Commutation Failure Analysis in HVDC Systems Using Advanced Multiple-Run Methods

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Abstract-- Failure of the commutation process is a serious malfunction in the operation of HVDC converters. The complexity and nonlinearity of the systems usually prohibits a closed form representation of the problem, and hence limits the applicability of analytical methods to study this phenomenon. In this paper a new index to assess the susceptibility of an HVDC system to commutation failure is introduced, and two simulation-based approaches are proposed for its evaluation. In the first method, the multiple runs (MR) of an electromagnetic transient simulation program (PSCAD/EMTDC) are conducted through a specialized algorithm whose successive iterations solve the problem with arbitrary accuracy. In the second approach, the problem of finding the proposed index is formulated as an optimization problem and by using the results of the first method the paper shows that the optimization surface in this problem has several closely located local minima. In this method, a dedicated optimization algorithm addresses the multi-modality of the optimization surface. A genetic algorithm (GA) approach is combined with a transient simulation program and the combined tool is used to tackle the problem. The paper shows that both methods are successful in finding the critical value of the index.

Keywords: HVDC, commutation failure, transient simulation, genetic algorithms.

I. INTRODUCTION

FAILURE of the commutation process is a serious malfunction in HVDC converters and is mainly caused by the ac side faults resulting in severe voltage drops [1]. Although research into the causes and consequences of this phenomenon has resulted in practical countermeasures, further research is necessary to develop methods for predicting the likelihood of the occurrence of commutation failure. Since commutation failure is a short-term transient phenomenon, electromagnetic transient simulation programs are perfectly suited for the studies pertinent to it. This paper presents two novel approaches to conducting multiple runs (MR) of an emtp-type simulation program (PSCAD/EMTDC) to assess the susceptibility of an HVDC system to the occurrence of commutation failure. In the proposed methods, the ac voltage drops on the ac terminal are simulated through switching an appropriately sized 3-phase inductor. The smallest value of the inductor bank that can be switched without causing commutation failure is a good index for measuring the susceptibility of the system to commutation failure [2]. The occurrence of the commutation failure is a function of the size of the inductor as well as the point-on-wave connection time. Evaluation of this index, however, is found to be challenging, since the complexity and nonlinearity of the system usually prohibits a closed form formulation, and therefore analytical methods will be less applicable. The paper proposes two simulation-based techniques for solving this problem. In the first method, the MR is conducted through a specialized algorithm, which performs an interval-based search, and determines an interval around the smallest value of the inductor that does not cause commutation failure. Successive iterations of the algorithm cause this surrounding interval to become arbitrarily small until the desired accuracy is obtained. The solution of the problem using the above-mentioned method is significantly faster than a conventional multiple-run solution and results in considerable savings in computer resources. Using the results of the above method, the paper shows that the solution surface in this problem has several closely located local minima. This provides strong incentives to further examining the problem using a formal optimization algorithm, and forms the basis for the second solution method, which uses optimization-enabled transient simulation [3]. Here, a dedicated optimization algorithm strategically feeds appropriate test parameters, i.e., inductor value and point-on-wave connection time, to the MR and each transient simulation run is used to evaluate the performance of the system for these parameter sets. To address the multi-modality of the optimization surface, a genetic algorithm (GA) approach is combined with transient simulation and the results are reported in the paper. The paper shows that this method is successful in finding the globally smallest value of the inductor. The paper investigates the problem in detail, and provides an in-depth overview of the implementation of the two solution methods and compares their performance in terms of computational intensity and adaptability to higher order problems.

