The Use of Genetic Algorithms in Validating the System Model and Determining Worst-case Transients in Capacitor Switching Simulation Studies

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Abstract: This paper presents two applications of the genetic algorithm (GA) for capacitor switching simulation studies, namely validation of the system model and determination of the worst case transients. For validating the system model, using both recorded and simulated data seems to be an efficient way. By modifying the system parameters, replaying the captured event, obtaining simulated waveforms, and comparing the simulated and recorded waveforms, the accuracy of the system model may be scrutinized and enhanced. For determining the worst case transients due to the capacitor switching, we are interested in the high frequency content, voltage peak value and transient duration. This paper has proposed genetic algorithm based approaches for addressing both of the two issues. Analysis results using data contributed by the sponsoring utilities are reported.

Keywords: Power Quality, Simulation, Genetic Algorithms, Capacitor Switching, Switching Transients, System Model Verification

I. INTRODUCTION

Capacitor banks are widely used by utilities in electric power systems for the purpose of reactive power compensation and voltage support. Customers may also add capacitors for power factor improvement. However, the capacitor switching events may cause detrimental overvoltages [1-6]. For example, a high voltage peak value may impose higher demands on the system insulation limits as well as cause the malfunction of surge protection systems [4]. The switching overvoltages may also have serious adverse impacts on the behavior of some electronic loads like adjustable speed drives. Many nuisance trips of the adjustable speed drives have been reported due to the DC side overvoltage [5-6].

It has been recognized that the characteristics of the transient voltages heavily depend on the closing times of the three phase switches. Usually, the three phase switch will not close its poles at the same time due to the mechanical limitations. The difference between the phase closing moments is normally within 3 ms [7]. To minimize the effects of switching overvoltages, specially designed equipment such as synchronously controlled breakers, circuit breakers with pre-insertion resistors and other devices have been suggested [8-10]. These approaches do entail additional control circuits and increased costs.

The standard three-phase switches continue to be utilized in some substations for closing the capacitors. Simulation studies have shown that the voltage peak value, high frequency content and switching transient duration are multi-modal functions of the closing times of each phase of the switches. It is therefore necessary that the characteristics of the switching transient voltages such as the voltage peak value, high frequency contents and transient duration be analyzed and predicted using simulation studies before an actual switching event may be experienced.

This paper discusses two issues related to the simulation studies of the capacitor switching transients, namely validation of the system model and determination of the worst case transients [7,11].

To deal with the issue of validating the models, utilities often install various types of transient recorders for capturing the voltage and current waveforms during the switching events. By using simulation studies, the simulated waveforms can be obtained and compared with the recorded waveforms. If the recorded and simulated waveforms match well, it may be safe to say that the system model used for simulation is quite accurate. Otherwise, the parameters or configurations of the system model need to be modified. The upgrading of the model is formulated as a multi-variable optimization problem and is dealt with in the paper using GA based approaches.

The second issue is the use of the models to determine the worst case transients. No systematic approach has been available in the past for finding the worst possible case in terms of the peak value, high frequency content or transient duration. Our objective is to apply the genetic algorithms (GA) for solving this complex optimization problem given the system model.

In the following sections, the genetic algorithms are introduced first. Then, applications of the genetic algorithms for system model validation purposes are presented. Next the GA based approaches for finding the worst case for the capacitor switching event are described. For each application, case studies are given using the data contributed by the sponsoring utilities.

II. GENETIC ALGORITHMS

Generally speaking, the GA is a simple yet powerful tool for finding the global solution to an optimization problem. It is suitable for large-scale optimization problems, has tendency to find the global optimal solution and shows little effects of the discontinuities in the objective function on the overall optimization performance [12]. The GA solution to the problem: Maximize $y = f(x_1, x_2, ..., x_n)$, where y is a real valued function and $x_i \in [a_i, b_i]$, takes the following main steps [12].

