

Article

Frequency Scanning-Based Dynamic Model Parameter Estimation: Case Study on STATCOM

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Abstract: The integration of power electronic equipment with complex internal structures, which are represented by switching elements or black-box models, is increasing because of the growing penetration of renewable energy into the power grid. The increase in model complexity causes greater computational workload and presents challenges for grid stability analysis. To address this issue, this paper proposes a method for estimating the parameters of a simple generic model capable of emulating the dynamic behavior of complex power-electronic models. For the estimation, the frequency scanning method is utilized, involving the injection of various frequency inputs into the complex model. The responses obtained are then utilized in the optimization process as the objective function. The use of frequency scanning is reasonable because it can cover a wide frequency range, thus comprehensively capturing the dynamic properties of the model. The optimization process aims to minimize the difference in responses to frequency scanning between the complicated and simple generic models. The accuracy of the generic model with estimated parameters is verified by Bode plot comparison and time-domain simulations. Simulation results demonstrated that the generic model, optimized via parameter estimation using the frequency scanning method, accurately replicated the response of the reference model, particularly in the low-frequency range. The proposed method allows for the integration of power electronic equipment, which may represent switching-based components or lack internal information, into stability analysis using existing power-system analysis tools.



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Keywords: dynamic response equivalent; parameter estimation; frequency scanning; small signal analysis

1. Introduction

In recent decades, the integration of power electronic devices has significantly increased owing to the widespread adoption of DC devices, such as inverter-based renewable energy sources and high-voltage direct current systems, in power networks [1–6]. The dynamic modeling of these power electronic devices is inherently complex, involving numerous dynamic equations, unlike traditional synchronous generators. Additionally, these DC devices exhibit high-frequency operating characteristics due to solid-state switches. Consequently, simulations of such models are primarily conducted using electromagnetic transient (EMT) simulation tools, which provide results closely approximating real-world operations. However, performing stability analyses in large networks with these devices using EMT tools is challenging because of the substantial computational burden [7,8]. Therefore, for analyzing large systems, it is more practical to conduct transient stability analysis (TSA) first [9]. Furthermore, power electronic devices are often provided as

black-box models, which conceal internal operating structures for technical security reasons [10]. This lack of internal information limits the application of other system analysis tools, including small signal analysis (SSA), which linearizes complex system models at the operating point and analyzes the eigenvalues to determine stability. Thus, simplifying power-electronic-device models for use in TSA and SSA tools becomes a critical research question.

The model order reduction (MOR) method has been previously studied to address the aforementioned challenges [7,8]. The MOR method simplifies complex power-electronic-device models by eliminating dynamics with minimal influence on desired behavioral characteristics, typically fast dynamics. This reduction reduces computational demand and the time required for stability analysis. The MOR method is categorized into three types: polynomial approximations, state truncations, and parameter optimizations [8]. The first two methods reduce the model order by discarding dynamics with negligible effects on the response of interest. Conversely, the parameter optimization method seeks to optimize the parameters of a simplified model so that it closely replicates the response of the original device. The method presented herein falls under the parameter optimization category. Relevant work has been conducted on a technique known as optimization-enabled electromagnetic transient simulation (OE-EMTS) [11–14]. This approach optimizes the model by measuring the response of the power electronics system to specific contingencies, facilitating the limitation of dynamic responses even when the device is presented as a black box.

The method of generating reduced-order models by polynomial approximation or state truncation is only applicable if the internal structure of the power electronics model is accessible [7,8]. By contrast, parameter optimization approaches do not require detailed internal information and can be implemented with a black-box model because they only require the time-domain simulation outcomes. However, the results of such an optimization can converge to a local minimum, which closely mimics the response only under the conditions assumed for the simulation and may not be as effective for other scenarios. To address the local-minimum problem, various solutions have been proposed, including incorporating a range of test scenarios during the optimization process. For instance, in [11], both external disturbances and changes in internal setpoints were included in a single simulation for optimization. Nonetheless, this approach is not foolproof because the criteria for defining a comprehensive range of scenarios remain vague. As another example, studies have been conducted to measure the impedance (or admittance) of a system containing a black-box model at various frequencies and assess system stability based on the corresponding transfer function. This study adopts the frequency scanning technique from [15], which will be described in detail later. However, since this method relies on transfer function-based stability analysis, its effectiveness depends on the measurement location of the impedance, potentially leading to variations in stability assessment results.