II. ANALYSIS OF COMMUTATION FAILURE IN THE HVDC CONVERTER

Fig. 1 shows the basic equivalent circuit of a line commutated converter, for which the process of commutation between valve 1 and valve 3 is illustrated. Corresponding

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voltage and current waveforms are shown in Fig. 2. Under normal circumstances, the voltage across the valve being turned off has to remain negative for a certain period of time after the extinction of its current (denoted by the extinction angle γ in Fig. 2) so that it becomes capable of blocking the forward voltage. Should the valve voltage become positive prematurely, the valve may turn on even without a firing pulse, resulting in the failure of the commutation process. Commutation failure is mostly observed at the inverter side of HVDC links, where large firing angles are used [4]. The minimum value of the extinction angle required for the proper operation of a valve is specified by the valve manufacturer; however, at the inverter side of HVDC systems the extinction angle is regulated to a value higher than the valve specifications to allow control adjustments and also leave an adequate safety margin for unforeseen events in the power system, such as faults. Severe faults such as the voltage drops, phase shifts, or sudden increase in dc current may cause the commutation process to fail.

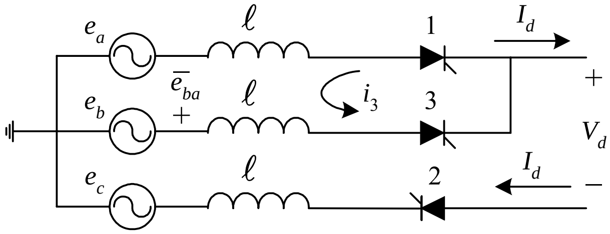

Fig. 1. Basic equivalent circuit during the commutation

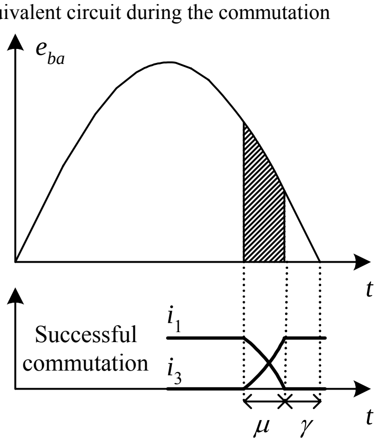

Fig. 2. Voltage and currents during the commutation

In a simple case as shown in Fig. 1, it is possible to set up and solve the equations and check if an event, such as a certain amount of voltage drop, will cause commutation failure or not [1]. In a real system however, there are many devices connected to the ac terminal of the converter including the filters, capacitor banks, etc. The model of the ac network will have more details as well. Besides, control system parameters also affect the likelihood of commutation failure. For such cases, the analytical approach becomes prohibitively impractical if not impossible.

One of the major reasons of commutation failure is the faults on the ac system, to which the inverter is connected. In [2] an index is proposed to assess the likelihood of commutation failure in a converter after occurrence of a remote 3-phase to ground fault. The index used is the minimum size of an inductor, whose switching to the ac terminal does not cause commutation failure. This index, denoted by L_{min}, proves to be a useful indication for the vulnerability of the system to commutation failure [2]. Other indices, such as the Short Circuit Ratio (SCR), which is essentially based on steady state quantities, are also proposed; however, since commutation failure is a phenomenon with a transient nature, L_{min}, which is obtained through the analysis of the transient behavior of the system, is better suited.

III. Case Study

Fig. 3 shows a schematic diagram of an HVDC system. Z_f represents all the filters and capacitors and Z_s is a model of Thevenin impedance of the ac network. The CIGRÉ HVDC Benchmark model [5] is used as the base case for the studies in this paper. A model of the system along with its controls is developed in the PSCAD/EMTDC. Voltage drops are modeled by connecting a 3-phase inductor bank to the ac bus; occurrence of the commutation failure is checked within five cycles after the switching instant (to allow steady state to be reached).

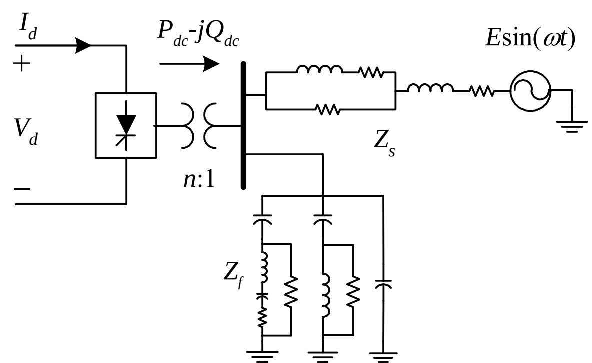

Fig. 3. Schematic diagram of an HVDC system

Test for the commutation failure is carried out using the following equation, which can be verified readily to hold under normal operating conditions.

$$|i_a|+|i_b|+|i_c|=2I_d \tag{1}$$

Should the above be violated under steady state conditions, it is considered to be an indication of commutation failure.

