Electromagnetic Transients Simulation as an Objective Function Evaluator for Optimization of Power System Performance

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Abstract – **This paper presents a new method for power systems performance optimization using Electromagnetic Transients Simulation. In this method, an emtp-type program (PSCAD/EMTDC) becomes the inner objective function calculation loop of a non-linear optimization program. The procedure is conducted in a Graphical Environment and with the use of specially designed blocks, allows for the selection of any arbitrary objective function. This approach of mixing non-linear optimization with emtp-type simulation is very powerful in addressing complex optimization problems in modern power networks. The usefulness of this approach is demonstrated with the selection of optimal controller gain settings for two different Power-Electronic Systems: a dc-dc converter and an HVDC transmission system.**

Keywords – nonlinear optimization, electromagnetic transients simulation, SIMPLEX, HVDC Transmission, dc-dc Converter

I. INTRODUCTION

Electromagnetic Transients Simulation programs (referred to as emtp-type programs) are useful tools for the analysis of transients in large power networks. They allow for a very precise representation of the power network, which is far more detailed as compared to representations used in load flow and stability programs. If the power network contains Flexible Ac Transmission (FACTS) or other power electronic apparatus, the emtp-type program is able to model the operation of individual semiconductor switches, and is also able to represent the controls in detail. Similarly, transmission line, cable and machine models used in emtp-type programs are very accurate and valid to high frequencies. Emtp-type programs, are thus very useful in a range of applications such as the determination of equipment stresses, controller tuning of FACTS devices and so on. Their drawback is that they are relatively slow and it takes a long time to complete the studies.

Optimization problems form an important category of power system studies that are often very hard or even impossible to solve using analytical techniques. As a brute-force approach to solving such problems, transients simulation programs usually host a 'multiple run' feature in which a series of runs is conducted, with the optimization parameters being successively varied over their corresponding feasible ranges, with a view to determining the best (or worst) case [1]. In this approach, the parameters to be varied are changed in a well-defined manner such as with linear, logarithmic or pseudo-random increments. This approach is wasteful in simulation time because no intelligence is used in determining the parameters for the next run based on the accumulated experience of the earlier runs

The approach of non-linear optimization theory provides a means by which the above mentioned optimization process can be significantly speeded up [3]. In this approach, the desired objective is numerically quantified as a function of the input parameters. Several runs are carried out with a view to minimizing (or maximizing) this objective function, the parameters for each of which are judiciously selected from the earlier run results using a procedure such as non-linear Simplex, maximum gradient descent, genetic algorithms etc. As the parameters are intelligently selected, the overall procedure provides the optimal answer in a significantly shorter time as compared to random or linear/logarithmic searches.

This paper discusses the incorporation of non-linear optimization within electromagnetic transient simulation programs. In the following sections, the individual structures of a typical transients simulation program and a nonlinear optimization algorithm are first presented; followed by a discussion of the approach used to combine them into one coherent package. A brief overview of the simulation possibilities unlocked by this approach is also discussed. To demonstrate the capability of the proposed scheme, the combination of the emtp-type program (PSCAD/EMTDC) and the nonlinear simplex optimization method of Nelder and Mead is employed to find the optimal controller settings in two different example cases. In the first case, six different controller parameters in a High Voltage Dc Transmission network, are optimized, and in the second, the optimal gains for proportional –integral (PI) controller for a dc-dc converter (chopper) are determined.

II. INTERFACING TRANSIENTS SIMULATION AND OPTIMIZATION ALGORITHMS

Incorporating an optimization algorithm into a transients simulation program requires a thorough understanding of the structure of each. By way of example, the following section presents the procedure adopted to link PSCAD/EMTDC with the Simplex optimization method of Nelder and Mead. The procedure however is sufficiently general and has also been used by the authors to amalgamate other optimization methods.

A. General Structure of PSCAD/EMTDC

PSCAD/EMTDC [2] is a powerful transients simulation program based on the trapezoidal admittance matrix approach introduced by Dommel [4]. Over the years, a rich library of elements and components have been developed for PSCAD/EMTDC, which have made it an ideal tool for accurate simulation of complex power systems including power electronic converters, HVDC systems, and FACTS. One powerful feature in the program is the ability for users to interface arbitrary FORTRAN code via a FORTRAN subroutine called DSDYN (Digital Simulator DYNamic subroutine).

