Electromagnetic Transients Simulation-Based Surrogate Models for Tolerance Analysis of FACTS Apparatus

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***Abstract*—This paper introduces a computationally efficient surrogate model-based approach for tolerance analysis of power systems. Surrogate models are heuristic, simple representations of complex systems that are obtained through an automated sensitivity analysis of electromagnetic transient simulations results. These simpler models are shown in this paper to be significantly faster than full-detail simulation models to obtain accurate statistical tolerance information about complex power networks. Usefulness of the proposed approach is demonstrated by two application examples. In the first example, surrogate models are used for determining the statistical distribution of undesired remnant harmonics produced by a voltage-source converter, given the uncertainty in the firing angles. In the second example, the impact of variations in the system parameters around the nominal values on the transient behavior of a static compensator is analyzed.**

***Index Terms*—Selective harmonic elimination (SHE), static compensator (STATCOM), tolerance analysis electromagnetic transient (EMT) simulation, uncertainty analysis.**

I. Introduction

An IMPORTANT step in design is to carry out tolerance analysis to assess the impact of factors, such as manufacturing tolerances, aging related parameter variations, unpredictable operating condition, etc. on performance. In many cases, the statistical distribution of parameters, such as component values, is known, and it is of interest to the designer to quantify the impact of such variations on system performance. Often, the performance of a system can be represented by a set of performance indices that are suitably defined functions of the system's outputs. Tolerance analysis is applied to determine the statistical distribution of these performance indices resulting from variations in the input parameters [1]–[5]. For example, in a voltage-source converter (VSC) with a selective harmonic elimination switching scheme, the total harmonic distortion of the output voltage is a commonly used performance index. The performance index is normally selected so that the smaller its value, the closer the achievement of the goal, in this case, the elimination of harmonics.

The methods for tolerance analysis of power systems can be classified into two major categories: 1) analytical methods [1], [2] and 2) black-box methods [6]–[14]. Analytical methods are usually applicable to simple systems, where a mathematical formula can be derived for the relationship between system inputs and outputs. The formula can be then be used to determine the distribution of the performance index from knowledge of the distribution function of input parameters. Some of the common techniques for such studies include interval arithmetic [2], affine arithmetic [1], and variance analysis [20], [21].

The second alternative "black-box" approach is used when the relationship between the inputs and outputs is unknown (or is difficult to obtain). Here, a simulation program such as an electromagnetic-transient (EMT) simulation program acts as a function evaluator, which returns the values of performance indices for each set of system input parameter values [16], [17]. EMT programs are widely used for the simulation of power systems with embedded power-electronic apparatus, as they represent the system in its fullest detail. Such detail is necessary when considering multiple subcycle switching operations of the power-electronic switches [15]. The distribution of the performance index can be determined by conducting Monte-Carlo-type simulation, in which a large number of simulations were conducted, with randomly selected input parameter values [6]–[9]. The drawback of EMT simulation is that it is an extremely computation-intense procedure that takes a long time to conduct on a digital computer. Hence, Monte-Carlo simulation using such detailed simulation tools is extremely inefficient.

One of the recent methods for expediting the tolerance analysis process is to use surrogate models [10]–[12], [14], [18], [22]. Surrogate models are models that capture the essential behavior of the system, but are not necessarily based on physics. A simple type of surrogate model is a formula relating the variation of the performance index as a function of relatively small variations of the input parameters. Such a formula can be obtained by conducting a limited number of simulations around the operating point, with each simulation having a slightly different (perturbed) input parameter. By determining first- and second-order sensitivities, the performance index can be written as a Taylor-series expansion with the input parameters as variables. Once all surrogate models are obtained, they can be used for purposes, such as Monte-Carlo simulation, instead of the detailed simulation model. Since the surrogate model is very

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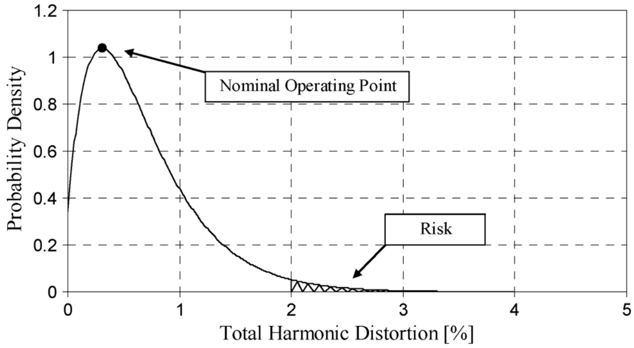

Fig. 1. Statistical tolerance analysis.

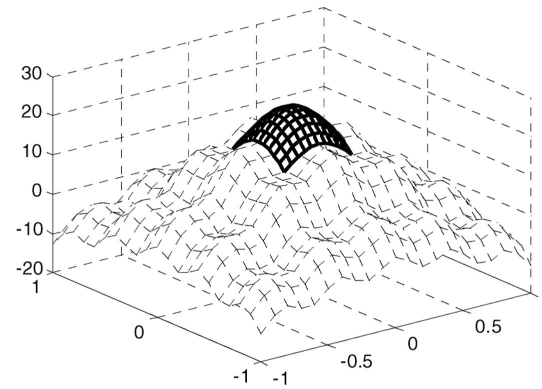

Fig. 2. Concept of a surrogate model.

simple, the time savings can be in the range of several orders of magnitude.

The proposed method has been implemented on the EMT simulation program PSCAD/EMTDC, and a tool has been developed that automatically generates the surrogate models and performs the tolerance analysis. Two practical application examples demonstrate that the proposed method is capable of producing accurate results in a much shorter time compared to the conventional multiple-run approaches.

II. Tolerance Analysis

This section introduces basic tolerance analysis concepts which are used later in this paper. As mentioned in Section I, in tolerance analysis, a set of indices is defined to represent different aspects of system performance. The goal of tolerance analysis is to quantify the impact of input parameter variations on these indices. Two types of tolerance analysis problems are of interest. The first one is worst-case analysis, in which the designer determines the potential worst-case performance index values, with the input parameters taking on any value within specified ranges [1], [3], [5], [18], [19]. Often, the designer may not just be interested in the worst cases, but would also like to know the distribution of the performance indices. For example, the designer may want to have a total harmonic distortion (i.e., the performance index) below 2%, with a probability of 95% or greater. Hence, the second type of tolerance analysis problem is statistical tolerance analysis [11], [12], [14], [20]–[22]. Here, the designer finds the probability distribution of the performance index.