This paper presents a frequency scanning-based model parameter estimation method for complex power electronics components. Frequency scanning can be performed by inserting a series voltage source or a parallel current source at the connection point between the equipment and the grid. Signals of different frequencies are injected through the inserted source, and the proposed method utilizes the equipment response for parameter estimation. The objective is to create a simple generic model that mimics the behavior of the reference model by minimizing the difference between the responses of the reference and generic models to frequency scanning. This response can include dynamic characteristics over wide frequency ranges, in contrast to prior studies that typically utilize the device response to specific contingencies. For these reasons, this approach can be a superior alternative for parameter estimation. Furthermore, because the frequency scanning method

is measurement based, it enables the estimation of parameters of a generic model even if the equipment to be simplified is provided as a black-box model. For validation, the proposed method is applied to a static synchronous compensator (STATCOM) model. The accuracy is verified by comparing the Bode plots and time-domain simulations of the reference and generic models. To further validate the applicability of the proposed method to EMT black box models represented as switching elements, the same process was performed using such models as reference models. To evaluate how accurately the model with parameters estimated by the proposed method replicates the complex model, three-phase faults were applied to both models, and their time-domain responses were compared.

The remainder of this paper is organized as follows: Section 2 describes the proposed method, which uses the model response to frequency scanning as the objective function for the optimization algorithm. Section 3 presents the validation of the proposed method by Bode plots comparison and time-domain simulations between the reference and optimized generic models. Finally, the conclusions are summarized in Section 4.

2. Proposed Method

Frequency scanning, a technique inspired by the impedance-based method [15–19], is known for its effectiveness in analyzing system stability coupled with power electronic models. This technique, illustrated in Figure 1, involves configuring a system with a series voltage source or a parallel current source inserted at the grid connection point of the target device. A signal with varying frequency is then injected through this source. Block diagrams illustrating such systems are depicted in Figure 2. From Figure 1, the system transfer function for the injected signal and the corresponding system response can be derived as (1) and (2):

$$\frac{V_{res}}{I_{inj}} = \frac{Z_1(s) \cdot Z_2(s)}{Z_1(s) + Z_2(s)} = \frac{Z_1(s)}{1 + Z_1(s)/Z_2(s)}, \quad (1)$$

$$\frac{I_{res}}{V_{inj}} = -\frac{1}{Z_1(s) + Z_2(s)} = -\frac{1/Z_2(s)}{1 + Z_1(s)/Z_2(s)} \quad (2)$$

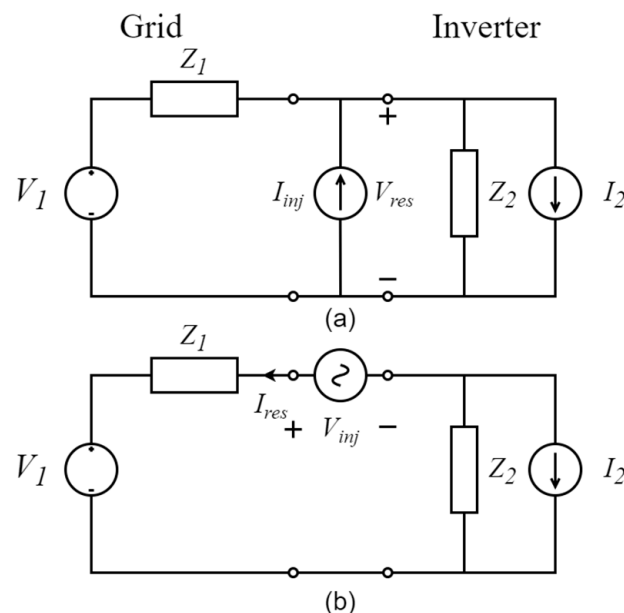


Figure 1. Equivalent circuit for frequency scanning with (a) a shunt current source and (b) a series voltage source [15,17].

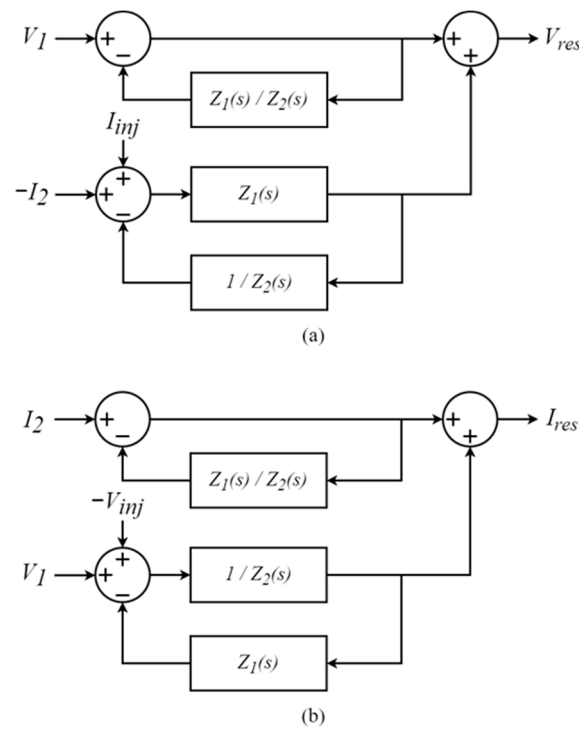


Figure 2. Block diagrams of the systems in Figure 1: (a) shunt current source injection and (b) series voltage source injection.

