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Estimation of Reactive Power and Harmonics by Simulating a 12-Pulse Converter Power Supply for Tokamak Superconducting Coils

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Abstract: - Fusion experiments utilizing the Tokamak concept, which involves toroidal magnetic confinement, necessitate several magnet coils arranged in a specific configuration. For extended operations, superconducting coils emerge as the most economical choice due to their near-zero resistance and inductance values ranging from 2 mH to 1200 mH. These coils are capable of generating high magnetic fields with precisely profiled high direct current (DC). When selecting a power supply for the superconducting magnet coils, various configurations are available, and the decision is influenced by factors such as the requirement for high current with relatively low voltage DC output, the need for high ramp voltage versus low hold voltage, and the efficiency of converter devices. In this paper, we model the power supply for one of these superconducting magnet coils using MATLAB® and simulate it with Simulink®. This setup comprises a 12-pulse AC-DC converter equipped with an extended delta D(+150)y0-y6 converter transformer, an H3 bridge (a Half Bridge configuration featuring three thyristors arranged in a bridge setup within a three-phase system), and an Inter-phasing Reactor.

Keywords: Tokamak, Superconducting Coils, AC-DC Power Conversion, Rectifiers, Power Conversion Harmonics

I. INTRODUCTION

For fusion experiments utilizing the Tokamak concept, superconducting magnet coils must generate the required magnetic fields according to specific physics requirements. These experiments consist of two phases: the ramp phase and the flat top phase. During the ramp phase, direct current in the different Toroidal Field (TF) and Poloidal Field (PF) coils is gradually increased to predetermined values. In the flat top phase, the currents are maintained nearly constant and may last up to 1000 seconds, with the coil current profile for different pulses ranging from 5% to 100%. Furthermore, to ensure accurate shaping and position control of the plasma, the direct current supplied to the superconducting magnet coils must be precisely controlled.

To fulfill the power supply requirements for low-voltage, high-current direct current (DC) power supply for superconducting magnet coils, various configurations of AC-DC converters are employed. The choice of a specific configuration depends on factors such as dynamic performance, harmonic generation, and stability.

The conversion of alternating current (AC) to direct current (DC) introduces harmonics into the AC supply system. The load profile, which specifies the DC load current requirements of the TF and PF coils, varies significantly due to the fluctuations in plasma physics. Superconducting magnet coils exhibit high inductance values and nearly zero resistance. The coil current profile necessitates a higher voltage during the ramp phase compared to the hold phase. Given these parameters and characteristics, the behavior of the AC/DC power conversion and supply system is highly dynamic, making it challenging to analyze through analytical methods.

Moreover, since the system's behavior is very dynamic under different operating conditions, practical measurement of harmonics is often insufficient to determine an optimal harmonic filter solution for the system. Therefore, simulation emerges as the most suitable method for analyzing such a system, as various operating scenarios can be easily simulated, and the system's behavior can be effectively analyzed through accurate modeling.

The power supply for one specific superconducting magnet coil has been modeled using MATLAB® and simulated using Simulink®. This model features a 12-pulse AC-DC converter with an extended delta D(+150)y0-y6 converter transformer, half-bridge (H3) configured thyristors, and an interphasing reactor. The configuration has been selected to meet the system's requirements.

- High current output at low voltage.

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- High ramp up phase voltage as compared to hold phase voltage.
- Dynamic current balance between transformer windings.

To meet the rated current requirement of approximately 10 kA to 20 kA for the magnet coils, multiple thyristors are connected in a parallel configuration (referred to as a thyristor set) in actual systems. However, for simulation purposes, a single thyristor has been used in each phase leg.

The superconducting coils have resistance values in the range of nanohms (nΩ). The connecting busbars, cables, terminal connections, and other components are assumed to contribute a resistance of about 1 milliohm (mΩ). Therefore, the superconducting magnet coils have been modeled as an RL load with a resistance value of 1 mΩ.

The desired load profile for a typical magnet coil has been simulated to verify the performance of the model.