The concept of statistical tolerance analysis is illustrated by the sample plot in Fig. 1. The distribution in parameter values creates the variation in the performance index resulting in the probability density function for the total harmonic distortion (the performance index) of Fig. 1. With nominal parameter values, the total harmonic distortion (THD) has a value of 0.3%. The chance of having nonsatisfactory performance (i.e., the risk of having $\mathrm{THD} > 2\%$) is the integral of the probability density curve (hatched area) in the region $(2\%, \infty)$. If the resulting risk is sufficiently small to be acceptable to the designer (e.g., less than 5%), the designed system passes the tolerance analysis stage; otherwise, the system should be redesigned.

III. Multiple-Run Simulations and Tolerance Analysis of Power Systems

As mentioned before, one approach for tolerance analysis of a system is the use of the multiple-run feature available in most of the commercial EMT simulation programs [17]. It allows the user to conduct several simulation runs with sequential or randomly selected parameter values. The designer has to specify a range and distribution for each input variable, and then the program automatically conducts several simulation runs. Normally, for worst-case tolerance analysis problems, the parameter values are selected sequentially to cover all possible combinations of input parameter values. For statistical tolerance analysis problems, the parameters are selected randomly (with specified probability densities). Each of the several runs provides one value of the performance index, and the corresponding statistical distribution of this index can be determined once all runs are completed. This method has been extensively used for insulation coordination studies where the impact of random lightning strikes has to be studied [6]–[9]. Although use of multiple-run simulations is an effective approach for tolerance analysis of power systems problems, this approach requires a large number of EMT simulations of potentially large simulation models, which makes it impractical for complex systems with several input parameters.

IV. Surrogate Models for Tolerance Analysis

In this paper, it is proposed to use surrogate models for the tolerance analysis of power systems. A surrogate model is a mathematical function, which represents a performance index in a certain range of system parameter values. Fig. 2 illustrates the concept of surrogate models. In the figure the dotted surface shows the performance index values for a range of system parameter values, and the solid surface is a second-order polynomial surrogate model of the performance index. Surrogate models are normally obtained by applying surface fitting methods (such as method of least-squares) to a number of performance index samples (obtained through EMT simulations). Although initially obtaining the models is time consuming as it requires detailed EMT simulation, once such models are obtained there is no need for further EMT simulations and the tolerance analysis can be done using these models.

This paper proposes to use second-order polynomial surrogate models for tolerance analysis of power systems. The surrogate models are obtained using the Taylor's expansion of the performance index around the operating point as in (1). Using the second-order approximation not only increases the accuracy of analysis for normal operating points, but also allows tolerance analysis to be carried out for operating points, at which the first-order derivatives are close to zero (this is especially the case for optimal operating points [27])

$$\begin{aligned} f(x_1+\Delta x_1,\cdots,x_n+\Delta x_n) &\approx f(x_1,\cdots,x_n)+\frac{\partial f}{\partial x_1}\Delta x_1 \\ &+\cdots+\frac{\partial f}{\partial x_n}\Delta x_n+\frac{1}{2}\frac{\partial^2 f}{\partial x_1^2}\Delta x_1^2+\cdots+\frac{1}{2}\frac{\partial^2 f}{\partial x_n^2}\Delta x_n^2 \\ &+\frac{\partial^2 f}{\partial x_1\partial x_2}\Delta x_1\Delta x_2+\cdots+\frac{\partial^2 f}{\partial x_1\partial x_n}\Delta x_1\Delta x_n \\ &+\frac{\partial^2 f}{\partial x_2\partial x_3}\Delta x_2\Delta x_3+\cdots+\frac{\partial^2 f}{\partial x_{n-1}\partial x_n}\Delta x_{n-1}\Delta x_n. \end{aligned} \quad (1)$$

In (1), f is the performance index and $x_1,\ldots,x_n$ are the input parameters with uncertainties.

The derivatives in (1) are obtained using EMT simulations by implementation of a supervisory algorithm that conducts several runs of the EMT simulation program and records the resulting performance index values. By using forward and backward differences, the first- and second-order derivatives are obtained as in (2). Each function evaluation (e.g., $f(x_1,\cdots,x_i+\Delta x_i,\cdots,x_n)$) is the output of one EMT simulation. Additional details for the calculation of these sensitivities (i.e., first- and second-order derivatives in (2)) are given in an earlier paper [27]. (See (2) at the bottom of the page.)

From (2), it can be seen that with n system parameters, the generation of a surrogate model requires $M = n(n+1)+1$ function evaluations (i.e., M transient simulation runs of the EMT transient simulation program). The EMT program used here is PSCAD/EMTDC [28].

Once the models are obtained, the supervisory algorithm automatically performs Monte–Carlo simulation using the surrogate models and provides statistical information. Consequently, the required computational time is significantly reduced, as will be shown later. The block diagram of the proposed method is shown in Fig. 3.

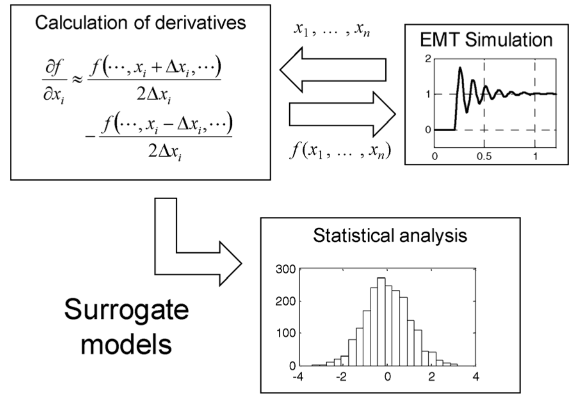

Fig. 3. Block diagram of the proposed method for tolerance analysis.

V. Case Study I: Selective Harmonic Elimination

In this section the proposed method is used to determine how uncertainties in the switching instances of a VSC converter affect the performance of selective harmonic elimination (SHE) switching scheme.