Examining the denominators of (1) and (2) reveals that the impedance ratio on both sides aligns with an open-loop transfer function. According to [19], a transfer function characterized by this open-loop transfer function form contains critical dynamic characteristics crucial for system stability analysis. Given that the system response to injected signals incorporates these dynamic features, this work integrated these signals into the objective function of the optimization process.

In this work, a frequency scanning technique was employed for parameter estimation, as shown in the flowchart in Figure 3. The parameters of the generic model, which is a simplified representation of the power electronics model, are estimated to mimic the reference power electronics model. Initially, frequency scanning was conducted on the reference model to acquire its dynamic response data ($I_{reference, f_i}$). In this flowchart, the insertion of a series voltage source is assumed; hence, current data were utilized for optimization purposes. The parameters (x) were then optimized to ensure that the response of the simple generic model ($I_{generic, f_i}$) closely approximated the reference response. A widely used model in TSA tools was adopted as the generic model.

After obtaining the response data from the frequency scanning of the reference model, a signal-processing procedure was configured to make the results of the EMT frequency scanning simulation available for optimization. For frequency scanning, a series voltage source injected a signal with a constant magnitude (0.01 p.u.) but varying frequency every 0.5 s, as depicted in Figure 4. The injected signal was set to have a small magnitude to ignore the dynamics caused by the fundamental frequency component. Following the injection of the signal, the current magnitude corresponding to the injected frequency (f_i) was obtained by applying the fast Fourier transform to the measured current data (I_{abc}). The objective function for optimization was defined as the absolute value of the difference between the current magnitude responses of the reference model ($I_{reference, f_i}$) and the generic model ($I_{generic, f_i}$). The parameter set (x) was then optimized, as expressed in (3), by utilizing the Nelder–Mead simplex method [20] as the optimization algorithm. Note that no constraints were needed for the parameter estimation process.

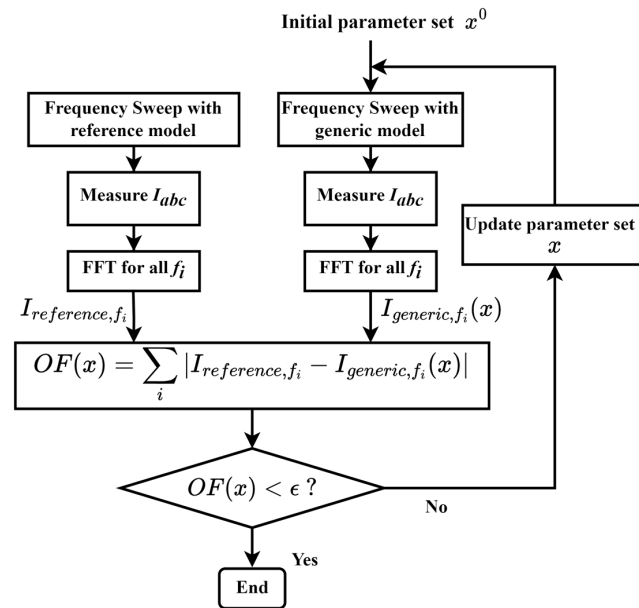


Figure 3. Flowchart for the parameter estimation process.

$$x^* = \underset{x}{\operatorname{argmin}} \left(\sum_i |I_{reference, f_i} - I_{generic, f_i}(x)| \right) \quad (3)$$

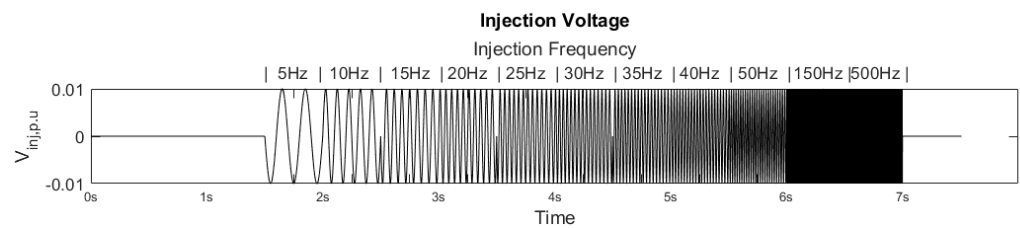


Figure 4. Injection voltage signal.