II. BASIC SCHEMATIC

The conversion of alternating current (AC) to direct current (DC) supply introduces harmonics into the AC supply system. The load profile, specifically the DC current requirements of the transformer (TF) and power factor (PF) coils, exhibits significant variation due to fluctuations in plasma physics. Superconducting magnet coils have high inductance values and nearly negligible resistance. Consequently, the coil current profile necessitates a higher ramp phase voltage in comparison to the hold phase voltage. Considering these parameters and characteristics, the operation of the AC/DC power conversion and supply system is highly dynamic.

The basic schematic of the AC-DC converter is depicted in Figure 1 below. It features two converter transformers: one with an extended delta (D(+150)) primary and two secondaries (one configured in y0 and the other in y6). The second transformer has an extended delta (D(-150)) primary with the same y0 and y6 secondary connections. This configuration yields a 12-phase secondary output voltage waveform, with a 30-degree phase displacement between successive phases.

Each secondary line connects to a set of thyristors (multiple thyristors arranged in parallel as needed for the rated capacity). The combined output voltage from one secondary winding parallels the outputs of the other three windings, resulting in a total of 12 thyristor sets associated with phase-shifted windings, thereby generating a 12-pulse output DC voltage waveform.

The positive terminal of the 12-pulse output DC voltage connects to the resistive-inductive (RL) load (the magnet coil), while the negative terminal is linked to the neutral terminals of the four secondaries through an interphasing reactor.

Load current control is achieved by adjusting the output DC voltage via the firing angle control of the thyristors.

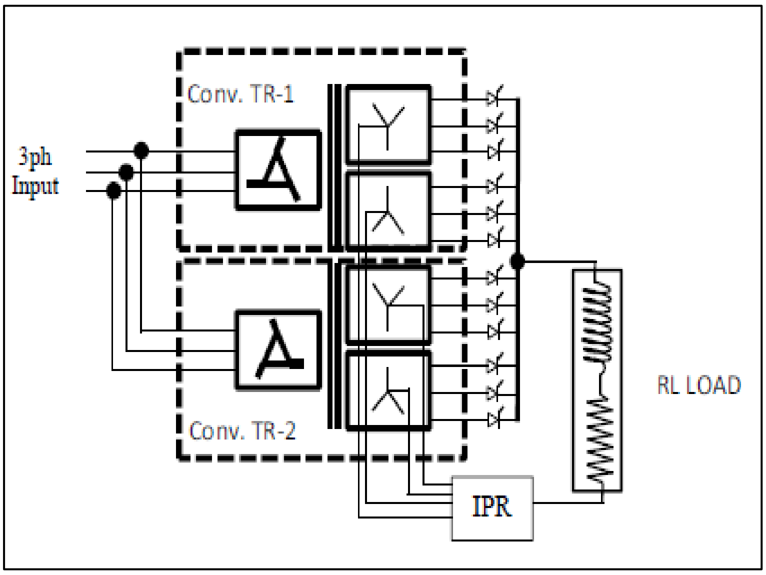

Fig. 1. Basic Schematic of the 12-pulse AC-DC Converter.

III. SIMULATION OF THE CONVERTER TRANSFORMER

The winding connection diagram for the extended delta D(+150)y0y6 connection is shown in Fig. 2.

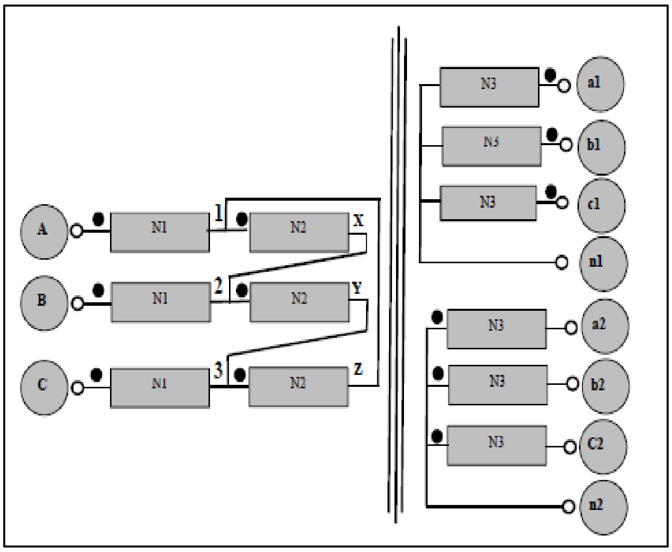

Fig. 2. Connection Diagram for Extended Delta Converter Transformer (D+15^0 y0 y6).