A. Selective Harmonic Elimination

The technique of selective harmonic elimination [26] is explained with reference to Fig. 4 and Fig. 5 below. To generate an ac waveform on phase a, the switches S_1 and S_4 are operated so as to apply a voltage of $+V_d$ or $-V_d$ to phase "a," resulting in a waveform as shown in Fig. 5. The n instances of switching, labeled by angles $\alpha_1,\alpha_2\ldots\alpha_n$. can be selected so that $n-1$ number of lower order harmonics are eliminated and the desired magnitude of fundamental-frequency voltage is obtained. Fig. 5 is drawn for $n = 5$

$$\begin{aligned} V_1 &= \left|\frac{2\sqrt{2}V_{\mathrm{dc}}}{\pi}\left(1+2\sum_{i=1}^{n}(-1)^i\cos(\alpha_i)\right)\right| \\ V_k &= 0 = \left|\frac{2\sqrt{2}V_{\mathrm{dc}}}{k\pi}\left(1+2\sum_{i=1}^{n}(-1)^i\cos(k\alpha_i)\right)\right| \\ &\text{where } k\in\{k_1,k_2,\cdots,k_{n-1}\}. \end{aligned} \quad (3)$$

For the idealized case, where the dc-link voltage V_{dc} is constant, the n switching angles $\alpha_1,\alpha_2\ldots\alpha_n$ can be calculated an-

$$\begin{aligned} \frac{\partial f}{\partial x_i} &\approx \frac{f(x_1,\cdots,x_i+\Delta x_i,\cdots,x_n)-f(x_1,\cdots,x_i-\Delta x_i,\cdots,x_n)}{2\Delta x_i} \\ \frac{\partial^2 f}{\partial x_i^2} &\approx \frac{f(x_1,\cdots,x_i+\Delta x_i,\cdots,x_n)+f(x_1,\cdots,x_i-\Delta x_i,\cdots,x_n)}{\Delta x_i^2}-\frac{2f(x_1,\cdots,x_n)}{\Delta x_i^2} \\ \frac{\partial^2 f}{\partial x_i\partial x_j} &\approx \frac{f(x_1,\cdots,x_i+\Delta x_i,\cdots,x_j+\Delta x_j,\cdots,x_n)}{2\Delta x_i\Delta x_j}+\frac{f(x_1,\cdots,x_i-\Delta x_i,\cdots,x_j-\Delta x_j,\cdots,x_n)}{2\Delta x_i\Delta x_j} \\ &\quad -\frac{f(x_1,\cdots,x_n)}{\Delta x_i\Delta x_j}-\frac{1}{2}\frac{\Delta x_i}{\Delta x_j}\frac{\partial^2 f}{\partial x_i^2}-\frac{1}{2}\frac{\Delta x_j}{\Delta x_i}\frac{\partial^2 f}{\partial x_j^2} \end{aligned} \quad (2)$$

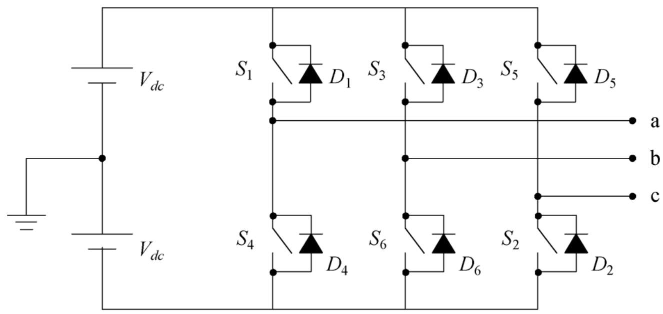

Fig. 4. Two-level inverter.

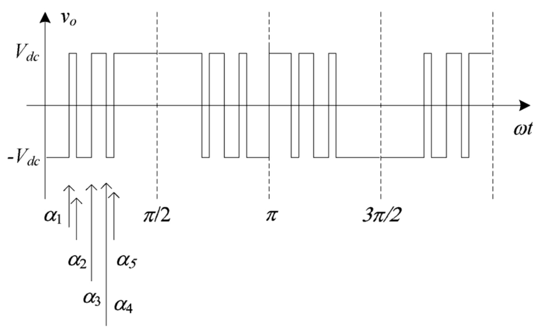

Fig. 5. Harmonic elimination switching pattern.

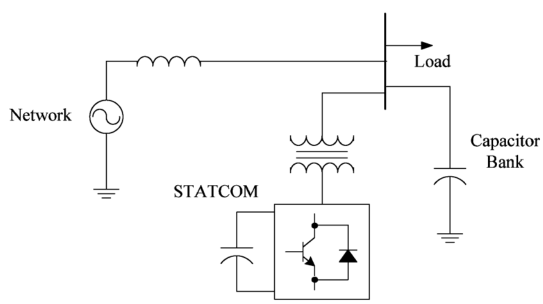

Fig. 6. Two-level STATCOM case.

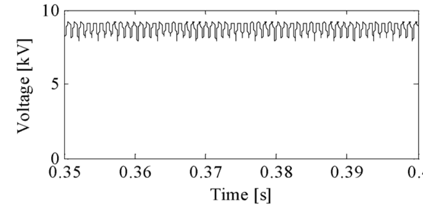

Fig. 7. STATCOM dc-bus voltage.

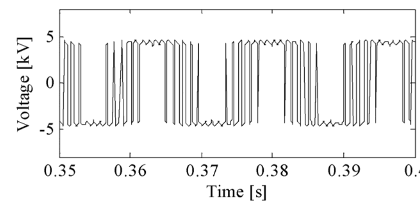

Fig. 8. Output voltage of the STATCOM converter.

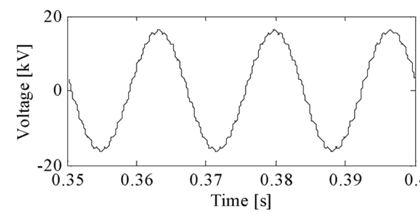

Fig. 9. Load ac voltage.

TABLE I
SYSTEM SPECIFICATION FOR THE STATCOM CASE

Network	20 kV, 60Hz, SCR = 5
STATCOM Transformer	4.8 kV/20 kV, 8.0 MVA, X_l = 15%
Capacitor Bank	10 MVAR
Load	25 MVA, pf = 0.85
STATCOM Converter	4.8 kV, ±8MVAR, C = 0.4 pu

alytically [26] by solving the set of n nonlinear equations of (3). In (3), V_1 is the desired magnitude of the fundamental voltage and $k_1, k_2 \ldots k_{n-1}$ are the orders of the $n-1$ harmonics targeted for elimination.

B. Tolerance Analysis

Voltage-source converters normally have a dc-side capacitor. Unlike an idealized dc source a capacitor will experience voltage fluctuations during normal and transient operations of the converter. Although provisions for minimizing such fluctuations are incorporated into the design of the capacitive dc buses, small voltage ripple will still be present. Having this ripple on the voltage waveform makes it difficult to find an analytical solution for the SHE scheme; however, the proposed technique can be still used for analyzing the performance of the scheme.