3. Case Study

3.1. System Modeling and Verification

The power electronics device utilized was a STATCOM, which employs the CSTCNT model as a generic representation. STATCOM is used as a type of power electronics equipment only for the case study in this paper, and how accurately the proposed method mimics the behavior of the reference model is not restricted to STATCOM. Instead, the main concern is how well the power system containing the power electronics model simplified by the proposed method exhibits similar behavior. As shown in Figure 5, the CSTCNT model includes a second-order lead–lag compensator, integrator, and other components [21]. It takes the bus voltage magnitude as an input and outputs the reactive current magnitude. The model is characterized by seven parameters: four time constants (T_1 to T_4) for the lead–lag compensator, a gain (K_i) for the integrator, a droop factor (K_{droop}), and an impedance (X). This model can be represented as the product of a PI controller, a first-order phase compensator, and a first-order lag element, as shown in Equation (4). This structure enhances voltage control and enables the adjustment of the STATCOM's response characteristics based on parameter values [13]. The simulations were conducted using a three-bus test system, as depicted in Figure 6. The reactance of all transmission lines was set to 0.05 p.u., and the power ratings of the system at each bus are as follows: $P_{G1} = 250$ MW, $P_{G2} = 150$ MW, $P_{G3} = 100$ MW, $P_{L1} = 300$ MW, $P_{L2} = 200$ MW,

$Q_{L1} = 0$, $Q_{L2} = 0$. The voltage at all buses was set to 1 p.u., and the reactive power of each generator varies depending on the reactive power output of the STATCOM.

$$\frac{(1+sT_1)(1+sT_2) \cdot K}{(1+sT_3)(1+sT_4) \cdot s} = \left(T_2 \cdot K + \frac{K}{s}\right) \left(\frac{1+sT_1}{1+sT_3}\right) \left(\frac{1}{1+sT_4}\right) = \left(K_P + \frac{sK_I}{s}\right) \left(\frac{1+sT_a}{1+sT_b}\right) \left(\frac{1}{1+sT_c}\right) \quad (4)$$

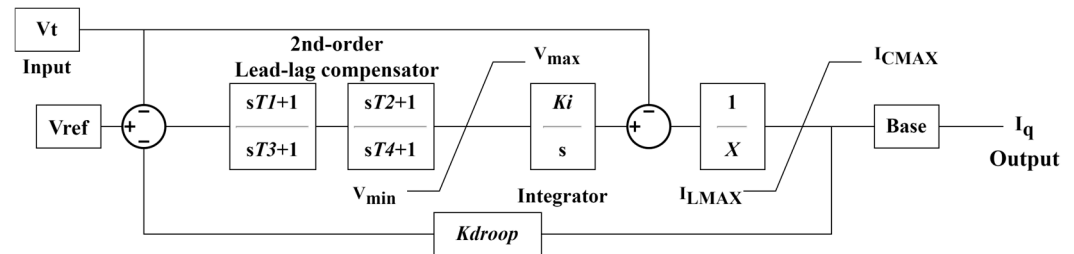


Figure 5. Block diagram of the CSTCNT.

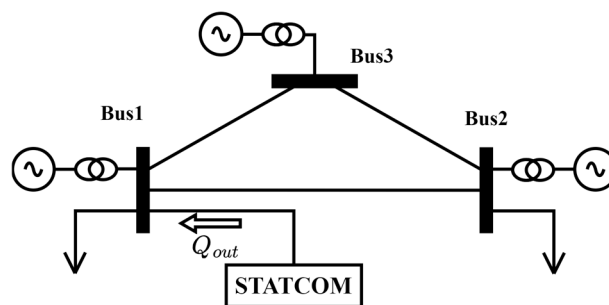


Figure 6. Three-bus test system with a STATCOM.

The performance of the proposed method was evaluated using two different reference models. First, a generic model with known parameters was used as the reference. For the evaluation, the three-bus test system was developed with the generic CSTCNT model using the TSA tool. The optimization procedure was implemented in a MATLAB/Simulink R2024a environment, and the test case was simplified using Thevenin equivalence, as shown in Figure 7. The performance was evaluated from three different perspectives. First, Bode plots were compared in the frequency domain. Second, an SSA was conducted on the entire three-bus system, and then the eigenvalues were compared to show the interaction between the STATCOM and the grid. Finally, a time-domain simulation was performed to verify the dynamic behavior of the systems with STATCOM. The SSA and time-domain simulations were carried out using SSAT_19.0 and TSAT_19.0 from Powertech Labs, respectively. Furthermore, models with parameters estimated under specific scenario were compared to validate the improvements achieved by the proposed method in relation to the previous optimization study.

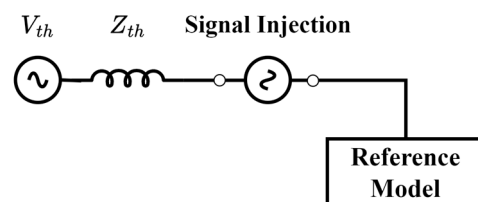


Figure 7. Thevenin equivalent used for the optimization process in MATLAB/Simulink.