1) Encoding and Decoding: The most commonly used binary encoding approach is described here. Suppose the variable x_i ($a_i \le x_i \le b_i$) is to be represented by a binary string (also called chromosome) of length L_{bi}. Then the encoded value x_{bi} for the variable will be

$$x_{bi} = \mathrm{round}((x_i - a_i)(2^{L_{bi}} - 1)/(b_i - a_i)) \quad (1)$$

and the decoding process is given by

$$x_i = (b_i - a_i)x_{bi}/(2^{L_{bi}} - 1) + a_i \quad (2)$$

2) Fitness Evaluation: This stage evaluates the performance of a solution according to the following fitness function

$$y = f(x_1, x_2, ..., x_n) \quad (3)$$

The larger the value obtained by this equation, the better the solution is.

3) Selection of Parents: A parent is defined as a vector of binary strings of all the variables obtained through the encoding process that will be used to produce the offspring. The standard Roulette wheel approach is adopted here.

4) Crossover and Mutation: Crossover and mutation are the two processes through which the parents produce the offspring. In the crossover, the two parents exchange some bits of their binary strings. In the mutation, the offspring obtained through the crossover process complement some bits of their binary strings. Appropriate values for the crossover probability P_c and mutation probability P_m need to be selected. Normally we take $P_c = 0.6 \sim 0.9$ and $P_m = 0.01 \sim 0.1$. Elitism principle is adopted during which the best chromosome (or a few chromosomes) is (are) first copied to the new population, and the rest is done in the classical way. Elitism can greatly increase the performance of GA because it prevents losing the best found solution.

In practical applications, an initial value for the solution is given. Then the above procedure is iterated until the convergence criterion is met. The criterion is normally defined as when the offspring strings are dominated by an individual string or the total iteration times exceed a specified value or the fitness value reaches a specified value. The general flowchart of the genetic algorithm is shown in Fig. 1. In the figure, the ranges of the variables can be estimated according to their typical values. Applications of GA for system model validation and determination of the worst case transients are illustrated in the following sections.

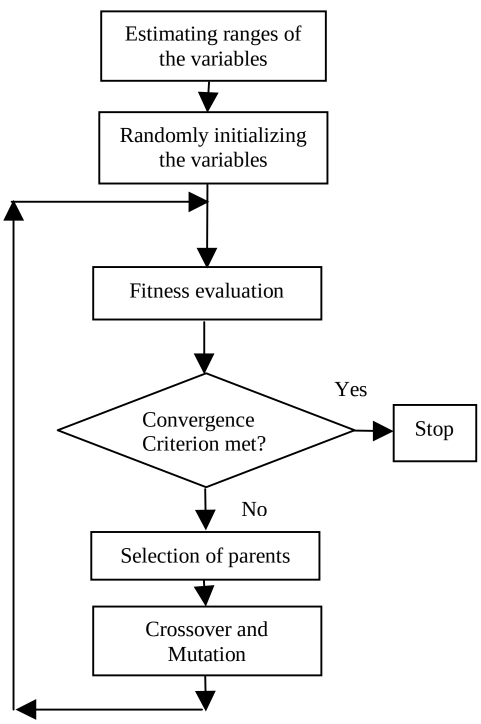

Fig. 1 The general flowchart for the genetic algorithm

III. MODEL VALIDATION USING GA

A. Problem Formulation

The system model validation is to verify the accuracy of the system model and evaluate certain parameters used for the simulation studies. The validation is done by comparing the simulated waveforms and data recorded during specific events. The data usually include the voltage or/and current waveforms that may be collected by diverse types of digital recorders. Without losing generality, all the data here are supposed to be recorded by the DFRs. By replaying the event using simulation packages like Electromagnetic Transients Program (EMTP) and comparing the simulated and recorded waveforms, the degree of accuracy of the system model can be evaluated [13]. If the matching does not satisfy pre-defined criteria, certain model parameters or configurations may be modified. The event is replayed and then the simulated and recorded waveforms are compared again. This process is iterated until certain pre-defined criteria are met. The number of unknown or uncertain parameters of a system may be several depending on the size of the system. The most credible values for these parameters are those values that will generate the waveforms that best match the recorded waveforms. In the work presented here, we are trying to match the frequency spectra of the voltages and currents obtained from the EMTP simulations and those obtained from the DFRs using Fourier transform. The mathematical formulation of the problem is illustrated next using a capacitor switching example.