In this section, a two-level static synchronous compensator (STATCOM) is considered as a practical application of SHE switching scheme with a non-ideal dc bus. A STATCOM is a flexible ac transmission systems (FACTS) device mainly used for fast VAR compensation and voltage regulation in power networks [23]–[25]. The STATCOM case is shown in the following figure.

The specifications of the system studied in this section are listed in Table I. SHE switching pattern with five switching angles (as shown in Fig. 5) is used in order to shape the output voltage waveform generated by the converter.

In the following figures, the simulation results of the nominal operating point of the STATCOM are shown. The figures show the dc-bus voltage, the output voltage of the converter, and the ac voltage at the load bus. Note that the ripple on the dc voltage deforms the output voltage of the converter. In addition, harmonics injected by the STATCOM introduce distortion to the network voltage as well.

The harmonic content of the STATCOM voltage is studied using the proposed simulation-based method. In order to verify the results obtained from the surrogate models, Monte-Carlo simulations have also been done using EMT simulations. For the purpose of analysis, it is assumed that the maximum firing mismatch for the switching angles is 0.1°, and it is also assumed that the distribution of this switching mismatch is uniform (i.e., each firing angle may vary uniformly within a $\pm 0.1^\circ$ interval

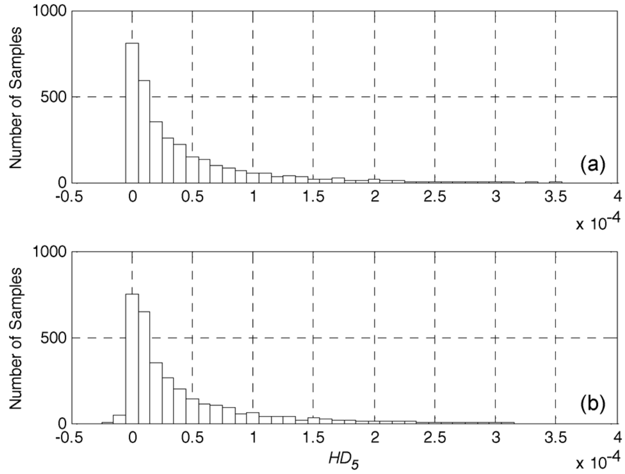

Fig. 10. Histogram of HD_5. (a) Full EMT simulation. (b) Surrogate model.

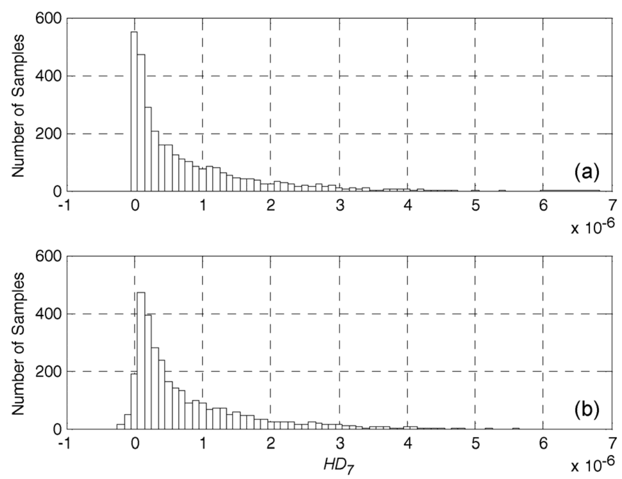

Fig. 11. Histogram of HD_7. (a) EMT simulation. (b) Surrogate model.

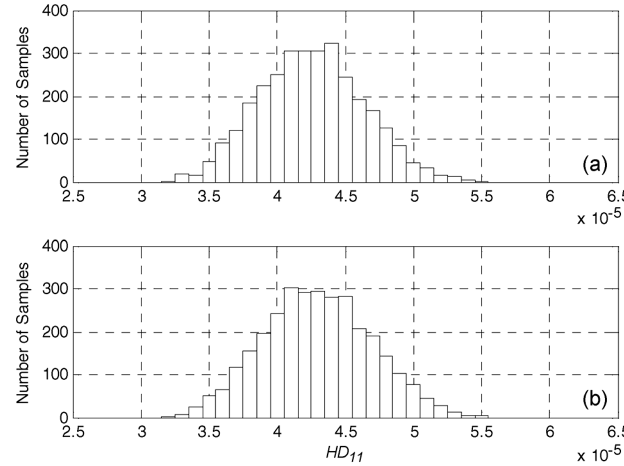

Fig. 12. Histogram of HD_{11}. (a) Full EMT simulation. (b) Surrogate model.

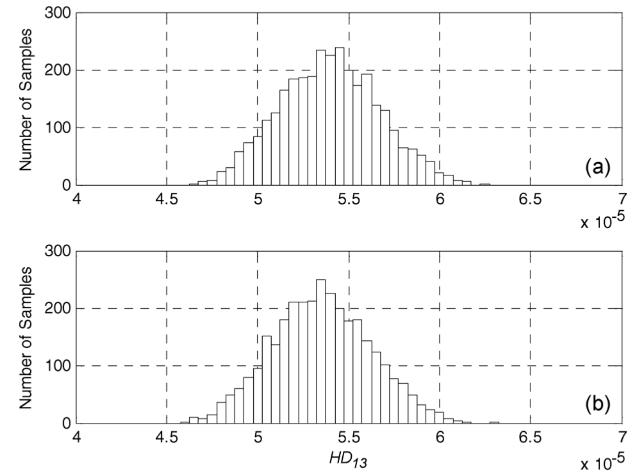

Fig. 13. Histogram of HD_{13}. (a) Full EMT simulation. (b) Surrogate model.

around its optimal value). In order to quantify the harmonic content, the following performance indices have been used:

$$\mathrm{HD}_5 = \frac{V_5^2}{V_{\mathrm{ref}}^2}, \mathrm{HD}_7 = \frac{V_7^2}{V_{\mathrm{ref}}^2}$$
$$\mathrm{HD}_{11} = \frac{V_{11}^2}{V_{\mathrm{ref}}^2}, \mathrm{HD}_{13} = \frac{V_{13}^2}{V_{\mathrm{ref}}^2}. \tag{4}$$

The above performance indices show the level of each individual harmonic (5th, 7th, 11th, and 13th). The statistical distributions of the indices from both methods (the actual EMT simulations and the surrogate models) are presented in Figs. 10–13. As can be seen in the figures, the results from the surrogate model-based analysis are reasonably close to results obtained by conducting the same analysis using the fully detailed simulation model. Note that the Monte-Carlo approach gives more accurate results as the number of samples is increased, and so the small differences could be partly due to a limited number of samples.

