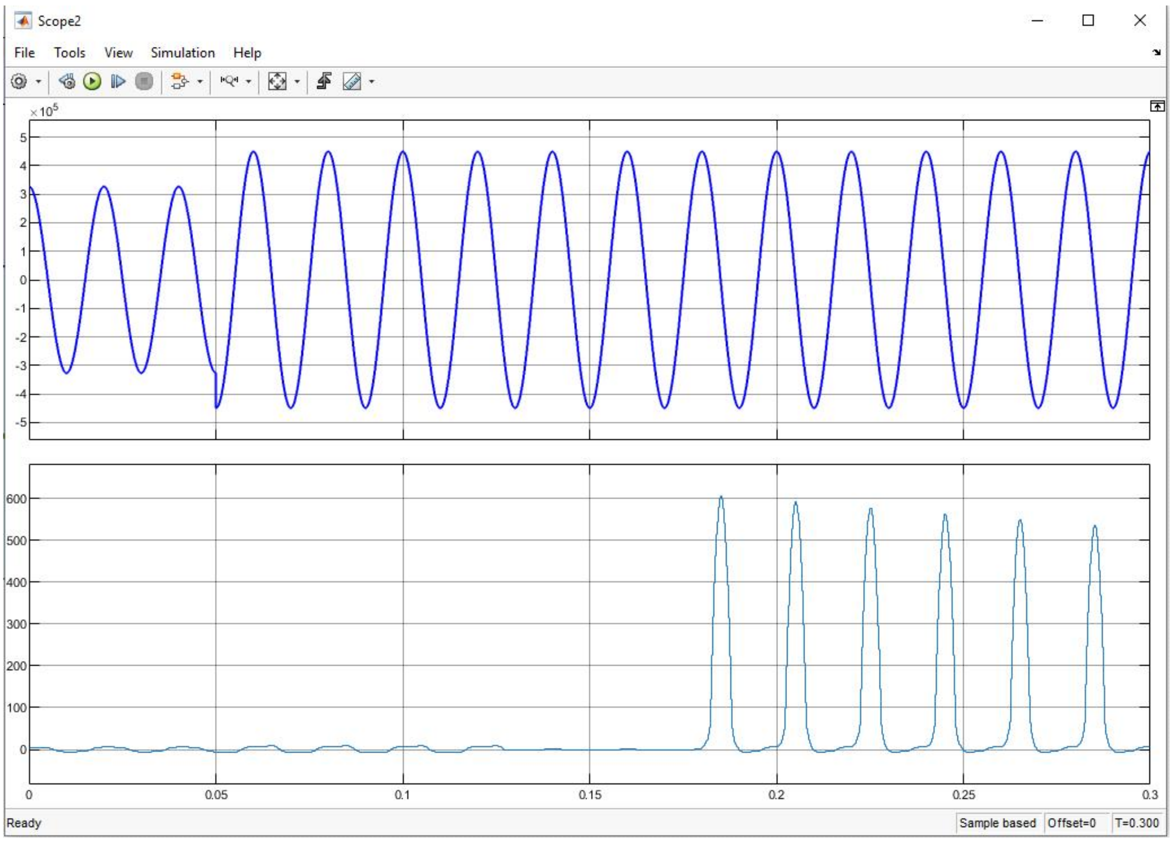
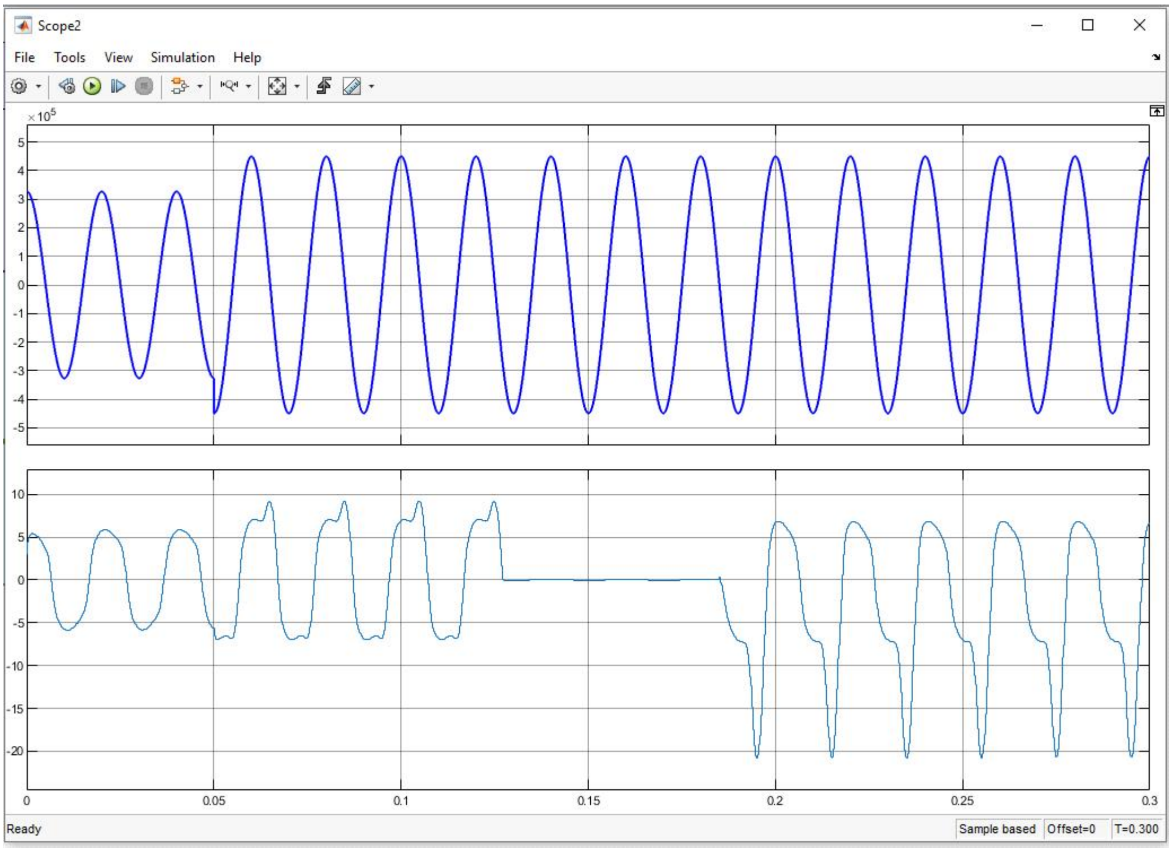