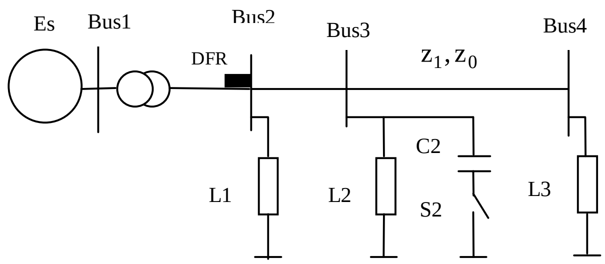

Fig. 2 A sample distribution system

The one-line diagram of a sample distribution system is shown in Fig. 2. L_1, L_2, and L_3 represent the loads. C_2 is the capacitor bank installed at bus3 for improving the power factor of load L_2. S_2 is the switch used for controlling the open or close status of C_2. z_1 (= $r_1 + jx_1$) and z_0 (= $r_0 + jx_0$) are the positive sequence and zero sequence impedance of the feeder between bus3 and bus4. For simplicity, suppose that for the system, only z_1 and z_0 are the parameters that have uncertain values and need to be evaluated. Suppose that a switching event occurred when the switch S_2 closes the capacitor bank C_2. The voltage and current waveforms during the switching event were recorded by the DFR installed at bus2.

Suppose that the switch S_2 is a normal switch without any supplementary synchronizing control circuits, and the closing times for the three phases are designated as T_a, T_b and T_c respectively. Due to mechanical limitations of the physical switch, these closing times are rarely the same and normally satisfy the following equations [7].

$$|T_a - T_b| < \delta \tag{4}$$

$$|T_a - T_c| < \delta \tag{5}$$

$$|T_b - T_c| < \delta \tag{6}$$

δ denotes the maximum difference between the closing times for different phases and is chosen as 3 ms here.

Then the problem of evaluating r_1, x_1, r_0 and x_0 can be formulated as finding the values for r_1, x_1, r_0, x_0, T_a, T_b and T_c that minimize

$$f_c(r_1, x_1, r_0, x_0, T_a, T_b, T_c) = \sum_{k=1}^{N_v}\{r_{kv}\sum_{n=1}^{H_v}|V_{ks}^n - V_{kr}^n|\} + \sum_{k=1}^{N_i}\{r_{ki}\sum_{n=1}^{H_i}|I_{ks}^n - I_{kr}^n|\} \tag{7}$$

or maximize

$$f_f(r_1, x_1, r_0, x_0, T_a, T_b, T_c) = -f_c(r_1, x_1, r_0, x_0, T_a, T_b, T_c) \tag{8}$$

where

$f_c(r_1, x_1, r_0, x_0, T_a, T_b, T_c)$: the defined cost function.

$f_f(r_1, x_1, r_0, x_0, T_a, T_b, T_c)$: the defined fitness function. The larger the value of the fitness function, the better the solution is.

k : the index of the voltage or current quantities

n : the harmonic order for voltages or currents.

r_{kv} and r_{ki} : the weights for the errors of the voltages and currents respectively.

V_{ks}^n and V_{kr}^n : the voltage magnitude of the n-th harmonic occurring during the event obtained from EMTP simulation and from DFRs respectively.

I_{ks}^n and I_{kr}^n : the current magnitude of the n-th harmonic during the event obtained from EMTP simulation and from DFRs respectively.

H_v and H_i : the total number of harmonics calculated for the voltage and current waveforms respectively.

N_v and N_i : the total number of the voltage and current quantities respectively.

The term harmonic is often used to denote the steady state phenomena and the switching transients do not belong to this category. Hence it is worth noting that the term harmonic here is used to represent the spectra of the signal, and does not mean the steady state harmonics. All the spectra components are calculated using one cycle Fourier transform on the sampled voltage data in the cycle immediately following the occurrence of the switching event.

It is noted that the largest fitness value defined by (8) is equal to zero and can be reached if the spectra of the simulated waveforms exactly match those of the DFR waveforms. Therefore, the best estimate for the unknown parameters would be the one that maximizes (8).