Table II presents the average value and the standard deviation of each parameter obtained from the surrogate models and the actual simulations. Coefficients of the surrogate model as in (2) are listed in the Appendix. In the table, the results are based on 3125 samples for each method. As seen in Table II, the average and standard deviation obtained from the actual simulations are close to the ones obtained from the surrogate models.

TABLE II
STATISTICAL ANALYSIS RESULTS

Statistical Analysis on the Harmonic Performance of the STATCOM*				
	Average		Standard Deviation	
	Sensitivity Model	Simulation Results	Sensitivity Model	Simulation Results
HD_5	0.0361	0.0388	0.0480	0.0502
HD_7	0.0007	0.0007	0.0008	0.0009
HD_{11}	0.0430	0.0425	0.0039	0.0038
HD_{13}	0.0534	0.0540	0.0027	0.0027
THD_4	0.3741	0.3825	0.0491	0.0508

* All values to be multiplied by 10^{-3}

The simulation time required for the first method, which uses direct EMT simulations of the network, is about 8.5 h; whereas the required evaluation time for the second method using surrogate models is about 6 min (using a computer with 4 GB of RAM and a 3-GHz AMD AthlonTM 64 X2 dual core processor). This 8500% speedup is due to the fact that the proposed response surface approach requires only 31 EMT simulation runs to obtain the parameter values of the sensitivity models. Once the

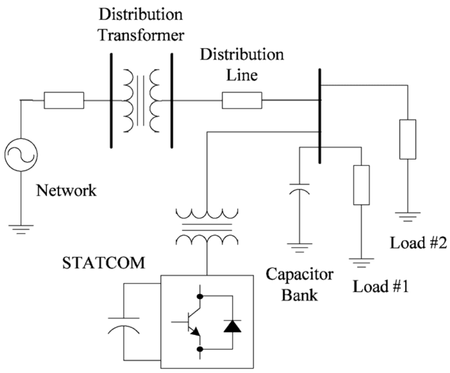

Fig. 14. Schematic diagram of the STATCOM and ac system.

TABLE III
SYSTEM PARAMETERS

AC network	115 kV, SCMVA = 500 MVA at 80°
Distribution transformer	115 kV / 20 kV, 30 MVA, X_l = 10%
Distribution line	Resistance = 0.04 pu, Reactance = 0.10 pu
Load #1	10.0 MVA, pf = 0.9
Load #2	10.0 MVA, pf = 0.85
STATCOM converter	3.3 kV, 10 MVA, C = 0.5 pu
STATCOM transformer	20 kV/3.3 kV, 10 MVA, X_l = 14%
Capacitor Bank	8 MVAR

surrogate models are obtained, Monte–Carlo-type evaluations can be done on these simple models, which only take a few seconds. On the other hand, performing Monte–Carlo simulation of the fully detailed model requires 3125 simulations of the full system (each simulation takes about 10 s, which results in total simulation time of 8.5 h).

Statistical analysis results provide important information that helps the designer in the decision-making process. For example, assume that in the above example, one of the design requirements is to keep each individual harmonic below 1.5% of the fundamental component. For example, from Fig. 10, although at the worst-case scenario, the magnitude of the 5th-order harmonic exceeds 1.95% of the fundamental voltage (equivalent to $\mathrm{HD}_5 = 3.8 \times 10^{-4}$), statistical analysis shows that the probability of having a 5th-order harmonic level more than 1.4% (equivalent to $\mathrm{HD}_5 > 2 \times 10^{-4}$) is very low (less than 100 samples out of 3125 samples). In such a situation, the designer may accept a small risk of design degradation (having a 5th-order harmonic level above 1.5%) in order to reduce the price of the system by using smaller-size filters.

VI. Case Study II: Transient Response of Static Compensator

In this example, the surrogate models are used to estimate the impact of uncertainties on the transient performance of a three-level static compensator (STATCOM).

A. Description of Modeled Network

Fig. 14 shows the schematic diagram of the network used in this example with the data as given in Table III.

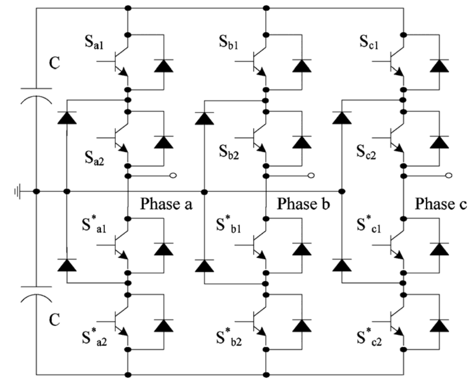

Fig. 15. Three-level diode clamped converter used in the STATCOM; S and S^* switches receive complementary gate pulses.

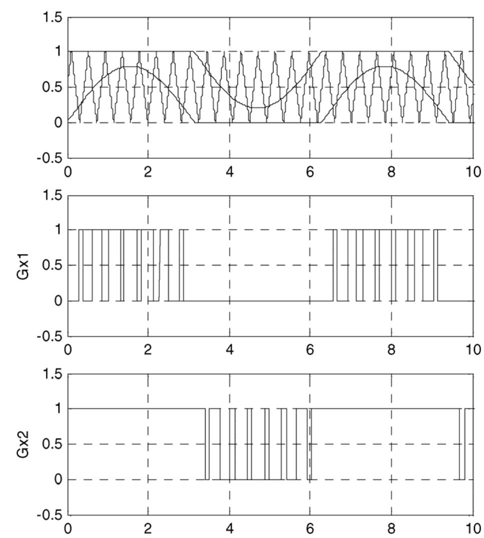

Fig. 16. Generation of gate signals. G_{x1} and G_{x2} correspond to S_{x1} and S_{x2} switches (x denotes the respective phase).

The STATCOM uses a three-level SPWM-controlled voltage-source converter as shown in Fig. 15. Gate pulses for the upper and lower switches are generated by comparing reference sine waves with a triangular carrier based on the method presented in [23]. The lower sine wave is used for generation of the gate signals for upper switches, and the other sine wave is used for the lower switches as shown in Fig. 16.

Control of the dc-bus voltage and the ac network voltage is conducted through a de-coupled control system [25] (dotted enclosure) as shown in Fig. 17. This controller regulates the d and q components of the STATCOM current to their desired reference values i_d^* and i_q^*.