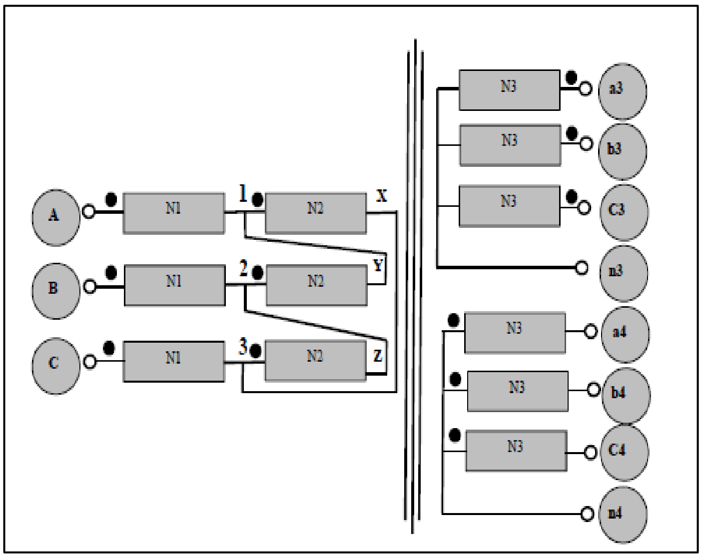

Fig. 3. Connection Diagram for Extended Delta Transformer (D-15^0 y0 y6)

As illustrated in Fig. 2, the primary winding consists of two sets of coils, with N1 and N2 turns per phase. The N2 coils are connected in a delta configuration and are then wired in series with the N1 coils. The secondary winding is configured in a wye arrangement with N3 turns per phase. This configuration is referred to as an extended-delta connection [2].

The winding connection diagram for the extended-delta D(-150)y0y6 connection is presented in Fig. 3. Additionally, the secondary voltage waveforms for each of the four secondary windings, along with their combined output, are displayed alongside the primary supply voltage waveform in Figs. 4a and 4b.