IV. Study Methodology

As mentioned earlier, study of the commutation failure involves two parameters being the size of the inductor bank and its point-on-wave switching instant. For every instant of (point-on-wave) switching time, there exists a minimum inductor size that does not cause commutation failure. Obviously, any larger inductor can be connected at this instant of time without the risk of commutation failure. The proposed index, L_{min}, is the largest of all the minimum inductor sizes so determined, i.e., $L_{\min} = \max\{\min\{L(T)\}\}$, where $L(T)$ is the size of an inductor that can be connected at time T without causing commutation failure, and T spans an entire fundamental frequency period.

A. Conventional Multiple-Run

Multiple-run is a feature of an electromagnetic transient simulation program, which allows the user to conduct parametric studies by consecutively running a simulation case with a series of sequentially or randomly generated parameter sets.

Fig. 4 shows the results of a parametric study of the commutation failure using the conventional MR for the CIGRE HVDC benchmark model. The graph shows the occurrence of the commutation failure as a function of the inductor bank size and the point-on-wave switching instant (covering a full period of 20 ms). Occurrence of commutation failure is indicated by a +1 level. For an acceptable accuracy in finding the L_{min}, it is necessary to consider at least 100 points in a cycle [1]. If the size of the inductance is required to have the same resolution, total number of simulations through the MR will be extremely large, resulting in excessive computational burden. Therefore, finding other approaches with better efficiency is inevitable.

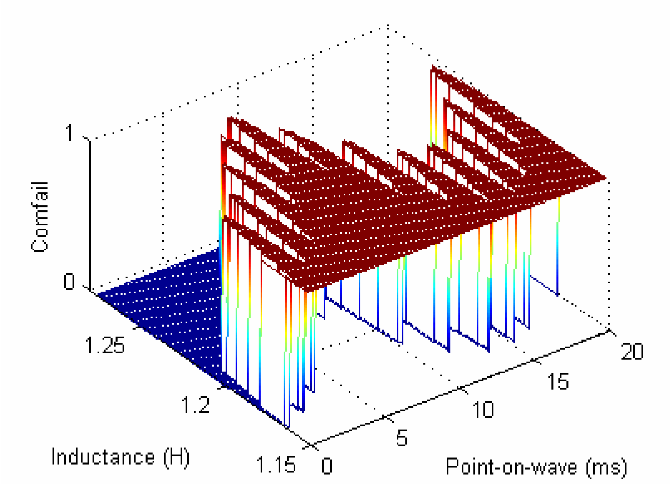

Fig. 4. Test of comfail for each inductance and point-on-wave pair

The main drawback of the MR approach is the excessively large number of simulations, which is initiated by the fact that the search is unintelligently spanned over areas that could be eliminated using enhanced methodologies. For example if a certain value of inductance does not cause commutation failure at a given instant of time, then there is no need for trying larger inductances at that point. It should however be stated that the MR is a powerful method when parametric studies are required as it provides an (arbitrarily) accurate representation of the interdependencies of complicated networks.

B. Strategically Guided Multiple-Run

The conventional multiple-run method, as described above, is capable of fining the value of L_{min}, at the expense of a large number of simulations. This is due to the lack of intelligence for eliminating the regions that do not contain the solution. To address this issue, an enhanced search methodology is developed and coupled with the transient simulation so that MR simulations are intelligently supervised.