For this multi-variable optimization problem, it is difficult to use the gradient-based method to find the global optimal solution because of the multi-modality nature of the problem. An exhaustive search through every possible solution may be too time-consuming and hence impractical. Applications of GA for solving this problem are illustrated as follows.

When applying the GA to the system model verification and parameter evaluation, (8) will be the actual form for the fitness function. r_1, x_1, r_0, x_0, T_a, T_b and T_c are the seven changing variables. In the flowchart as shown in Fig. 2, the ranges during which the variables vary can be decided as follows. r_1, x_1, r_0, and x_0 can be selected as typical values according to the type of the feeder used. T_a, T_b and T_c can be selected from 0 to 16.67 ms subject to (4-6).

It is noted that if the parameters r_1, x_1, r_0, x_0 are known, then the variables in the GA will only need to include T_a, T_b and T_c. In such a case, the proposed method simply serves the purpose for replaying the recorded events, i.e. finding the closing times that can generate simulated waveforms that best match the recorded ones. Replaying a recorded event may be helpful for a better understanding of the event as well as of the system under study.

B. An Example

This section presents an example for illustrating the concept described above. Part of a distribution system provided by the TXU Electric and Gas is depicted in Fig. 1. A switching event is created by switching in the capacitor C_2. The transient overvoltage waveforms at bus2 caused by the switching event are recorded using Dranetz 4300 recorder with a sampling frequency of 7680 Hz and shown in Fig. 3.

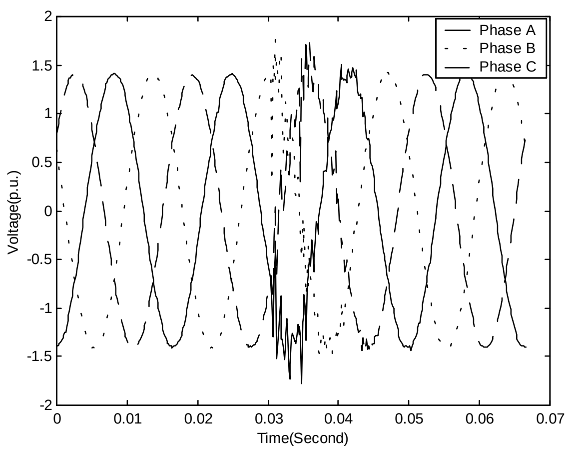

Fig. 3 The recorded voltage waveforms at bus2

In the GA based approach, the length of the strings for the each of the three variables is chosen as 10 bits. The number of population in each generation is selected as 10. The crossover probability is chosen as 0.8 and mutation probability chosen as 0.01. After 66 iterations, the GA obtains the following results: T_a = 0.0306, T_b =0.03137, T_c =0.03138, r_1=0.38, x_1=0.88, r_0 =1.24, and x_0 =3.10 with time in second and impedance in p.u.. The simulated voltage waveforms with these parameters are plotted in Fig. 4 that shows a quite close matching between the simulated and the recorded waveforms. This verifies that the model of the system as well as the estimated parameters are reasonably accurate.

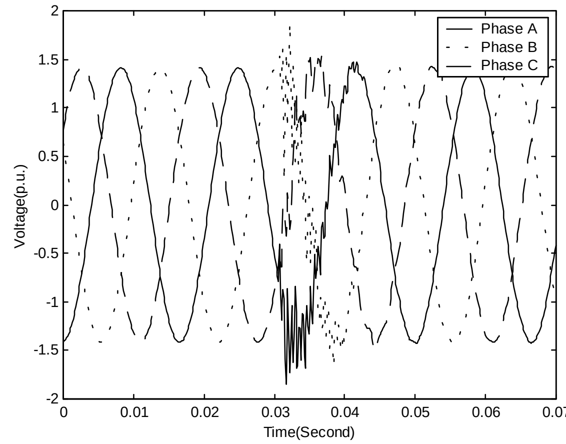

Fig. 4 The simulated voltage waveforms at bus2

IV. DETERMINATION OF THE WORST CASE TRANSIENTS USING GA

A. Problem Formulation

After the system model is validated, various simulation studies may be carried out for planning purposes. This section illustrates how the worst case transients due to capacitor switching are determined utilizing genetic algorithms. The procedure is related to finding the maximum voltage peak value, maximum high frequency contents and maximum transient duration. These quantities are defined as follows.