The diagram of Fig. 1 shows a simplified outline of the flow of the program. The brute force 'multiple-run' feature is an integral part of EMTDC, which can be enabled to perform the additional runs as needed.

B. Structure of an Optimization Algorithm

In general, optimization routines require successive evaluations of the objective function for each test point, and based on the results obtained, new candidates are generated until the convergence criterion is met. In the proposed approach, the transients simulation program serves to evaluate the objective function for each point

One of the algorithms widely used for optimizing non-linear functions of several variables is the Simplex method of Nelder and Mead [3,5]. An important feature of this algorithm is that unlike gradient-based methods, it needs only objective function evaluations and does not require first and higher orders derivatives.

A simplex is a geometric object formed by $N+1$ points in the N-dimensional space. The optimization process starts with the evaluation of the objective function at each of the vertices of the starting simplex. The worst vertex (with highest objective function value, assuming a minimization problem) is discarded and a new vertex is chosen which is the reflection of the discarded vertex through the centroid of the remaining vertices. The same procedure is repeated, and in this way, the simplex 'rolls' down towards lower objective function values. In order to speed up the process, the reflected point can be accelerated (expanded), if found to have a very low objective function value; or contracted if the reflected point has too large a value. The process continues until the simplex zooms in close enough around an optimal point. The example case below illustrates the procedure.

Consider the two-variable function defined below:

$$f(x_1, x_2) = (x_1 - 1)^2 + (x_2 - 1)^2 + (\sin x_1)^2 \cdot x_2{}^2 \qquad (1)$$

The function has a minimum of 0.38 at (0.79,0.69), as indicated by the low-density area of the associated contour map in Fig. 2. The simplex in this case is a triangle as the space has two dimensions. The initial simplex has objective function values of 9.3, 12.4 and 19.8 respectively.
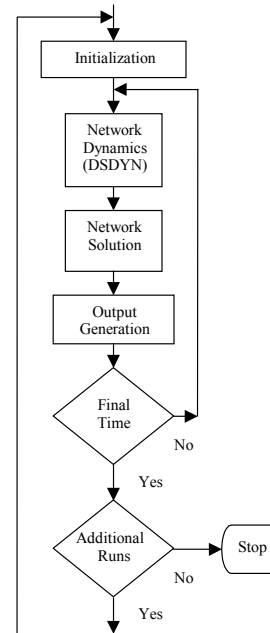

Fig. 1 General structure of PSCAD/EMTDC

In the first step, the highest vertex (19.8) is discarded and replaced with the reflected vertex (I) with the objective function value 5.5. This vertex is even smaller (in objective function value) than the smallest of the original simplex and thus indicates a favorable direction for movement, causing an expansion to a new vertex (II) with value 4.0. The procedure is continued, and generates successive vertices III, IV, V…and so on. Sometimes the reflected vertex has to be discarded and a contraction called for (i.e., vertex III is dropped in favor of IV as its function value was higher than at any of the vertices of the reflection centroid). The process continues until the function evaluations at the vertices differ by an amount smaller than the convergence criterion.

C. Interfacing the Parts

The ability of PSCAD/EMTDC to interface with user-defined FORTRAN code as described earlier, provides the means to couple the optimization program to the simulation program (to be used for objective function evaluation).
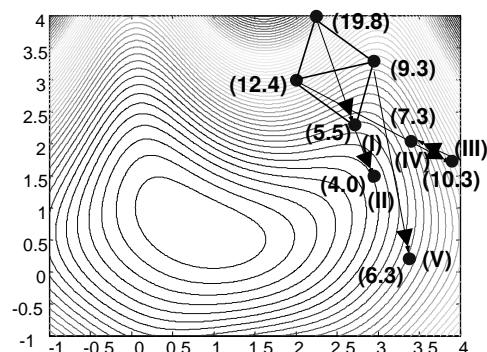

Fig. 2 Simplex evolution

Fig. 3 shows a schematic diagram of the interface between the two parts. As shown, at the beginning of each run, the optimization algorithm generates a new point in the optimization search space and submits it to EMTDC. The coordinates of this point represent the values of the parameters that are being optimized. For example, in a controller design study, these would represent the controller setting values. In other studies these coordinates could represent network parameters such as resistance or inductance values. PSCAD/EMTDC conducts the next run using these coordinate values. From the computed transient, the desired objective function is extracted. For example, in a controller optimization study, this objective function could be the peak overshoot or the integral squared error (the integral of the square of the deviation of the response from the desired reference). This value is returned to the optimization program, which then uses it to determine the next point to be investigated.

