Impact of Zero-Sequence Susceptance on Protection Coordination in Non-Stabilized Star–Star Transformers

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Abstract— **This paper investigates transformer zero sequence susceptance (B_0), crucial for fault analysis and protection. Conventionally, B_0 and positive sequence susceptance (B_1) are presumed to be equal, particularly when a Delta connected winding is present, providing a path for zero sequence currents to circulate. However, post-fault analysis and field data from the Independent Power Transmission Operator (IPTO) reveal that solidly earthed Star–Star transformers without a stabilizing Delta tertiary exhibit B_0 values multiple times higher than B_1. This anomaly significantly increases zero sequence currents during ground faults, challenging conventional assumptions and affecting relay coordination and protection settings. Using analytical magnetic circuit modeling and transformer Factory Acceptance Test (FAT) data, the study quantifies B_0 and identifies contributing magnetic flux paths through the core and external steel of the transformer. Simulations validate these findings, emphasizing the importance of transformer winding configurations in system modeling and protection design.**

***Index Terms*--zero-sequence susceptance, transformer modeling, magnetic circuit analysis, ground fault protection.**

I. INTRODUCTION

The accurate representation of transformer sequence parameters is fundamental to reliable power system analysis, particularly in protection, stability, and fault studies. Among these, the zero-sequence impedance and susceptance play a decisive role in determining system behavior during unbalanced or ground fault conditions, influencing both the magnitude of fault currents and the selectivity of protective relays [1], [2]. Classical theory and several benchmark studies generally assume that the zero-sequence magnetizing susceptance B_0 is approximately equal to the positive-sequence susceptance B_1, especially for transformers featuring a delta-connected winding that provides a closed path for zero-sequence currents [3], [4]. This assumption has been widely adopted in analytical models, short-circuit studies, and network simulation tools utilized by utilities and equipment manufacturers [5], [6].

Recent field investigations by IPTO (Transmission System Operator of Greece), however, reveal significant deviations from these theoretical expectations. In particular, solidly grounded Star–Star (Y–Y) power transformers without a stabilizing delta tertiary winding have shown zero-sequence susceptance values several orders of magnitude higher than B_1, with recently calculated ratios from IPTO ranging from 800 to 9600. This observed behavior diverges sharply from traditional transformer models and carries important implications for fault studies, residual current magnitudes, and relay coordination [7]-[9]. This paper systematically investigates this anomalous behavior through analytical derivation, magnetic circuit modeling and simulation-based validation using transformer Factory Acceptance Test (FAT) data. The research identifies the electromagnetic and structural mechanisms to unusually high B_1 in non-stabilized Y–Y (or Y-Y-Y) transformers and underscores the need to revisit traditional modeling assumptions in protection studies.

The paper is organized as follows: Section II introduces the theoretical framework of transformer sequence networks. Section III details the analytical derivation of zero-sequence susceptance. Section IV presents simulation results and field case studies from the Greek transmission system that demonstrate the examined problem and solution. Section V concludes with key findings and recommendations.

II. BACKGROUND AND THEORETICAL FRAMEWORK

A. Transformer Sequence Networks

In symmetrical component analysis, transformer behavior under unbalanced or ground fault conditions is represented using positive, negative, and zero-sequence networks. For balanced three-phase transformers, positive and negative sequence networks are generally similar, reflecting balanced flux distributions within the core. In contrast, the zero-sequence network represents the system's response to homopolar currents flowing simultaneously in all phases with identical magnitude and phase angle [1], [2].

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The presence or absence of a delta winding critically affects zero-sequence current flow. In grounded Y–Δ transformers, zero-sequence currents can circulate within the delta, providing a low-impedance internal return path. Conversely, in Y–Y transformers lacking a delta winding, the zero-sequence flux must traverse the external path —including neutral grounding and surrounding system components—producing markedly different impedance characteristics [3], [4]. The same principle applies also for 3-winding transformers in Y-y-y connection, without a delta winding.

B. Zero-Sequence Magnetizing Susceptance B_0

Conventional transformer models assume that the zero-sequence magnetizing susceptance B_0 is approximately equal to the positive-sequence susceptance B_1, i.e., $B_0 \approx B_1$, an assumption embedded in industry standards such [3], [4] and applied in commercial analysis tools.

The magnetizing susceptance under open-circuit conditions is given by:

$$B = \frac{I_{OC}}{3V_{OC}} \tag{1}$$

where I_{OC} is the open circuit test current and V_{OC} is the rated per-phase voltage [8]. Under balanced excitation, this corresponds to the core's per-phase magnetizing admittance. For simplicity, the resistive part of the core admittance is ignored. For zero-sequence excitation, admittance Y_0 and consequently susceptance B_0 is measured by energizing all three phases in parallel to observe the flux path through the core and transformer external steel (tank, clamp).