1) Voltage peak value (V_{peak}): the maximum absolute value of the sampled voltage waveform

2) High frequency content (V^n): the n-th harmonic content of the sampled voltage waveform

3) Transient duration (T_d): the time between the starting moment of the switching event and the end of the transient

As described in the previous section, capacitor banks may be switched on using non-synchronized switches whose three phase closing times are normally not the same and satisfy (4-6). The characteristics of the transient overvoltages due to the capacitor switching event are significantly affected by the closing times. The voltage peak value, high frequency content and transient duration are multi-modal functions of the closing times. As an example, Fig. 5 shows the voltage peak value versus the phase b and phase c closing times with the phase a closing time fixed. It is therefore difficult to solve this optimization problem using the traditional gradient-based or sequential search-based approaches, and this motivates the use of the GA based method.

The flowchart of the GA method for system validation is the same as that shown in Fig. 2. The GA variables include T_a, T_b and T_c. The fitness functions are defined as the voltage peak value, high frequency content of interest, or the transient duration respectively.

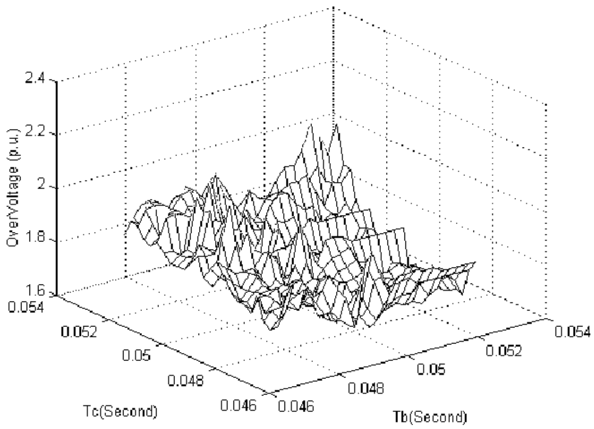

Fig. 5 The voltage peak value versus the closing times of phase b and phase c

B. An Example

This section describes an actual example illustrating the proposed approach for finding the worst case transients due to the capacitor switching events. Fig. 6 shows a sample distribution system that is the same as that shown in Fig. 1 except the capacitor bank C_2 is already in service, and a new capacitor bank C_1 is to be switched on by the switch S_1. The capacitor bank C_1 is aimed at improving the power factor of the load L_1. Before switching on C_1, simulation studies need to be carried out for observing the overvoltage characteristics due to the switching of C_1. The purposes of doing this are to foresee the possible effects of the switching event and to take measures if needed to mitigate the adverse effects.

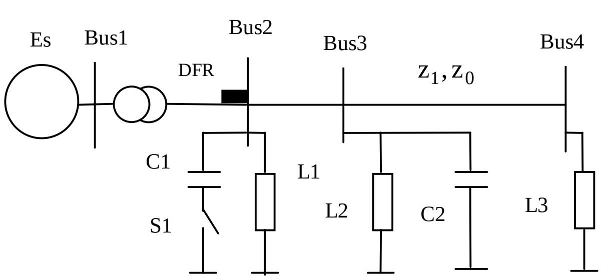

Fig. 6 A sample distribution system

The proposed GA approach is used to find the maximum voltage peak value, high frequency content and transient duration as follows. In the following applications, the length of the strings for each of the three variables is chosen as 10 bits. The number of population in each generation is selected as 20. The crossover probability is chosen as 0.8 and mutation probability chosen as 0.01.