A certain amount of bookkeeping is necessary in order to make the interface work properly. For example, the PSCAD/EMTDC run can be initiated from different points within the optimization routine. After the PSCAD/EMTDC run, the flow must return to this point. This requires the setting of a flag to indicate the point of re-entry.

D. Software Implementation

The optimization routine is associated with a graphical component block within PSCAD/EMTDC. Placing this
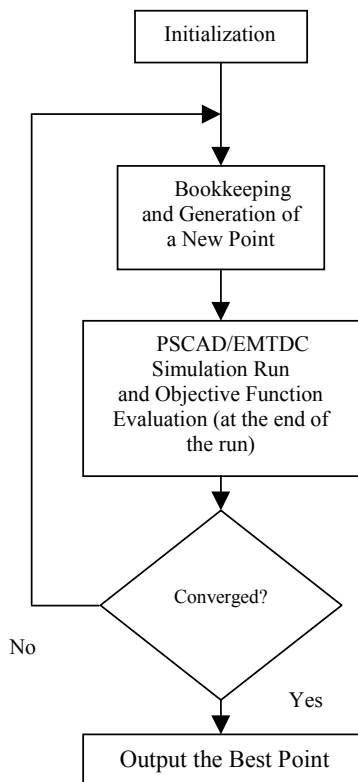

Fig. 3 Interfacing outline

block on the circuit drawing indicates that optimization is to be performed. Clicking on the block brings up an entry menu into which optimization control parameters such as the dimension of the problem, starting vertex coordinates (i.e. initial conditions) and the desired exit criterion can be specified. The optimization algorithm is itself written in FORTRAN 90.

III. SAMPLE CASE STUDIES

This section presents two optimization problems that were successfully solved with the developed program. In the first case, the proportional gain and integral time constant of a dc-dc converter (chopper) are optimized in order to ensure that the current response follows the reference as closely as possible. In the second case, the gains and time constants of the controllers of a dc link are set so as to provide the fastest possible startup.

A. Optimal PI Controller for a DC-DC Converter

The output voltage of the dc-dc converter (often referred to as a 'chopper') shown in Fig. 4 is controlled through adjustment of the ON and OFF durations (T_{ON} and T_{OFF}) of the pass transistor Q. Assuming for the moment a constant voltage E on the input side dc capacitor, the voltage applied to the resistor-inductor (*R-L*) load during the transistor's ON state is E. During the transistor's OFF state, the load current freewheels through the output diode, thereby applying zero voltage to the *R-L* load. Thus on average, the voltage applied to the load is:

$$V_d = D \cdot E \text{, where } D = \frac{T_{ON}}{T_{ON} + T_{OFF}} \tag{2}$$

Effecting a change in the dc voltage V_d, via the duty cycle D, can regulate the load current. The controller in Fig. 5 compares the measured current with the reference and passes the error through the proportional-integral block and produces a correction ΔD to the steady state duty cycle D_0 so that the error is eventually (ideally) reduced to zero. The gain K and time constant T of this controller play an important part in ensuring a good response. If set incorrectly, they can produce an oscillatory, or even unstable response.