To evaluate the effectiveness of the proposed method further, a switching-based STATCOM model was used as the reference and optimized. The switching-based model employed was the 48-pulse GTO (Gate Turn-Off Thyristor) STATCOM model provided by

MATLAB/Simulink [22]. The accuracy of the optimized generic model in mimicking the switching model was analyzed by time-domain simulations, considering reactive power fluctuations in the load and three-phase-to-ground fault scenarios.

3.2. Using the Generic Model as a Reference

With the generic model as a reference model, the parameter sets for the reference, initial generic, and optimized generic models are presented in Table 1. When comparing the parameters of the reference model with the optimized parameters, Kdroop and X were fine-tuned to closely match their reference value. However, the response of CSTCNT depends on the relative magnitudes of parameters T1, T2, T3, T4, and Ki. Consequently, the optimized parameters differ from the reference parameters in Table 1 [13].

Table 1. Parameters of the reference model (Reference), initial condition (Initial), and optimization result (Result).

CASE	T1	T2	T3	T4	KDROOP	X	KI
REFERENCE	0.8	1	0.5	0.6	0.05	0.18	300
INITIAL	1	1	1	1	0.03	0.1	100
RESULT	0.7933	0.6782	0.1801	0.6912	0.0495	0.1783	184.4

The frequency range of the injection signal is given by (5). The simplified model is intended for use in the TSA simulation; thus, the primary consideration is made under the synchronous frequency.

$$f_{inj} = [5, 10, 15, 20, 25, 30, 35, 40, 50, 150, 500] \quad (5)$$

The optimization results are presented in Figure 8, illustrating the magnitudes of the response currents corresponding to injection frequencies. With these optimization results, the error rate was calculated using (6), yielding a value of 0.692%. This indicates that the response of the generic model closely approximates that of the reference model, demonstrating a high degree of similarity.

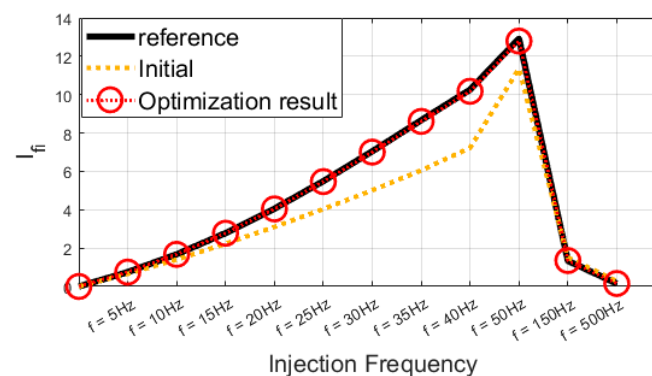


Figure 8. Comparisons of current magnitude, I_{f_i} .

$$\%e = \frac{\sum_{i=1}^{11} |I_{reference, f_i} - I_{generic, f_i}|}{\sum_{i=1}^{11} I_{reference, f_i}} \times 100, \quad \{f_i \cdots f_{11}\} \in f_{inj} \quad (6)$$

The frequency-domain characteristics of the reference model, the model optimized using the previous method, and the model optimized using the proposed method were compared through Bode plots, as depicted in Figure 9. In contrast to the model optimized

using the previous method, the model optimized using the proposed method produces results that closely align with those of the reference model.

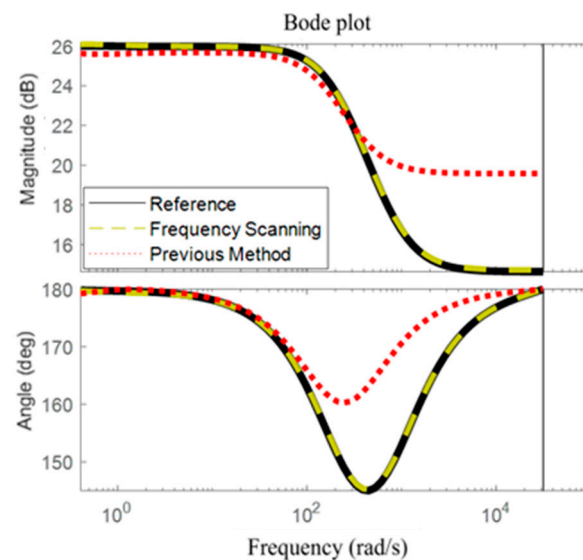


Figure 9. Comparison of Bode plots for the generic STATCOM models with different parameter sets.