C. Implications for Protection and System Studies

Incorrectly assuming $B_0 \approx B_1$ in system models leads to significant underestimation of zero-sequence currents during ground faults. This can cause relay miscoordination, delayed fault clearance, or loss of selectivity. Accurate representation of B_0, derived from factory or field measurements, is therefore essential for reliable protection design and system studies.

III. Mathematical Derivation and Analytical Modeling

A. Equivalent Magnetic Circuit Representation

For a core transformer without a delta tertiary, equal zero-sequence voltages on all windings generate magnetomotive forces (MMFs) that do not cancel within the core. The resulting flux is forced to return through external steel parts, such as the tank and clamps, forming a higher-reluctance path. The equivalent magnetic circuit is thus represented by a series combination of the core and external reluctances, where the total zero-sequence flux traverses through these low-permeability paths as follows:

$$\mathcal{R}_m = \mathcal{R}_c + \mathcal{R}_t \tag{2}$$

where $\mathcal{R}_c$ is the core reluctance, $\mathcal{R}_t$ the external steel return path reluctance and $\mathcal{R}_m$ the equivalent magnetic reluctance.

B. Derivation of Zero-Sequence Susceptance

For a magnetic circuit excited by flux Φ and turns N, the magnetizing susceptance is:

$$B = \frac{\mathcal{R}_m}{\omega N^2} \tag{3}$$

where ω is the angular frequency.

Hence, for the zero- and positive-sequence components respectively:

$$B_0 = \frac{\mathcal{R}_c + \mathcal{R}_t}{\omega N^2} \tag{4}$$

$$B_1 = \frac{\mathcal{R}_c}{\omega N^2} \tag{5}$$

yielding the ratio:

$$\frac{B_0}{B_1} = \frac{\mathcal{R}_c + \mathcal{R}_t}{\mathcal{R}_c} \tag{6}$$

Hence, the greater external path reluctance $\mathcal{R}_t$ ($\mathcal{R}_t \gg \mathcal{R}_c$) in series with the core reluctance $\mathcal{R}_c$ increases the core susceptance B_0 for the zero sequence equivalent circuit—consistent with field measurements indicating greatly high B_0/B_1 ratios.

C. Estimation from Factory Acceptance Test (FAT) Data

In practice, B_0 is obtained from open-circuit tests under zero-sequence excitation, as also given in (1), where I_0 and V_0 are the measured zero-sequence current and voltage, respectively. The resistive component of the magnetizing admittance is typically neglected, allowing the approximation $Y_0 \approx jB_0$.

These experimentally derived B_0 values, when incorporated into simulation models, closely reproduce measured ground-fault responses and ensure accurate relay coordination in practical systems.

IV. Simulation Results and Case Studies

A. Simulation Framework and Data

The simulations were conducted on a representative model of the Hellenic Interconnected System (HIS), concentrating on the electrical vicinity of the VETTA substation (S/S), as illustrated in Fig. 1. In this configuration, the VETTA S/S is directly interconnected with the EPVA S/S through its nearest remote bus, while the EPVA S/S is further coupled to the KAVALA S/S. The main transformer installed at VETTA is a 150 kV/20 kV three-winding unit with Y–y–y connections and no delta (tertiary) winding. On the medium-voltage (20 kV) side, several photovoltaic (PV) generator feeders are connected, representing typical renewable integration in the Greek grid.

Since the focus of this study is the transformer's zero-sequence behavior, detailed line and feeder parameters are omitted, as they exert minimal influence on the investigated phenomena. The emphasis lies on understanding the unusually high zero-sequence susceptance (B_0) of this transformer configuration and assessing its consequences on fault current

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magnitudes and protection coordination. It should be noted at this point that all simulations were performed with ASPEN OneLiner power system analysis software [16].

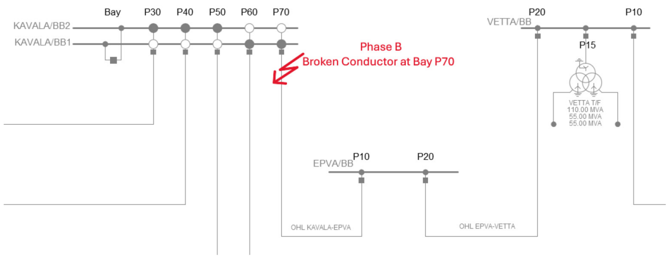

Figure 1. Single-line diagram of the examined VETTA–KAVALA substation area model.

The electrical and magnetic parameters of the transformer under study—including rated values, impedance, and magnetizing branch characteristics—are summarized in Table I. The same table also provides the calculated and measured values of the positive- and zero-sequence susceptances (B_1 and B_0, respectively), obtained using the methodology of Section III-C and verified against the Factory Acceptance Test (FAT) results. The measurements confirm that this non-stabilized Y–y–y transformer exhibits an exceptionally high ratio of B_0/B_1, aligning closely with the FAT observations.