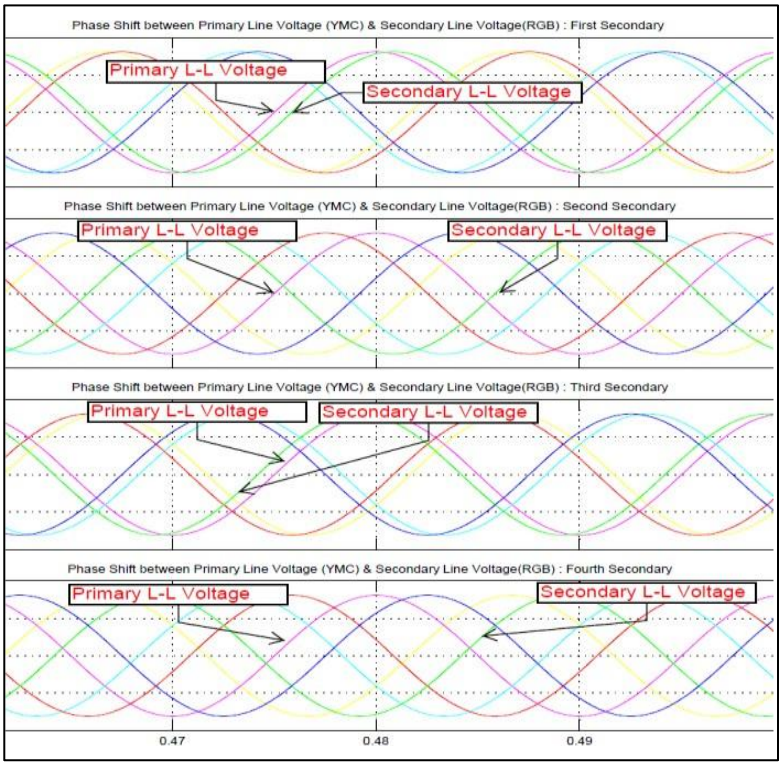

Fig. 4a. **Phase Shift between Primary Line Voltage and Secondary Line Voltage**

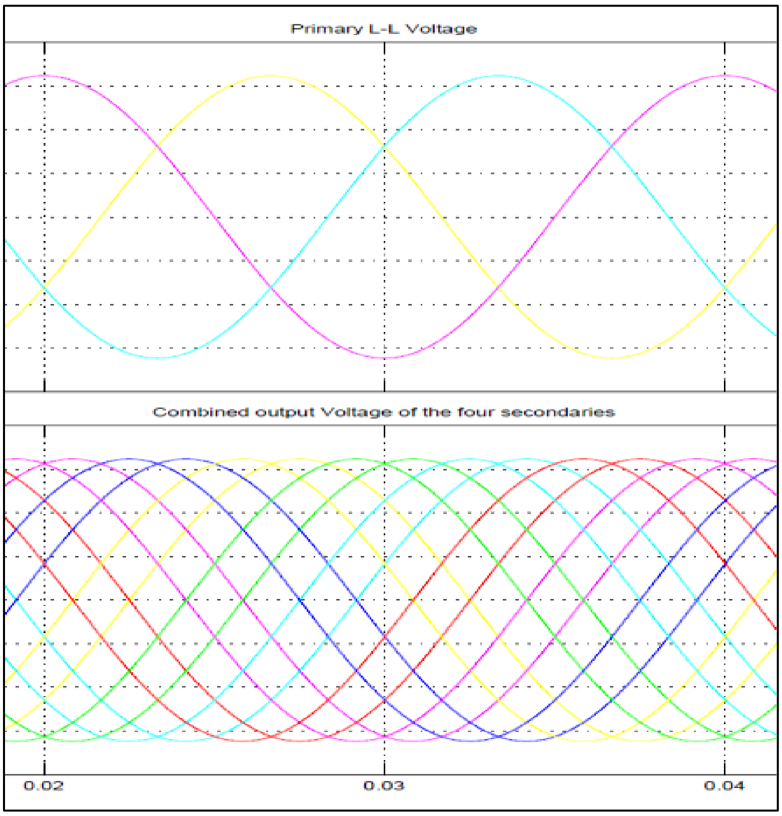

Fig. 4b. **Primary Line Voltage and Combined Secondary Voltage Waveform of the four secondaries**

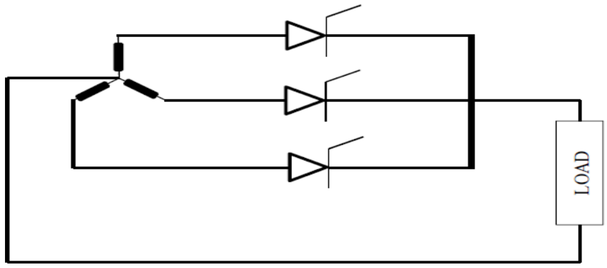

Fig. 5. Half Bridge (H3) Converter Configuration

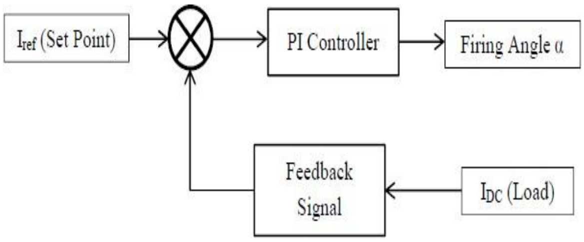

Fig. 6. Block Diagram of PI Controller

IV. SIMULATION OF THE HALF BRIDGE (H3) THYRISTORS

In a half-bridge configuration, each secondary phase is connected to a bank of thyristors. Therefore, three thyristor banks—one for each phase of the three phases of a single secondary—make up one set of half-bridge (H3) thyristors. A basic schematic of one H3 bridge linked to a secondary winding is shown in Fig. 5. Four such H3 thyristor sets (corresponding to the four secondaries) are connected in parallel.