The underlying assumption in this method is that for a given instant of time, having found an inductor size that does not cause commutation failure guarantees that larger inductors will not do otherwise (for the same point). The method is schematically represented in the flowchart of Fig. 5. As shown the method is based on establishing an interval around the global solution; it then squeezes the interval in several successive iterations. The encompassing interval around L_{min} can be arbitrarily small resulting in a very accurate solution (evidently obtained at the expense of more simulations). The procedure shown is implemented in the PSCAD/EMTDC transient simulation program as a component supervising and steering the MR simulations. Part of the simulation case is shown in Fig. 5.

The results obtained using the conventional MR method as well as the strategically guided MR (for each stage) described in this section are presented in Table I. As seen, the guided-MR results in the same solution in a significantly smaller number of simulations compared to the conventional MR (385 as opposed to 10000), resulting in a large amount of savings in terms of the number of simulations.

C. Optimization-Based Approach

Study of the susceptibility of HVDC systems to commutation failure, as presented in this paper, is essentially an optimization problem, the objective of which is minimization of the value of an inductor whose connection does not cause commutation failure at any switching instant. It is therefore technically possible to use an optimization algorithm to solve the problem. The implementation however proves to be challenging, firstly because the complexity of the nonlinear system prohibits a closed form representation of the objective function and secondly because the optimization surface is quite rough and contains several closely located local optima (see Fig. 4).

Optimization-enabled transient simulation [3] is an effective method for solving optimization problems where an explicit objective function (in terms of design parameters) does not exist. It is therefore perfectly suited to tackle the minimization problem of concern in this paper.

The underlying concept in the optimization-enabled transient simulation is to use a transient simulation program to evaluate the objective function while an optimization algorithm selects the parameter sets to be tested. Unlike the guided MR method described in the preceding section, which is specifically tailored for the determination of L_{min}, the optimization-enabled transient simulation provides a universal means for the optimal design of complex networks, and as such provides the flexibility to apply it to a wider range of problems.

The choice of the optimization algorithm to be used in conjunction with the simulation program largely depends on the nature of the problem under consideration. To address the multi-modality of the optimization surface in our problem, one has to use an optimization algorithm that provides a higher likelihood of finding the global optimum. Genetic Algorithms (GA) are known to have such a property and as such are chosen to be interfaced with PSCAD/EMTDC simulation program.