The synchronously rotating reference frame is locked to the positive sequence of the load busbar voltage. Hence, in the steady-state $v_d = V_m$ and $v_q = 0$, where V_m is the peak phase voltage. The q-axis current order i_q^* (indirectly the generated reactive power) for the decoupled controller is generated by an upstream proportional-integral (PI) controller that regulates the terminal voltage v_d to its reference value v_d^*. Another controller generates the direct axis current order (indirectly the generated real power) to charge or discharge the capacitor in order to

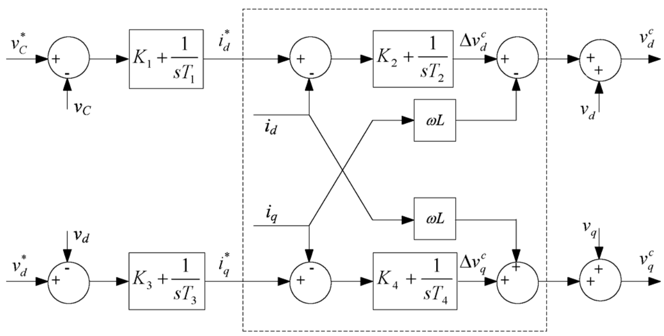

Fig. 17. STATCOM control scheme. (a) Capacitor voltage control loop. (b) Voltage-control loop.

TABLE IV
CONTROL SYSTEM PARAMETERS OF THE STATCOM

DC-capacitor voltage controller	K_1	0.23×10^{-1}
	T_1	0.16
i_d controller	K_2	4.5
	T_2	0.87×10^{-2}
Network voltage controller	K_3	0.18×10^{-1}
	T_3	0.57×10^{-1}
i_q controller	K_4	6.5
	T_4	0.87×10^{-3}
Filter time constants	$Tf1$	0.1×10^{-1}
	$Tf2$	0.1×10^{-2}
	$Tf3$	0.5×10^{-3}

regulate its voltage v_C to the desired reference v_C^*. The control system parameters are given in Table IV.

B. Tolerance Analysis

In this section, the impacts of variations of the system parameters on the transient response of the STATCOM are studied. The parameters of concern are distribution line resistance and inductance ($R_{\rm DL}$ and $L_{\rm DL}$), distribution transformer leakage inductance ($L_{\rm DT}$), size of the capacitor bank (C_B), STATCOM transformer leakage inductance ($L_{\rm ST}$), and load resistance and inductance (R_L and L_L). However, as in the system $L_{\rm DL}$ and $L_{\rm DT}$ are in series with each other and the same tolerance is considered for both of them, they have been replaced by one inductance (L_D) to simplify the problem to some extent. Note that although in this example only the aforementioned parameters are considered, in general, the choice and the number of uncertain parameters is up to the designer, and variations in other system parameters can also be included in the study.

In order to assess the transient behavior of the system, first, it is necessary to apply a disturbance to the system. In this case, in order to generate a transient phenomena, at $t = 0.5$ s, load #1 is disconnected from the system, and the STATCOM responds to it by adjusting the injected reactive power to maintain the network voltage at its desired level. In order to quantify the system performance during this transient phenomenon, the following performance index has been defined:

$$PI(R_{\rm DL}, L_D, C_B, L_{\rm ST}, R_L, L_L) = \int_{t=0.45s}^{t=0.95s} \left(\frac{v(t, R_{\rm DL}, L_D, C_B, L_{\rm ST}, R_L, L_L) - V_{\rm ref}}{V_{\rm ref}}\right)^2 dt. \quad (5)$$

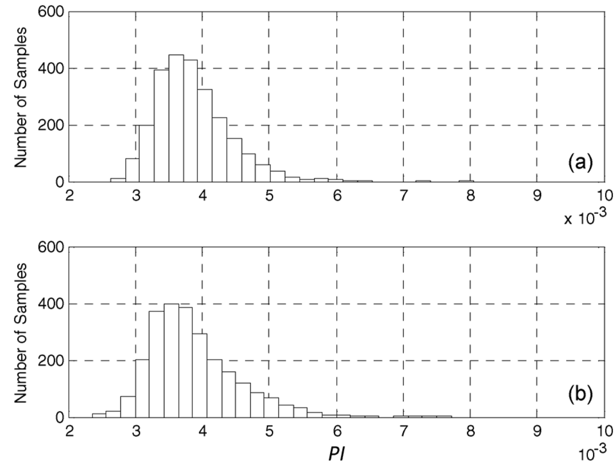

Fig. 18. Histogram of the performance index for the transient response. (a) Full EMT simulation. (b) Surrogate model.

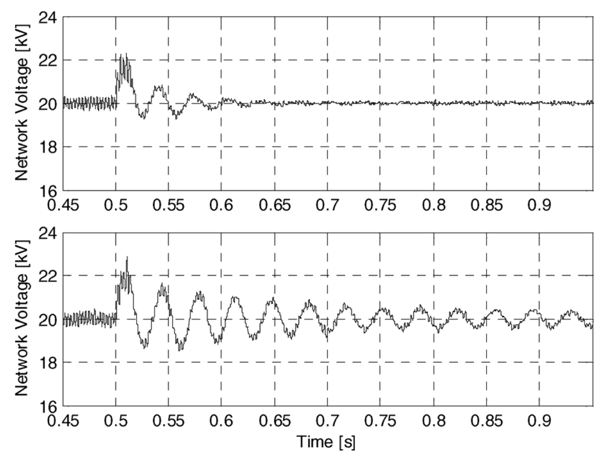

Fig. 19. STATCOM after the load interruption for $PI = 4$ (top) and $\mathrm{PI} = 10$ (bottom).

The above performance index integrates the squared error in the system voltage over the period in which the load is interrupted. As before, tolerance analysis has also been carried out using two different methods, namely, Monte-Carlo simulation with the EMT simulator, and Monte-Carlo simulation using the surrogate models. Fig. 18 shows the histogram of the results obtained from both methods after 2500 runs.

As seen, the results obtained from both methods are close to each other. However on a computer with 3.0 GHz AMD Athlon X2 64 Dual Core Processor and 4 GB of RAM, use of EMT simulation takes about 14 hours, whereas use of surrogate models takes about 15 minutes. In addition, it can be also seen that although at the worst-case scenario the value of performance index can reach 10×10^{-3}, in 98% of the cases, the performance index does not exceed 6×10^{-3}.

Table V shows the average and standard deviations obtained from both methods, indicating that the surrogate model gives essentially the same statistical information.