The SSA was conducted using the reference, and estimated parameters using the previous and proposed methods to compare the eigenvalues. The corresponding results are shown in Table 2. The specific scenario used for the previous method is Scenario 1 in Table 3. The three-bus system has a total of seven eigenvalues. λ_1 to λ_3 are the eigenvalues of the generator's swing equation, and all three systems exhibit similar values. In this case, [15–19] naturally arises from the synchronization mode of the entire system, which serves to establish a phase reference. Consequently, this eigenvalue is not relevant to the system's stability. In contrast, λ_4 to λ_6 , which correspond to the eigenvalues of the STATCOM, show noticeable differences among the three systems. Notably, the system with the STATCOM optimized by the proposed method closely mimics the reference system. Note that λ_5 and λ_6 in both the reference system and the system optimized by the proposed method, as well as λ_5 in the system optimized by the previous method, are eigenvalues that do not affect the system response due to pole-zero cancellation as depicted in Figure 10.

Table 2. Eigenvalue analysis results.

	Reference System	Proposed Method	Previous Method
λ_1	$-1.65 + 12.65i$	$-1.65 + 12.65i$	$-1.65 + 12.65i$
λ_2	$-0.055 + 12.59i$	$-0.055 + 12.59i$	$-0.055 + 12.59i$
λ_3	$-1.8127 + 0i$	$-1.8126 + 0i$	$-1.8126 + 0i$
λ_4	$-425.55 + 0i$	$-432.32 + 0i$	$-260.45 + 179.99i$
λ_5	$-1.2535 + 0i$	$-2.1871 + 0i$	$-0.7288 + 0i$
λ_6	$-0.9939 + 0i$	$-0.7571 + 0i$	

Table 3. Scenarios for time-domain simulation.

Scenario Number	Scenario Description
1	Three-phase fault at bus 2
2	Q variation at load 2
3	Three-phase fault at bus 1–3 branch

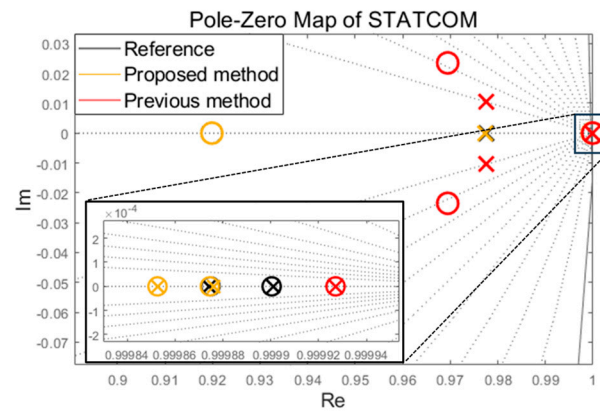


Figure 10. Pole-zero map of STATCOM (Circles denote zeros; crosses denote poles).

As the eigenvalue-based stability analysis relies on linearization, it requires further validation through time-domain simulations. To achieve this, the output of the STATCOM was measured under three scenarios, which are summarized in Table 3.

The STATCOM outputs for all scenarios are presented in Figure 11. In Scenario 1, the Critical Clearing Times (CCTs) were identical at 0.115 s across all three systems, and their dynamic responses under Scenario 1 during the CCT were nearly identical, as illustrated in Figure 11a. It should be noted that Scenario 1 was used to estimate the parameters using the previous method, as previously mentioned.

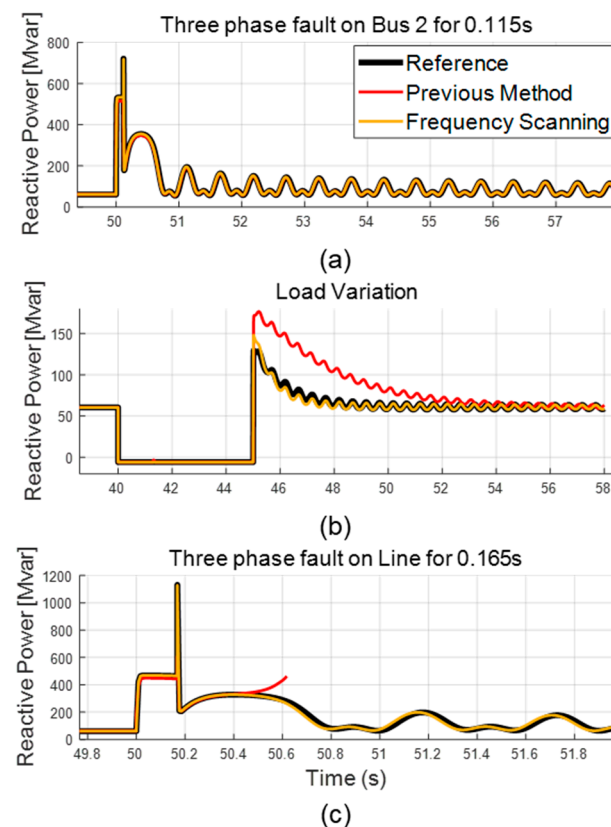


Figure 11. Time-domain simulation results; (a) Scenario 1, (b) Scenario 2, (c) Scenario 3.