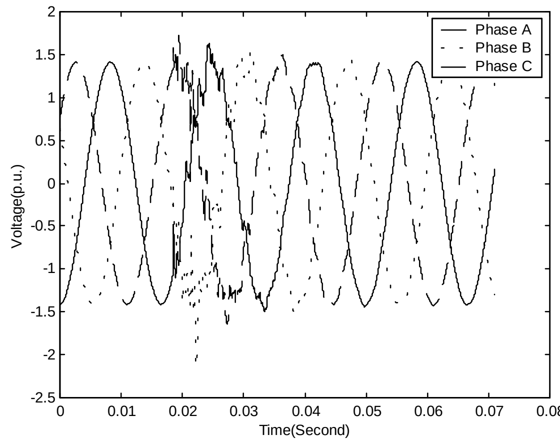

Fig. 7 The voltage waveforms with the highest peak value

1) Voltage peak value: The maximum voltage peak value is found to be 2.15 p.u. and it is reached with T_a = 0.01843 second, T_b =0.02134 second and T_c =0.02120 second. The total iteration number needed for convergence is 34. The transient voltage waveforms are shown in Fig. 7.

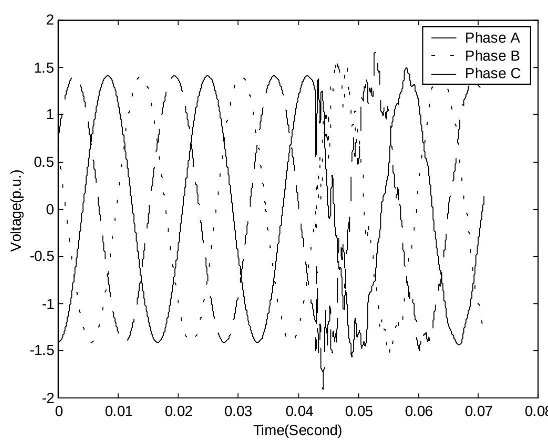

Fig. 8 The voltage waveforms with the highest 480 Hz content

2) High frequency content: it has been found that the dominant high frequency due to the system capacitance and inductance is 480 Hz. As an example, we are determining the maximum value for the 480 Hz content here. The maximum value obtained by the GA approach is 0.077 p.u. for phase c voltage with T_a = 0.04291 second, T_b =0.0451 second and T_c =0.04302 second. The total iteration number needed for

convergence is 17. The transient voltage waveforms are shown in Fig. 8.

3) Transient duration: The maximum transient duration obtained by the GA approach is 0.038 second with T_a = 0.04330 second, T_b =0.04158 second and T_c =0.04201 second. The total iteration number needed for convergence is 20. The transient voltage waveforms are shown in Fig. 9.

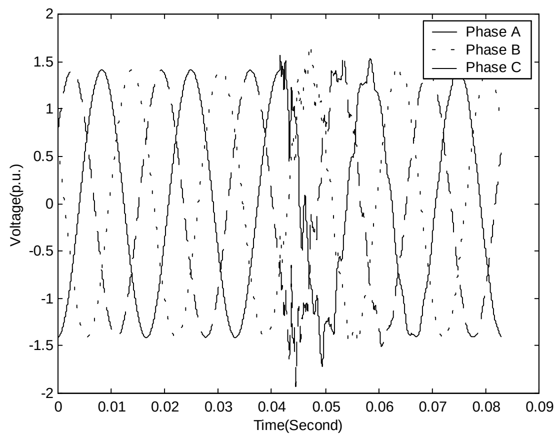

Fig. 9 The voltage waveforms with the highest transient duration

V. CONCLUSIONS

A genetic algorithm based approach for system model validation using recorded and simulated data is presented. The model used in the capacitor switching example is utilized for illustrating the concept. The system parameters to be evaluated and the three phase closing times are the changing variables in the genetic algorithm. The fitness function is defined as the difference between the spectra of the recorded and simulated waveforms. Also presented is a genetic algorithm based method for determining the worst case capacitor switching transients. The three phase closing times are the changing variables. The fitness function is defined as the maximum peak value, high frequency content or transient duration. In both applications, by iteratively changing the appropriate variables, running simulation, and processing and evaluating the simulated results, the genetic algorithm guides the process of searching for an optimal solution. It is shown that the genetic algorithm may be utilized for tackling various types of power system problems as long as they can be properly formulated as an optimization problem.

VI. ACKNOWLEDGEMENT

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VIII. BIOGRAPHIES

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