Figure 3: Inrush Current at 180° Switching Angle



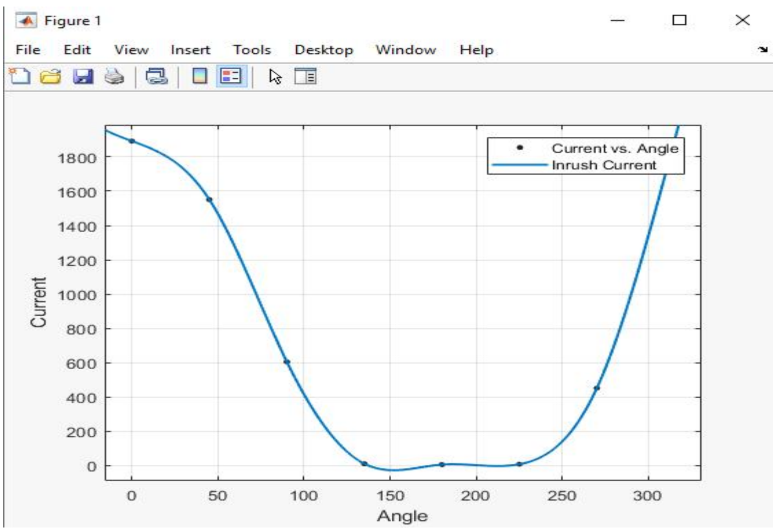
Conclusion

This project investigates the impact of switching angle on transformer inrush current through MATLAB/Simulink simulations. Contrary to common theoretical expectations, the simulation results show that the lowest inrush current occurs when the transformer is energized at 180°, while higher inrush values are observed at 0° and 90° switching angles.

These results indicate that in specific system conditions—such as initial flux, system impedance, and transformer saturation characteristics—the point of minimal inrush current may vary. The findings emphasize the importance of analyzing actual system behavior rather than relying solely on theoretical assumptions.

By identifying the optimal switching angle (180° in this case), inrush current can be significantly reduced, thereby improving system reliability, preventing nuisance tripping, and enhancing transformer lifespan. Future work may include analyzing the role of residual flux, using three-phase transformers, and implementing controlled switching logic for real-time applications.

Figure : Variation of Peak Inrush Current at Different Switching Angles



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