In order to set these gains to their optimal value, an objective function is selected as in Eqn. 3. This is the well-known "Weighted Integral Square Error (WISE)" popular in controls literature. Here, T_0 is the time at which the reference is changed and T_F is the total length of the simulation run. T_1 is a suitably selected intermediate point that permits the assignment of different weighting factors K_1 and K_2 to the initial and later portions of the response. This function is generated within the PSCAD/EMTDC environment and is made available to the optimization routine at the end of any given run. As is evident, the objective function has a zero value if the current faithfully reproduces the reference. Note that positive and negative deviations from the reference are penalized equally through the squaring function.

$$WISE = \int_{T_0}^{T_1} K_1 (I_{ref} - I_d)^2 dt + \int_{T_1}^{T_F} K_2 (I_{ref} - I_d)^2 dt \quad (3)$$

The circuit in Fig. 4, together with the controls in Fig. 5 were simulated within the new optimization/simulation environment. The aim was to improve the step response of the current controller to a reference step from 0 to 40 A. Table I shows the optimization parameters (weighting factors K_1 and K_2, the integration interval parameters T_0 and T_1 and the starting values for the optimization parameters K and T). The converged value of the optimization parameters are also shown in the table. Fig. 6 shows the progress of the optimization process as a function of the successive runs. It can be seen that the objective function value of 103 is gradually reduced to 57. The progress is largely monotonic, with a few minor bumps. The current traces shown in Fig 7 give a visual indication of the considerable improvement of the response after the initial set parameters is replaced by the optimal converged settings.

B. HVDC System Controller

In this exercise six different gain and time constant settings are simultaneously optimized in order to provide a rapid startup response for the dc current in a high voltage DC transmission system.

The model for the system is the CIGRE HVDC benchmark model [6] shown in Fig. 8, with the controller shown in Fig 9. The dc system is rated at 500 kV (dc), 1000 MW. The ac side systems are fairly weak; with short circuit ratios on the sending and receiving end systems of 2.5 and 2.35 with damping angles of 84° and 76 ^{o}. Additional details are provided in the appendix.

The controllers on the rectifier and inverter side are identical in structure, but have different set points. There are two principal control loops; one for controlling the dc current, and the other for controlling the extinction angle γ. At any given operating point, only one of these loops is enabled via the maximum select block as shown in Fig. 9. Although at any given instant, only one of the loops is active, during the startup transient, each of these loops may interchangeably come in and out of operation.
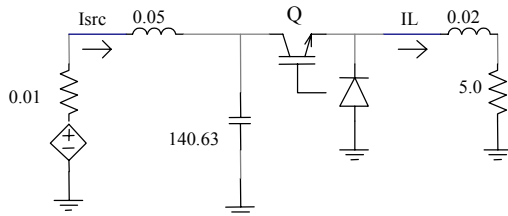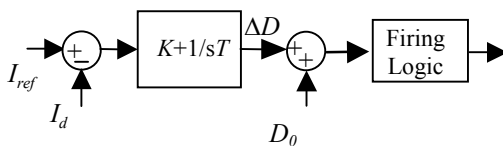
Fig. 4 A dc chopper with LC input filter

Fig. 5 Schematic diagram of a chopper control circuit

Table I Initial and Final Values of the Chopper's PI parameters

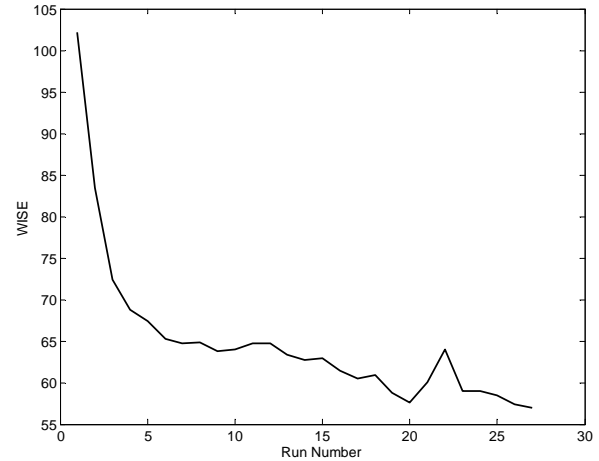| Parameter	K		T (sec)
Initial Value	1.6		0.01
Optimal Value	0.86		0.122
K_1	K_2	T_0 (sec)	T_1 (sec)
8.0	5.0	0.1	0.2