Subsequently, a time-domain simulation was conducted for Scenario 2, which involved a variation in the reactive power of Load 2. The results are presented in Figure 11b. The STATCOM with parameters estimated using the previous optimization method exhibited a significant deviation from the reference STATCOM due to the use of a different scenario

from that employed during the optimization process. In contrast, the STATCOM optimized by the proposed method demonstrated a response closely matching the reference STATCOM, as it was optimized considering a wide frequency spectrum around the operating point. This is numerically demonstrated in Table 4, which summarizes the settling time required to return to within 5% of the operating point for each system, as well as the peak value of the output reactive power after stabilizing at the load consumption reactive power. It can be observed that the settling time of the model estimated using the proposed method more closely matches that of the reference model compared to the model estimated using the previous method. Additionally, the peak value indicates that the STATCOM estimated by the proposed method exhibits improved performance, making it more similar to the reference model.

Table 4. Summary of simulation results for Scenario 2.

Parameter Estimation Method	Settling Time [s]	Peak Q Value [Mvar]
Reference system	47.87	129.63
Proposed method	47.34	148.02
Previous method	53.27	176.63

Finally, the time-domain response was simulated for Scenario 3, which considered a three-phase fault at a location different from Scenario 1, i.e., the bus 1–3 line. The CCT of the model optimized using the proposed method matched that of the reference model at 0.165 s, whereas the model optimized using the previous method yielded a different CCT of 0.160 s. Figure 11c presents the time-domain simulation results for Scenario 3 for 0.165 s. The model optimized by the previous method exhibits divergence post-fault clearance, while the model optimized by the proposed method returns to a stable state same as the reference model. These validations demonstrate that the model optimized using the proposed method closely replicates the reference model while capturing a broader spectrum of dynamic characteristics compared to previous optimization methods.

3.3. Using the Switching-Based Model as the Reference

In this section, the performance is evaluated with the switching-based model as the reference model. Since the reference model used in this section is an EMT model that cannot be analyzed with the TSA program, unlike in Section 3.2, the accuracy of the model whose parameters are estimated only from the time-domain response is compared. In this case, f_{inj} in (5) for the frequency range is used; the initial parameters are given in Table 5. The results of the optimization using these values are depicted in Figure 12.

When comparing the optimization results obtained using the switching model with those acquired using the generic model, notable errors occurred at relatively high frequencies (≥ 50 Hz). The error rate for the total frequency in the optimization result was 11.52%, indicating a relatively high value. Conversely, the calculated error rate for frequencies below 50 Hz was 4.95%, demonstrating that the optimized generic model replicated the switching model in the subsynchronous frequency range more accurately. It is crucial to note (as mentioned earlier) that the primary interest of the simplified model is to maintain the dynamic responses with the TSA simulation. Therefore, errors at high frequencies were deemed tolerable. For the performance evaluation of the simplified model, two different time-domain simulations were conducted (described below).

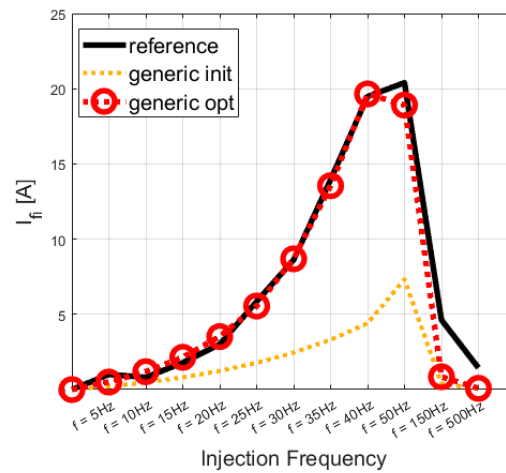


Figure 12. Comparison of current magnitude, I_{fi} .

Table 5. Initial parameters.

T1	T2	T3	T4	Kdroop	X	Ki
1	1	1	1	0.05	0.5	300

In the first scenario, the reactive power change of the load at bus 2 was considered. The reactive power output of the STATCOM and the voltage at bus 1 were compared; these comparisons are shown in Figures 13 and 14. The change in load reactive power is presented in Table 6. Figures 13 and 14 clearly show that the optimized generic model closely replicates the response of the switching model under the synchronous frequency. This confirms that the optimization incorporated with the frequency scanning method effectively captures the response characteristics of power electronics.

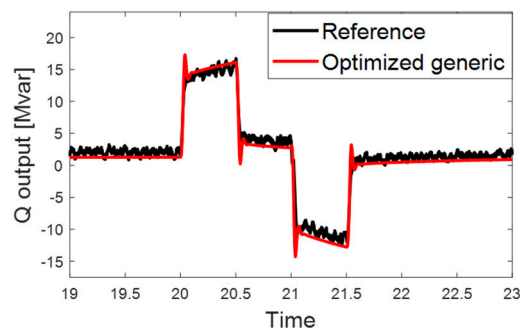


Figure 13. Comparison of reactive power outputs of STATCOMs with load reactive power variation.