TABLE I. ELECTRICAL AND MAGNETIC PARAMETERS OF THE EXAMINED TRANSFORMER (WITHOUT DELTA WINDING).

Description	***Symbol / Unit***	***Value***	***Remarks***
Rated Power	S_n [MVA]	110 / 55 / 55	(HV/MV1/MV2)
Rated Voltage	V_n [kV]	150 / 20 / 20	(HV/MV1/MV2)
Vector group	-	Y–y–y	No delta winding
Frequency	f [Hz]	50	Greece
Short-circuit impedance	$u_{k\_(HV\text{-}MV1)}$ [%]	15.42	(on 55 MVA base)
Short-circuit impedance	$u_{k\_(HV\text{-}MV2)}$ [%]	15.63	(on 55 MVA base)
No-load current	I_{CL} [%]	0.10	% of I_{rated}
Load losses (at 75 °C)	P_L [kW]	348.09	I^2R + stray losses
Posit.-sequence susceptance	B_1 [p.u.]	-0.00101	Section III, FAT
Zero-sequence susceptance	B_0 [p.u.]	-0.83816	Section III, FAT

B. Real System Field Case Study and Fault Response: 150/20/20 kV Transformer (Y-y-y) without delta winding

A real event recorded in July 2025 provided practical confirmation of the analytical findings regarding elevated zero-sequence susceptance. The case involved a 150/20/20 kV Y–y–y transformer operating without a delta tertiary winding, which produced zero-sequence currents approximately 125 times higher than the values predicted by standard transformer models. Subsequent offline measurements and analysis indicated a B_0/B_1 ratio of roughly 800, aligning closely with the theoretical expectations discussed in previous sections.

Specifically, as illustrated in Fig. 1, on July 3, 2025, at 14:00:11.270 (GMT+3), a fault occurred near the Kavala Substation. The incident involved a conductor detaching from its support structure at gate P70, meeting the ground and creating a single line-to-ground (SLG) fault on phase B. As anticipated, the bus differential protection of the Kavala substation operated immediately, tripping all associated feeders (P70, P30, P100, P60, P40, P15, P50, and P25) after approximately 300 ms, according to the relay logs and Sequence of Events (SOE) data.

During this same interval, however, the P15 feeder at the VETTA substation also tripped, only 150 ms after the fault inception, even though no fault was expected within its protection zone. This unexpected tripping prompted further investigation to determine the underlying cause.

Table II presents the relevant earth-fault overcurrent protection (ANSI 51N) settings that were active during the incident. The ground overcurrent relay settings of P15 were set to operate at 400 A ($3I_0$) with a 100 ms delay.

TABLE II. P15 EARTH-FAULT OVERCURRENT PROTECTION SETTINGS OF VETTA SUBSTATION

Pickup Current (A)	***Time Delay (s)***	***CT Ratio***
1.00	0.100	400:1

The COMTRADE records obtained from the P15 relay are shown in Fig. 2. Approximately 5 ms after the occurrence of the fault, the zero-sequence current (IG or equivalently $3I_0$) rapidly increased to around 500 A (orange curve), initiating the relay operation (50G1P). The trip command was issued roughly 105 ms later and physically executed 45 ms after that, i.e., at 14:00:11.425, approximately 100 ms before the Kavala bus differential protection completed its own tripping action.

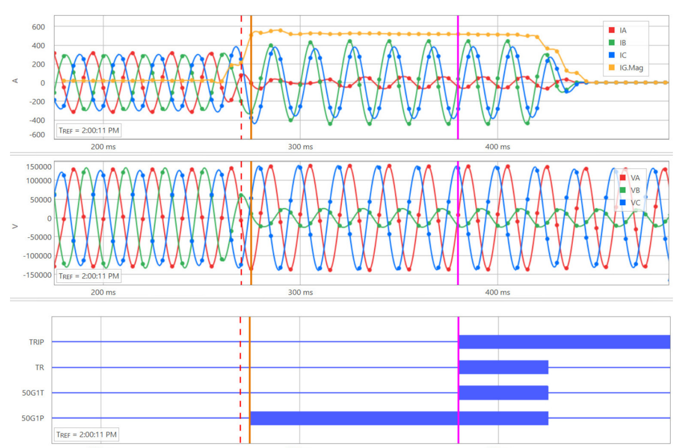

Figure 2. COMTRADE waveform of relay P15: zero-sequence current and trip timing.

To validate the observation, the same fault scenario was simulated using ASPEN OneLiner. When assuming B_0=B_1, as commonly adopted in literature and conventional system studies, the simulated zero-sequence current at P15 was merely 4.00 A — i.e. 125 times lower than the actual recorded value. This discrepancy explains why the original protection

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coordination study, based on standard assumptions, underestimated the ground fault current magnitude and consequently misconfigured the relay settings.