In order to provide visual sense about the performance index defined in (5), the transient response of the STATCOM has been shown below for two different values of the performance index,

TABLE V
STATISTICAL ANALYSIS RESULTS

Statistical analysis of the PI of the STATCOM*				
	Average		Standard Deviation	
	Surrogate Model	Simulation Results	Surrogate Model	Simulation Results
PI	3.8	3.9	0.63	0.55

* All values to be multiplied by 10^{-3}

namely, the average value (in Fig. 18) of 4×10^{-3}, and the worst-case value of 10×10^{-3}.

VII. Discussion of Computation Times

The main purpose of the paper is to develop a method which prevents repeated use of simulation, and yet gives enough information to see how the statistical variation in the performance of the system changes with uncertainty in the input parameters or values of the systems' components. In the example of Section VI, each EMT run takes approximately 21 s of CPU time. Using EMT simulation to conduct 2500 runs would take about 14 h, whereas the 43 runs (for 6 variables) required for obtaining the surrogate model takes only 15 min. The surrogate model is used in the 2500 runs hereafter, and only takes a total of approximately 6 s. The speedup, including the time required for creation of the surrogate model is 5600%. Note that if another investigation is required with a different statistical variation in input parameters, it would entail (perhaps) another 2500 runs, and another 14 h of CPU time. One does not need to recreate the surrogate model, and so the 2500 runs would only take about 6 s, which is a speedup of about 840,000%.

Note that the examples presented in this paper involve systems that are used for demonstrating the method and include a relatively small number of parameters to enable a better description of the proposed sensitivity analysis method. In practice, systems will generally have more complexity and a larger number of parameters. For such cases, the acceleration obtained by using the surrogate-based sensitivity analysis method will be even higher.

In addition, the design of FACTS controllers often involves several cycles of adjusting and tuning the parameters. In this context, time savings enabled by the proposed method will significantly shorten the design cycle.

VIII. Conclusion

This paper proposes a simulation-based surrogate model approach for fast tolerance analysis of power systems. A tolerance analysis tool based on the proposed method has been developed in conjunction with the PSCAD/EMTDC EMT simulation program. In the first step, the tool uses a multiple-run simulation approach to obtain the parameters of the second-order surrogate model. This model is then used for fast calculation of the performance indices. This paper also presents two practical application examples, in which the developed surrogate model successfully produced accurate tolerance analysis results in order(s) of magnitude shorter time than that required with a detailed simulation-based approach.

TABLE VI
SURROGATE MODEL COEFFICIENTS FOR HD5

	α_1	α_2	α_3	α_4	α_5
1	0.0	0.0	0.0	0.0	-0.1
α_1	3.2	-4.7	4.8	3.2	-4.3
α_2	-4.7	6.8	-5.5	-3.6	5.6
α_3	4.8	-5.5	4.6	2.9	-5.0
α_4	3.2	-3.6	2.9	2.0	-3.4
α_5	-4.3	5.6	-5.0	-3.4	5.5

* All values to be multiplied by 10^{-3}

TABLE VII
SURROGATE MODEL COEFFICIENTS FOR HD7

	α_1	α_2	α_3	α_4	α_5
1	-0.7	0.4	0.2	-0.8	0.2
α_1	9.6	-5.5	-2.3	11.5	-2.6
α_2	-5.5	2.4	1.8	-5.2	1.7
α_3	-2.3	1.8	0.6	-2.1	0.6
α_4	11.5	-5.2	-2.1	9.0	-2.2
α_5	-2.6	1.7	0.6	-2.2	0.2

* All values to be multiplied by 10^{-5}

TABLE VIII
SURROGATE MODEL COEFFICIENTS FOR HD11

	α_1	α_2	α_3	α_4	α_5
1	3.7	2.1	-3.6	-4.0	0.7
α_1	0.3	1.5	-1.3	-1.4	2.1
α_2	1.5	-1.0	-1.5	0.7	1.2
α_3	-1.3	-1.5	0.0	1.5	0.6
α_4	-1.4	0.7	1.5	-0.3	0.3
α_5	2.1	1.2	0.6	0.3	-2.4

* All values to be multiplied by 10^{-5}

TABLE IX
SURROGATE MODEL COEFFICIENTS FOR HD13

	α_1	α_2	α_3	α_4	α_5
1	-2.3	-2.3	1.1	-0.8	3.2
α_1	1.0	0.2	0.6	0.4	-2.1
α_2	0.2	2.3	0.2	-1.0	-1.7
α_3	0.6	0.2	0.6	-0.4	-0.6
α_4	0.4	-1.0	-0.4	2.3	-1.5
α_5	-2.1	-1.7	-0.6	-1.5	3.1

* All values to be multiplied by 10^{-5}

Appendix

In this appendix, the parameters of the surrogate models created for case study I and II are presented. Tables VI–XI provide first and second derivatives. For example, in the following table, $\partial HD_5/\partial\alpha_1$ is reported in the first column and first row of the data, and $\partial^2 HD_5/\partial\alpha_2\partial\alpha_3$ is reported in the third row and third column of the data.

TABLE X
SURROGATE MODEL COEFFICIENTS FOR PI

	R_{DL}	L_D	C_B	L_{ST}	R_L	L_L
1	0.0	1.1	0.1	0.4	0.0	0.1
R_{DL}	0.1	-1.6	0.2	-0.4	0.2	-0.6
L_D	-1.6	6.4	1.1	7.1	0.5	-0.2
C_B	0.2	1.1	1.3	0.0	-0.1	-0.6
L_{ST}	-0.4	7.1	0.0	1.9	0.2	-0.4
R_L	0.2	0.5	-0.1	0.2	1.4	-0.7
L_L	-0.6	-0.2	-0.6	-0.4	-0.7	1.2

* All values to be multiplied by 10^{-2}

TABLE XI
SCALING FACTORS FOR CASE STUDY II SENSITIVITIES

R_{DL}	L_D	C_B	L_{ST}	R_L	L_L
0.53 Ω	7.1 mH	53 μF	14.9 mH	34 Ω	55.9 mH

Please note that in calculation of the derivatives calculated for PI, the following scaling factors were used.

REFERENCES

[1] N. Femia and G. Spagnuolo, "True worst-case circuit tolerance analysis using genetic algorithms and affine arithmetic," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 47, no. 9, pp. 1285–1296, Sep. 2000.

[2] L. V. Kolev, V. M. Mladnev, and S. S. Vladov, "Interval mathematics algorithms for tolerance analysis," *IEEE Trans. Circuits Syst.*, vol. 35, no. 8, pp. 967–975, Aug. 1988.