The second scenario for the evaluation considered a fault condition. A three-phase-to-ground fault was applied at 20 s at bus 2 and cleared after 0.005 s. The output reactive powers of the STATCOMs were then compared and the corresponding results are presented in Figure 15.

Table 6. Reactive power variation of the load at bus 2.

Time [s]	~20	20	20.5	21	21.5
Q [Mvar]	0	30	0	−30	0

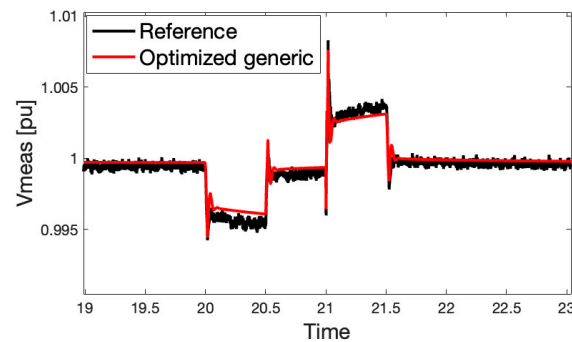


Figure 14. Comparison of bus voltage magnitude where the STATCOM is located with load reactive power variation.

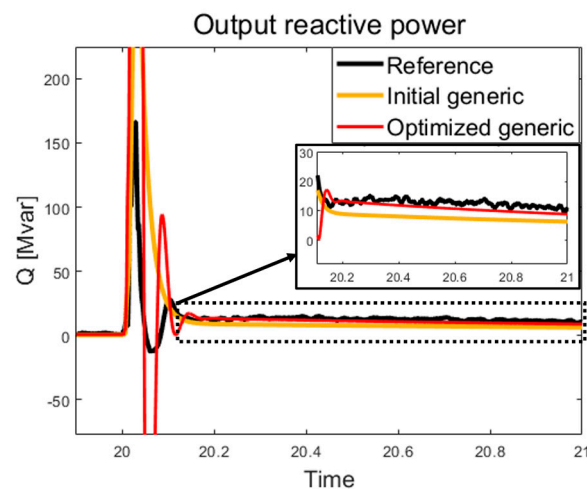


Figure 15. Comparison of the reactive power output of the STATCOM during a three-phase-to-ground fault.

Figure 15 shows that the optimized generic model closely replicates the behavior of the switching model during slow dynamic responses. However, the accuracy of the emulation decreases when the output of the reference model changes rapidly, which occurs when the response includes significant high-frequency components. This is because the generic model used for parameter estimation, CSTCNT, has a limited bandwidth to fully represent the switching-based STATCOM model [23].

4. Conclusions

This paper presents a parameter estimation method that utilizes the response to frequency scanning. Unlike previous methods that excited only specific modes and were susceptible to the risk of local minima, the proposed parameter estimation approach utilizes frequency scanning to capture a wide spectrum of dynamic characteristics. This method aims to estimate the parameters of a simplified generic model to ensure the close representation of power electronic devices, even when their internal structures include switching components. Thus, the complicated switching-based power electronics component can be simplified, and it can be used for traditional transient stability and SSAs. This strategy proposes a clear standard for the ambiguous emulation criteria used in existing parameter-optimization methods.

To validate the proposed method, various analyses were conducted using the TSA program and switching-based models, demonstrating its effectiveness and generalizability:

- To enable various analyses using the TSA program, the proposed method was validated with the TSA generic model as the reference, demonstrating improved generalizability compared to previous approaches.
- To verify the applicability of the proposed model when the reference model is provided as a switching-based black-box model, a validation process was conducted using a detailed model as the reference, confirming that the proposed model accurately replicates the reference model with high precision.

The proposed method facilitates power system stability analysis by enabling the integration of power electronic device models from various manufacturers into existing power system analysis tools. Simulations were conducted using the STATCOM model in MATLAB/Simulink, SSAT, and TSAT from Powertech Labs. The effectiveness of the optimized generic model was assessed using Bode plots in frequency- and time-domain simulations, demonstrating its capability to replicate the reference model. Moreover, the optimized generic model is able to maintain the responses of the switching model closely, particularly slow dynamic characteristics. Therefore, it is suitable for small-signal stability analysis or transient stability analysis under limited scenarios, such as faults at distant locations.

However, the generic model provided by the TSA program demonstrates limitations in capturing the high-frequency response of power electronics equipment. For this reason, using the TSA generic model to simplify power electronics equipment may be inappropriate for scenarios involving rapid changes in state, such as faults occurring near the equipment. Therefore, to simulate the transient response of power electronics in scenarios with rapidly changing grid conditions, future research should focus on developing modeling approaches that more accurately represent high-frequency dynamics.

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