After recalculating and updating the B_0 value according to the analysis presented in this paper, the simulation of the single earth fault on phase B in Kavala S/S (P70) produced a ground current of 488 A, as shown in Fig. 3. Thus, the updated B_0-based model reduced simulation error to less than 3.0% (measured 502A). This result strongly validates the revised modeling approach and demonstrates the critical importance of accurate zero-sequence susceptance representation (B_0) for protection coordination and fault response studies.

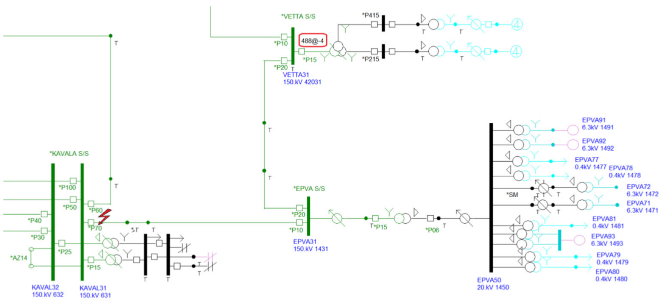

Figure 3. ASPEN simulation zero-sequence current at relay P15 (fault on phase B in KAVALA S/S).

C. System-Wide Assessment of Y–y and Y–y–y Transformers Without Delta Winding

TABLE III. ELECTRICAL AND MAGNETIC PARAMETERS OF THE MAIN HV/MV STAR–STAR (OR STAR-STAR-STAR) POWER TRANSFORMERS WITHOUT DELTA WINDING OF THE HELLENIC TRANSMISSION SYSTEM

Substation	***Parameter***				
	Rated Power [MVA]	**Voltage [kV]**	**B_1 [10^{-3} p.u.]**	**B_0 [p.u.]**	**B_0/B_1 ratio**
AHS AMYNTAIO	340/170/170	400/33/33	-0.59	-4.7784	8092
AHS KARDIA	340/170/170	400/33/33	-0.68	-54.400	8000
FYTEIES	110/50/60	150/20/20	-0.96	-0.7835	816
KYT ACHARNES	50	150/20	-0.39	-0.3590	923
KYT AGIOS STEFANOS	50	150/20	-0.32	-0.3043	951
KYT DILOFO	250/125/125	400/33/33	-0.58	-5.1255	8837
KYT KOZANIS	250/125/125	400/33/33	-0.33	-3.1813	9640
KYT MOUZAKI	100/50/50	400/20/20	-2.16	-1.7302	800
KYT PROCHOMA	340/170/170	400/33/33	-0.56	-5.0281	8986
KYT SKOPIAS	250/125/125	400/33/33	-0.58	-5.1255	8837
KYT VERMIO	175/87.5/87.5	400/33/33	-0.78	-4.6573	5971
LAVRIO	50	150/20	-0.53	-0.5093	970

The afore-mentioned analysis was extended to the main Y-y and Y–y–y power transformers operating within the Hellenic Interconnected System (HIS) that lack a delta (tertiary) winding. The assessment incorporated data from factory acceptance tests (FAT) and updated network models provided by IPTO. As seen in Table III, in nearly all examined cases the transformers exhibited zero-sequence susceptance (B_0) values significantly higher than those assumed in conventional studies, with B_0/B_1 ratios ranging between 800 and 9600, depending primarily on the magnetic core geometry and residual flux conditions.

Simulations confirmed that neglecting these values results in ground-fault current underestimation by multiple orders of magnitude, leading to potential miscoordination of earth-fault protections. Incorporating corrected B_0 values reduced the simulation-to-measurement deviation to below 5%, validating the generalized approach.

Based on these findings, IPTO has initiated a system-wide update of its database (ASPEN OneLiner and DIgSILENT PowerFactory) to reflect accurate zero-sequence parameters for all Y–y and Y–y–y transformer models, ensuring improved reliability of protection studies and contingency analyses across the Greek transmission network.

V. CONCLUSIONS AND RECOMMENDATIONS

Star–Star (or Star-Star-Star) grounded transformers without delta tertiary windings exhibit anomalously high B_0, often 800–9600 times higher than B_1. This arises from the zero-sequence magnetic flux path through the tank of the transformer. Analytical derivation, FAT data and simulations confirm the phenomenon.

These findings have significant implications for protection studies: inaccurate zero-sequence modeling may lead to miscoordination or loss of selectivity. It is therefore recommended to incorporate measured B_0 values in protection studies, explicitly account for magnetic flux paths through the core and structural steel of the transformer, and include delta tertiary windings where possible to ensure stable zero-sequence flux paths ($B_0 \approx B_1$).

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