[3] De Vivo, G. Spagnuolo, and M. Vitelli, "Worst-case tolerance analysis of non-linear systems using evolutionary algorithms," in *Proc. Int. Symp. Circuits Syst.*, 2003, vol. 4, pp. 576–579.

[4] H. Schjaer-Jacobsen and K. Madsen, "Algorithms for worst-case tolerance optimization," *IEEE Trans. Circuits Syst.*, vol. CAS-26, no. 9, pp. 775–783, Sep. 1979.

[5] T. Kato and T. Fukuyama, "Tolerance computation of harmonics in a power electronic circuit by parameter sensitivity analysis," in *Proc. 32nd IEEE Power Electron. Specialists Conf.*, Vancouver, BC, Canada, 2001, vol. 3, pp. 1730–1735.

[6] J. A. Martinez Velasco and F. Castro-Aranda, "EMTP implementation of a Monte Carlo method for lightening performance analysis of power transmission lines," *Ing.. Revista Chilena Ing.*, vol. 16, no. 2, pp. 169–180, Jun. 2008.

[7] S. J. Shelemy and D. R. Swatek, "Monte Carlo simulation of lightning strikes to the Nelson river HVDC transmission lines," presented at the Int. Conf. Power Syst. Transients, Rio de Janeiro, Brazil, Jun. 2001.

[8] K. C. Lee and K. P. Poon, "Statistical switching overvoltage analysis of the first B. C. hydro phase shifting transformer using the electromagnetic transients program," *IEEE Trans. Power Syst.*, vol. 5, no. 4, pp. 1054–1060, Nov. 1990.

[9] J. A. Martinez and F. Castro-Aranda, "Lightning performance analysis of transmission lines using the EMTP," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jul. 2003, vol. 1, pp. 295–300.

[10] J. Langston, M. Steurer, S. Suryanarayanan, T Baldwin, N. Senroy, S. Woodruff, M. Andrus, and J. Simpson, "Characterization of the transient behavior of an AC/DC conversion system for a notional all-electric ship simulation using sequential experimental design methodology," in *Proc. ACM Summer Comput. Simul. Conf.*, 2007, pp. 91–97.

[11] J. Langston, M. Steurer, T. Baldwin, J. Taylor, F. Hover, and J. Simpson, "Uncertainty analysis for a large-scale transient simulation of a notional all-electric ship pulse load charging scenario," presented at the Int. Conf. Probabilistic Meth. Appl. Power Syst., Rincon, Puerto Rico, May 2008.

[12] S. S. Isukapalli, S. Balakrishnan, and P. G. Georgopoulos, "Computationally efficient uncertainty propagation and reduction using the stochastic response surface method," in *Proc. 43rd IEEE Decis. Control Conf.*, Dec. 2004, pp. 2237–2243.

[13] D. Hana, J. Hab, and R.-M. He, "Multi-parameter uncertainty analysis in power system dynamic simulation: A new solution based on the stochastic response surface method and trajectory sensitivity method," *Elect. Power Compon. Syst.*, vol. 40, no. 5, Feb. 2012.

[14] J. R. Hockenberry and B. C. Lesieutre, "Evaluation of uncertainty in dynamic simulations of power system models: The probabilistic collocation method," *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1483–1491, Aug. 2004.

[15] H. W. Dommel, "Digital computer solution of electromagnetic transients in single and multiphase networks," *IEEE Trans. Power App. Syst.*, vol. PAS-88, no. 4, pp. 388–399, Apr. 1969.

[16] A. M. Gole, "Electromagnetic transient simulation of power electronic equipment in power systems: Challenges and solutions," presented at the IEEE Power Eng. Soc. Gen. Meeting, Montreal, QC, Canada, Jun. 2006.

[17] J. A. Martinez and J. Martin-Arnedo, "Expanding capabilities of EMTP-like tools: From analysis to design," *IEEE Trans. Power Del.*, vol. 18, no. 4, pp. 1569–1571, Oct. 2003.

[18] T. Fukuyama and T. Kato, "Tolerance computation of a power electronic circuit by higher order sensitivity analysis method," *Trans. Inst. Elect. Eng. Jpn. D*, vol. 121-D, no. 8, pp. 835–840, 2001.

[19] L. Kolev, "Worst-case tolerance analysis of linear DC and AC electric circuits," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 49, no. 12, pp. 1693–1701, Dec. 2002.

[20] L. Junzhao, P. Lima-Filho, M. A. Styblinski, and C. Singh, "Propagation of variance using a new approximation in system design of integrated circuits," in *Proc. IEEE Aerosp. Electron. Conf.*, Jul. 1998, pp. 242–246.

[21] A. Graupner, W. Schwarz, and R. Schuffny, "Statistical analysis of analog structures through variance calculation," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 49, no. 8, pp. 1071–1078, Aug. 2002.

[22] Fimmel, S. Quitzk, and W. Schwarz, "Large-scale tolerance analysis," in *Proc. Int. Conf. Parallel Comput. Elect. Eng.*, Sep. 2004, pp. 33–38.

[23] R. W. Menzies and Y. Zhuang, "Advance static compensation using a multi-level GTO thyristor inverter," *IEEE Trans. Power Del.*, vol. 10, no. 2, pp. 732–738, Apr. 1995.

[24] C. K. Sao, P. W. Lehn, M. R. Iravani, and J. A. Martinez, "A benchmark system for digital time-domain simulation of a pulse-width-modulated D-STATCOM," *IEEE Trans. Power Del.*, vol. 17, no. 4, pp. 1113–1120, Oct. 2002.

[25] C. Schauder and H. Mehta, "Vector analysis and control of advanced static VAR compensators," *Proc. Inst. Elect. Eng., Gen., Transm. Distrib.*, vol. 140, no. 4, pp. 299–306, Jul. 1993.

[26] J. N. Chiasson, L. M. Tolbert, K. J. McKenzie, and Z. Du, "A complete solution to the harmonic elimination problem," *IEEE Trans. Power Electron.*, vol. 19, no. 2, pp. 491–499, Mar. 2004.

[27] M. Heidari, S. Filizadeh, and A. M. Gole, "Support tools for simulation-based optimal design of power networks with embedded power electronics," *IEEE Trans. Power Del.*, vol. 23, no. 3, pp. 1561–1570, Jul. 2008.

[28] A. M. Gole, O. B. Nayak, T. S. Sidhu, and M. S. Sachdev, "A graphical electromagnetic simulation laboratory for power systems engineering programs," *IEEE Trans. Power Syst.*, vol. 11, no. 2, pp. 599–606, May 1996.

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