Because the secondary voltage waveforms exhibit a 30-degree phase displacement between consecutive phases, synchronized firing pulses with a 30-degree phase shift between the various pulses should be applied to the gate terminals of the thyristors to achieve a 12-pulse output of DC voltage. The 'Synchronized 12-Pulse Generator' available in the Simulink® library has been utilized, with custom configurations tailored for this specific application.

V. SIMULATION OF INTERPHASE REACTOR

Interphase reactors are employed to manage AC voltage differences that exist between converter outputs, allowing the converters to function as though they are operating independently. However, these reactors do not assist in balancing the steady-state differences in DC voltage. The windings carry both DC and AC currents. Connections are arranged such that the DC currents flowing to the load create opposing ampere-turns on the core.

G. Park and S. I. Kim have provided a detailed analysis of multi-interphase transformers used for connecting power converters in parallel. Additionally, R.S. Bhide and S.V. Kulkarni have thoroughly discussed the modeling and analysis of two three-pulse controlled converters with interphase transformers.

VI. LOAD DC CURRENT CONTROL

To achieve controlled DC current for a load, a proportional-integral (PI) controller is utilized. This controller adjusts the firing angle of the thyristors, which results in a regulated output DC voltage, thereby controlling the load's DC current.

The feedback from the load current is fed into an error block, which compares it against a reference current set point. The resulting error signal is then processed by the PI controller. The output of the PI controller determines the firing angle (α) of the half-bridge thyristors. A block diagram of the PI controller is illustrated in Fig. 6 below.

The proportional gain (Kp) and integral gain (Ki) of the PI controller are configured to prevent any overshoot or undershoot of the load current.

VII. SIMULATION RESULTS

The desired load DC current profile for duration of 5sec, considered for simulation is shown in Fig. 7. The simulation results are shown in Fig. 8 to 10.

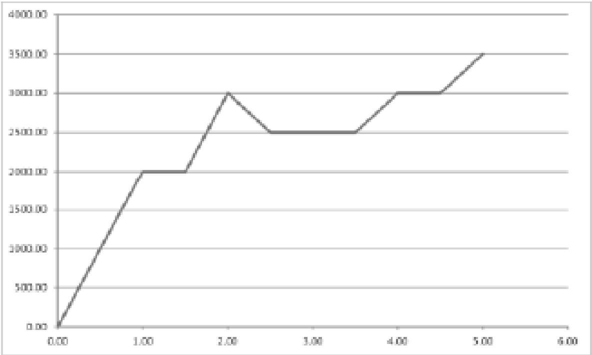

Fig. 7. Desired Load DC Current profile.

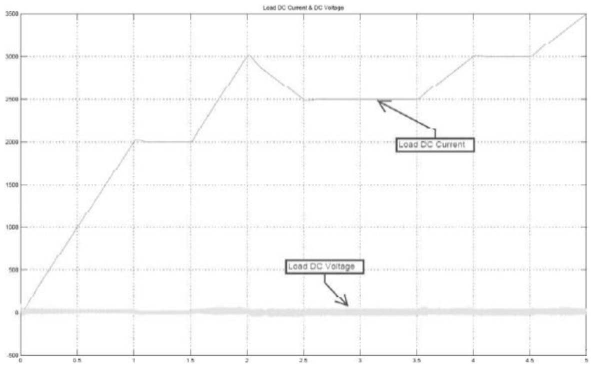

Fig. 8. Simulation Result for Load DC Voltage & Current

VIII. CONCLUSION

A 12-pulse AC-DC converter has been modeled and simulated using an extended delta D(+150)y0-y6 converter transformer with H3 thyristors and an interphasing reactor. The simulation results for the phase shift achieved in the converter transformer are presented. Additionally, the analyzed results include a desired load DC current profile and the supply line AC current. The harmonics generated in the supply line AC current showed a total harmonic distortion (THD) of 2.78%, which is well within the IEEE-519 limits. This MATLAB model will be used for further analysis of the harmonics generated by different superconducting poloidal field coils and toroidal field coils, with the aim of developing a comprehensive harmonic filtering solution and a consolidated dynamic VAR compensation scheme.

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