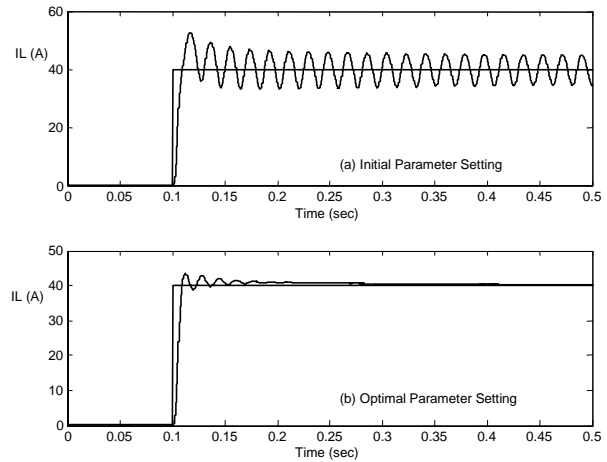Fig. 6 Objective function variations versus run number

Fig. 7 Load reference and actual currents

Each of these loops regulates its control quantity using a proportional-integral controller. The objective of this study is to select optimum settings for the gains and time constants (i.e., K_1, T_1, etc.) to achieve a good startup response. As the extinction angle loop at the rectifier side is normally inactive during startup, its gain and time constant are not included. This requires 6 variables to be set, corresponding to the gain and time constants of the two controllers on the inverter and the current controller on the rectifier.

The following integral squared error objective function is used in this problem:

$$ISE = \int_0^T (I_{ref} - I_d)^2\, dt \qquad (4)$$

where T is the final simulation time and I_{ref} and I_d are the reference and actual dc line current. Obviously the faster and smoother the current reaches its steady-state value asserted by I_{ref}, the smaller the value of *ISE*.

The startup of the system is simulated by ramping up the current order from 0 kA to 2 kA over 100 ms. As in the previous example, the control parameters within the transients simulation program are modified judiciously in each subsequent run by the non-linear Simplex algorithm; with the *ISE* objective function evaluation being carried out within the transients program. The initial and optimized values for the three pairs of gain and time constant are listed in Table II. Fig. 10 shows reference current and the actual current flowing through the line with initial and optimized settings, showing clearly the marked improvement in the response. The long duration of the simulation is deliberately chosen so as to allow the presence of any slowly growing unstable modes to be observed. In case such modes exist, they will increase the objective function value and thus be rejected.

The total number of simulation runs (objective function evaluations) for this case was 170. It is important to note that this is orders of magnitude smaller than what would be obtained with 'blind' search methods. For example, if each of the variables were varied over 10 increments, the total number of runs would have been 10^6. Even then, the granularity of the solution would have been excessive, with a potential error of 10%. Also, the proper selection of the search intervals for the parameters requires some a-priori knowledge of the location of the minimum (maximum); and for an improper choice, the minimum could lie outside the search ranges. Using the optimization approach requires no such knowledge, as the method will automatically find at least a local minimum (or maximum).
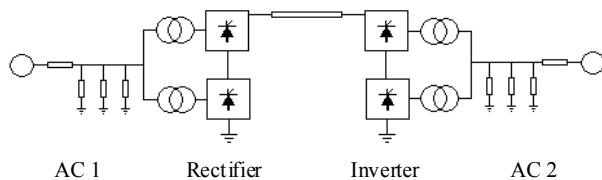