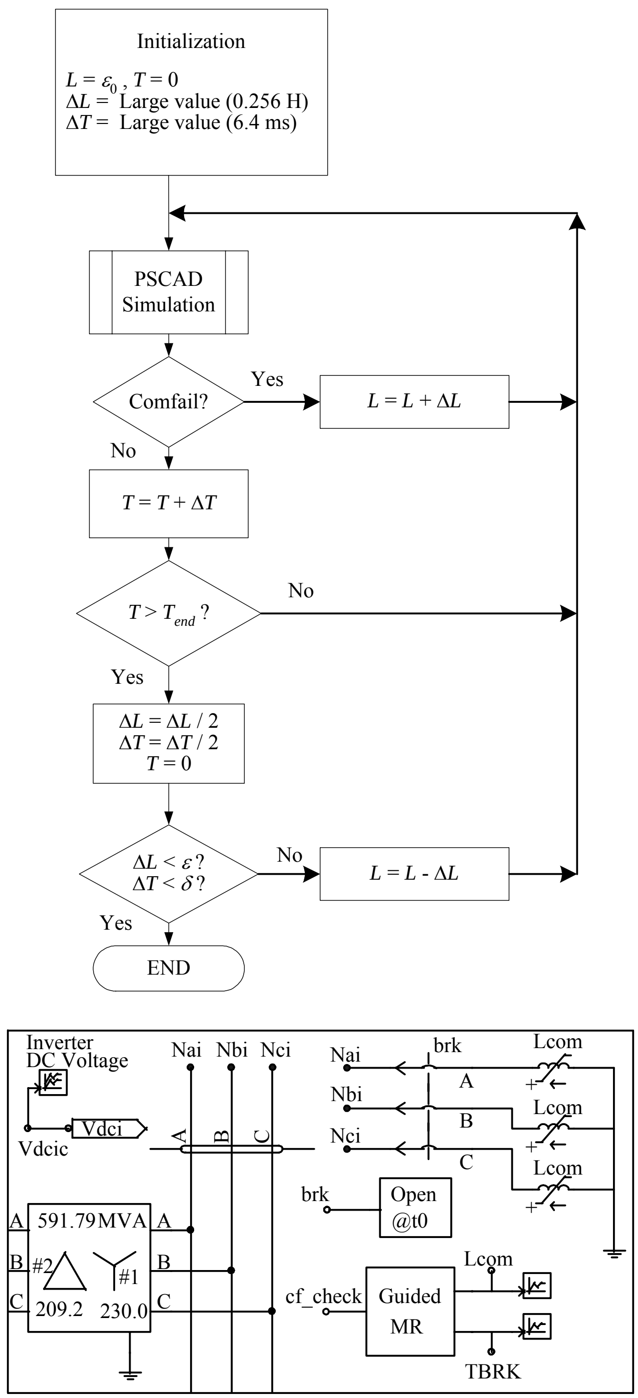

Fig. 5. Guided MR algorithm and its implementation in PSCAD/EMTDC

Genetic Algorithms are mathematical procedures imitating the evolution of biological organisms. In a GA formulation, design parameters (also referred to as genes) are coded into an ordered sequence known as a chromosome. The algorithm uses purposeful random operations on a population of chromosomes to evolve the current population into a successive generation with hopefully better traits (which in an optimization setup implies a better fit to the design objectives). Typically, a GA solution consists of the following sections.

1) Initial and Surviving Populations

As mentioned earlier, design parameters (in our case the value of the inductor and the point-on-wave switching time) are coded into chromosome in the form of two binary- or real-valued genes. The algorithm randomly initializes a large number of such chromosomes to form its initial population or first generation. Random distribution of the entries causes a wide scattering of the initial population members over the optimization space and increases the chance of estimating the global optimum. Evaluation of the initial population (in our case through simulation) results in the assignment of an objective function evaluation to each of the chromosomes.

To form the next generation, a fixed number of initial population chromosomes are selected (usually the ones with better objective function evaluations) and the number is fixed throughout the successive generations.

2) Selection of the Mating Pairs and Mating

Once the current population is formed, operations are carried out to produce the upcoming generation. Normally a number of better performing chromosomes are selected to form the mating pool and to re-produce the offspring. Several techniques exist to select the mating pool members (the parents) including random, Roulette Wheel (rank weighting and cost weighting) and tournament methods [6],[7].

Having selected the mating chromosomes, they are coupled to produce a given number of offspring that will replace an equal number of existing chromosomes. Various blending methods (crossover methods) are employed to generate suitable offspring that hopefully inherit good traits of their parents and to develop them into better features. The basic idea in the process of mating is to pass on the desirable features of the better performing chromosomes into the offspring so that the next generation has a better overall performance.

3) Mutations

The process of mating produces a complete generation of chromosomes, which consists of a number of mating pairs and their offspring. While mating aims at generating offspring with better objective function evaluations, it is likely that a generation such produced be trapped in a local optimum. To remedy this, a given number of chromosomes in the current generation are selected and their genes are randomly altered. This process, which is known as mutation (note the analogy to the biological mutation), randomly scatters some of the chromosomes to decrease the likelihood of convergence to a local optimum.

Implementation of a GA largely depends on the designer's discretion, as to how the parameters, such as the pairing and mating methods and mutation rates, are selected. The flexibility of a GA provides several degrees of freedom to adapt the method to a given application.

The major drawback of a GA approach is the number of objective function evaluations required. The solution usually produces several generations before convergence, and as such the total number of simulations can be quite high. While this can potentially be a concern in many applications, the fact that GAs are very affordable solutions in optimization of multi-modal and also mixed-integer problems makes them popular in a large number of applications.