Fig. 8 CIGRE HVDC benchmark model

Table II Initial and converged parameter values: HVDC Controller

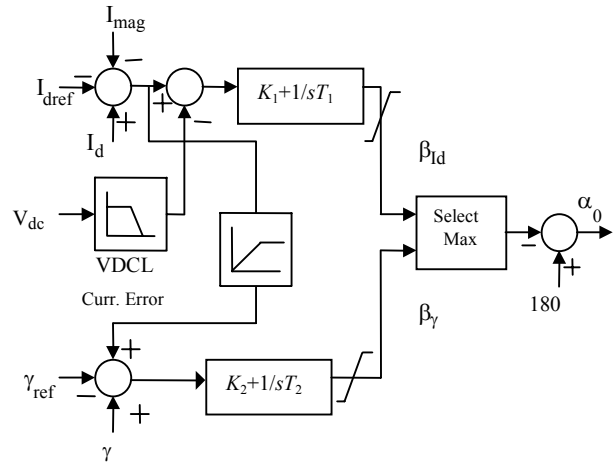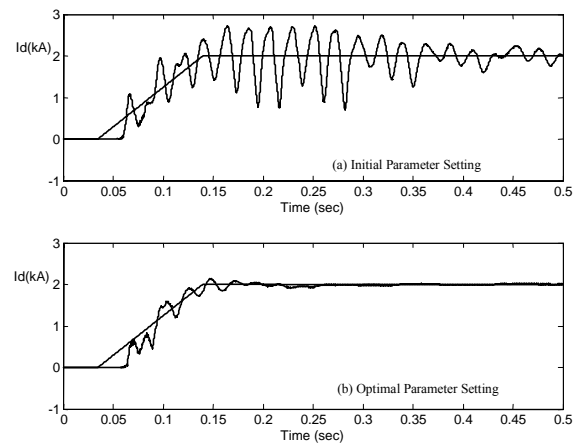| Parameter	Rectifier		Inverter (I)		Inverter (γ)	
	K_1	T_1	K_2	T_2	K_3	T_3
Initial	1.0	0.015	0.36	0.012	0.42	0.085
Final	1.37	0.004	0.81	0.01	0.33	0.065

Fig 9: Converter Controller

Fig. 10 DC link reference and actual currents

IV. CONCLUSIONS

A novel method for integrating optimization algorithms in transient simulation programs is introduced in this paper. Transient simulation is used to evaluate the optimization objective function, while the optimization algorithm serves as the engine for producing new candidate points in the optimization space. Using the proposed approach, a number of successive runs each with a new point in the optimization space are performed to find the maximum or minimum of the objective function. The approach significantly reduces the computational burden and time for the solution of complicated multi-variable non-linear optimization problems.

The power of this approach was demonstrated through determining the solution to two optimization problems concerning power electronic controller settings. The results obtained show considerable savings in computation time over the currently used 'multiple run' approach, where the optimization variables are varied over pre-specified ranges. It is also seen that unlike the blind search methods, an a-priori knowledge of the minimum is less important as the method is able to find the local minimum by varying its increments automatically.

REFERENCES

[1] PSCAD/EMTDC Users' Manual, Manitoba HVDC Research Center,, 1998.
[2] D.A. Woodford, A.M. Gole and R.W. Menzies, "Digital modeling of dc links and synchronous machines," IEEE Trans., Power App. and Syst., Vol. PAS-102 (6), pp. 1616-1623, 1983.
[3] G.V. Reklaitis, A. Ravindran, K.M. Ragsdell, *Engineering Optimization: Methods and Applications*, Wiley-Interscience, 1983.
[4] H.W. Dommel, "Digital computer solution of electromagnetic transients in single- and multi-phase networks," IEEE Trans., Power App. and Syst., Vol. PAS-88 (4), pp. 388-398, 1969.
[5] W.H. Press, S.A.Teukolsky, W.T. Vetterling, B.P. Flannery, *Numerical Recipes*, *2nd Edition*, Cambridge University Press, 1992.
[6] M. Sczechtman, et al., "First benchmark model for HVDC control studies," Electra, 135, pp. 54-73, 1991.

APPENDIX - HVDC SYSTEM DATA

The data pertinent to the CIGRE HVDC Benchmark Model is given below. More details can be found in [5].
Ratings: 500 kV, 1000 MW at rectifier,
Line resistance: 5.0 Ω,
Total smoothing reactance: 1.2 H
Rated Frequency: 50 Hz

Table III CIGRE HVDC model specifications

Rectifier Side		
AC System	Filters and Capacitors (MVAR)	Transformers (each)
378 kV	11th harmonic: 252	345/211.4 kV
SCR: 2.5 at 84°	13th harmonic: 252	597.8 MVA
	Capacitors: 125	Xs = 0.18 p.u.
Inverter Side		
AC System	Filters and Capacitors (MVAR)	Transformers (each)
218.2 kV	11th harmonic:252	207.2/230 kV
SCR: 2.35 at 76°	13th harmonic: 252	585.9 MVA
	Capacitors: 125	Xs = 0.18 p.u.