Table I summarizes the results of the solution of the commutation failure problem using the GA-based transient simulation. As shown the global optimum has been correctly identified by the algorithm, which confirms the capability of the GA in estimating the global optimum in spite of the multi-modality of the optimization surface. The optimum value of 1.26 is obtained after less than 5000 simulations. This is by far larger than that of the guided MR approach, however is still over 50% less intense than the conventional MR. Although the guided MR method has a better convergence rate than the optimization-enabled transient simulation, the GA solution does demonstrate the application of a dedicated, general-purpose optimization tool in the design of a multi-modal problem and provides a tool suitable for the optimal design of complex systems in other situations as well.

TABLE I
COMPARISON BETWEEN VARIOUS SOLUTION METHODS

<table>
<tr><th colspan="5">Conventional Multiple Run</th></tr>
<tr><td>Range for L</td><td>Range for T</td><td>ΔT (ms)</td><td>ΔL (H)</td><td>Number of runs</td></tr>
<tr><td>[1.0,1.4] H</td><td>[0,20] ms</td><td>0.2</td><td>0.004</td><td>10000</td></tr>
<tr><th colspan="5">Strategically Guided Multiple Run</th></tr>
<tr><td>Stage</td><td>ΔT (ms)</td><td>ΔL (H)</td><td>L_{min}</td><td>Number of runs (cumulative)</td></tr>
<tr><td>1</td><td>6.4</td><td>0.256</td><td>1.312</td><td>6</td></tr>
<tr><td>2</td><td>3.2</td><td>0.128</td><td>1.312</td><td>15</td></tr>
<tr><td>3</td><td>1.6</td><td>0.064</td><td>1.312</td><td>34</td></tr>
<tr><td>4</td><td>0.8</td><td>0.032</td><td>1.280</td><td>59</td></tr>
<tr><td>5</td><td>0.4</td><td>0.016</td><td>1.264</td><td>109</td></tr>
<tr><td>6</td><td>0.2</td><td>0.008</td><td>1.264</td><td>247</td></tr>
<tr><td>7</td><td>0.2</td><td>0.004</td><td>1.264</td><td>385</td></tr>
<tr><th colspan="5">Simulation-Based Genetic Algorithm</th></tr>
<tr><td>Initial population</td><td>Surviving population</td><td>Mating pool</td><td>Mating method</td><td>Mutation rate</td></tr>
<tr><td>200</td><td>100</td><td>50</td><td>Rank weighting</td><td>10%</td></tr>
<tr><td colspan="2">Number of generations</td><td colspan="2">Total number of simulations</td><td>L_{min}</td></tr>
<tr><td colspan="2">< 50</td><td colspan="2">< 5000</td><td>1.26</td></tr>
</table>

V. CONCLUSIONS

The paper has presented novel simulation-based approaches for the assessment of the likelihood of the commutation failure in HVDC converters. The study presented in the paper is based on the evaluation of the smallest size of an inductor bank whose connection does not cause commutation failure. To evaluate the proposed index, enhanced techniques based on multiple runs of a transient simulation program were developed. The guided MR method converges to the solution in much smaller number of simulations and produced results of high accuracy. To provide a more flexible method, which could also be easily applied to other nonlinear optimization problems, the paper developed a combined tool using genetic algorithms and a transient simulation program. The combined tool was also shown to be successful in estimating the globally smallest size of the inductor, although the random search nature of the underlying GA necessitated a large number of simulations. The proposed methods provide computationally efficient alternatives to the conventional MR in the study of commutation failure in the HVDC systems.

VI. REFERENCES

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VII. BIOGRAPHIES

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A. M. Gole (M'82, SM'04**)** obtained the B.Tech. (EE) degree from IIT Bombay, India in 1978 and the Ph.D. degree from the University of Manitoba, Canada in 1982. He is currently a Professor of Electrical and Computer Engineering at the University of Manitoba. Dr. Gole's research interests include the utility applications of power electronics and power systems transient simulation. As an original member of the design team, he has made important contributions to the PSCAD/EMTDC simulation program. Dr. Gole is active on several working groups of CIGRE and IEEE and is a Registered Professional Engineer in the Province of Manitoba.