Hardware In the Loop Optimization Using a Real Time Simulation Environment

In-Kwon Park, A. M. Gole, Paul Forsyth, Rick Kuffel

Abstract—**The optimization enabled electromagnetic transient simulation technique (OE-EMTP) has been confined to off-line simulation environments, a practice which disallows direct application of the technique to the real world device optimization issue. This paper proposes a new approach for incorporating the OE-EMTP technique into a real time simulation environment for the purpose of enlarging the application of the technique to real world device optimization problems. RTDS® (Real Time Digital Simulator) was employed as the real time simulation environment. The implementation of the proposed approach and test results are presented.**

Keywords: **Optimization, Hardware in the loop simulation (HILS), Optimization enabled electromagnetic transient simulation (OE-EMTP), Real Time Digital Simulation (RTDS)**

I. INTRODUCTION

SINCE the optimization enabled electromagnetic transient simulation (OE-EMTP) technique was introduced[1] and improved[2] , the technique has been applied successfully to solve various and difficult problems such as tuning HVDC system controller parameters[3] and finding optimization gating signal sequences of space vector modulation[4]. In the past, Electromagnetic Transient (EMT) type simulation has been one case at a time. In order to determine the optimum point, such as optimal controller parameters, multiple simulation runs were necessary. The traditional multiple run approach such as Monte Carlo simulation is wasteful. A more economical method to achieve the given objective (i.e., the optimization through multiple simulation runs) is to apply a non-linear optimization algorithm to steer the simulations. This technique (i.e., utilizing non-linear optimization algorithms for steering simulations) became feasible by adopting the existing simulation program as an objective function evaluator for the optimization algorithm employed in the overall process. The PSCAD® simulation software is an EMT-type program into which the optimization technique has been seamlessly incorporated. The technique utilizing non-linear, non-gradient based optimization algorithms (e.g., the Nelder-Mead down-hill Simplex algorithm[5]; the heuristics-based optimization algorithms - the Genetic algorithm[6] and the Particle Swarm algorithm[7]) can be applied for problems in which obtaining mathematically closed, analytical descriptions would be difficult.

However, the time required for computations in the off-line simulation programs such as PSCAD increases as the size of the simulation case expands in computational complexity[8], or as a greater number of iterations is required. Furthermore, discrepancies can exist between the modeled optimization subject and its real world implementation. In most cases, many discrepancies make the conceptual model and its real implementation different. In the instance of controllers, the difference can be caused by the parasitic filtering effects in the analog input/output stages. More fundamentally, the conceptual model of the controller cannot account for the implementation associated issues, such as limits in the floating point number representation, the environmental issues such as noise, and limits of signal quality level. The discrepancies can make the optimum controller parameters obtained from the optimization routine with an off-line simulation program less useful in the actual controller. This deficiency identifies a significant issue in the design procedure using the optimization enabled EMT simulation technique. Furthermore, in the instances of the real world system optimization, system manufacturers try to safeguard the detailed information regarding the internals of the system implementation. Under such circumstances, the only available information would be the input and output signal specification and the list of parameters which would be the subject of optimization. This non-availability of necessary data renders the subject of the optimization 'black box', and the application of the off-line OE-EMTP technique impossible, because the application requires the conceptual model to be built upon detailed information. The benefit of a real time simulation environment derived from executing the simulation in real-time can be mobilized to extend the capability of the OE-EMTP technique. Actual physical devices such as protective relays and control equipments can be connected to real-time simulators in a closed loop manner. Those real physical devices can be tested and evaluated as if they were interacting with real power systems, and then they can be optimized as well. The real physical system can be interconnected with real-time simulations without any conceptualization or intermediary. In other words, the real physical system can be considered as a black box and the testing can still produce the intended outcomes by using real-time simulations with the test subjects.

This paper presents a new approach for incorporating the OE-EMTP simulation technique with a real time simulation environment, thus allowing the optimization of the external subject. The paper is organized as follows: the proposed approach is outlined in section II. Then, an experimental set prepared for proving the effectiveness of the proposed approach is described in section III. The test results follow in

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section IV.

II. OE-EMTP TECHNIQUE WITH REAL TIME SIMULATION ENVIRONMENT

A. *The OE-EMTP Technique*

For decades, Electromagnetic Transient (EMT) programs have been the industry standard for studying the detailed behaviors of power system equipment, especially power electronic equipment and small power networks. Of all the power system analysis tools, the EMT programs incorporate the greatest details, including electromagnetic as well as electromechanical phenomena. The application areas for EMT simulation tools include insulation co-ordinations, study of over-voltages due to switching surges, power electronic transient performances, sub-synchronous resonances and ferro-resonance phenomena.

The OE-EMTP technique is the combination of the existing simulation capability from the EMT-type programs with non-linear optimization algorithms. The capability of the EMT-type simulation programs can be utilized as an objective function evaluator by an optimization algorithm which is external to the EMT-type simulation program itself. The desired optimum would be achieved as the result of iterative steps which would be conducted by the optimization algorithm. The parameters of each trial in the iterations are adjusted by the optimization algorithm based on the observed outcomes from the previous steps, with the aim of improving the desired objectives. Fig. 1 presents the concept of the OE-EMTP technique with the offline EMT-type program.

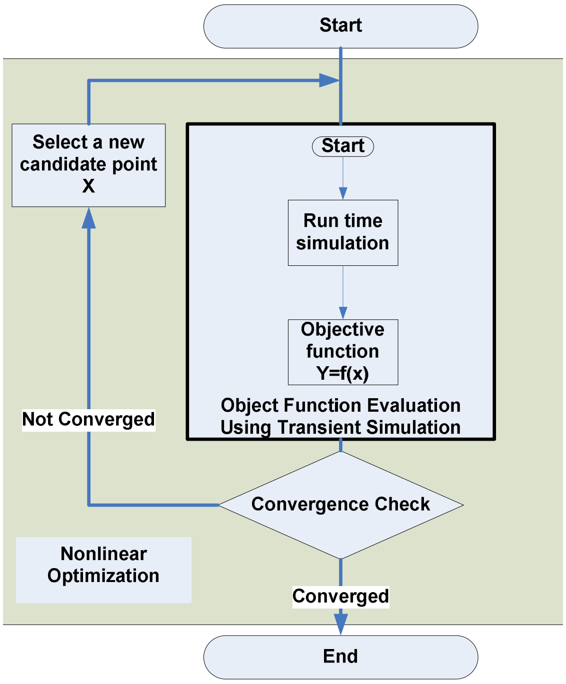

Fig. 1 OE-EMTP technique with offline EMT-program

B. *Real Time Digital Simulation*

Real-time digital simulation is an implementation of the EMT simulation algorithm that keeps in step with a real world clock. In this way, it becomes possible to feed discretized external signals to the simulation, as well as receive analog conversions of computed results in real-time. Thus, it becomes possible to connect physical equipment such as protective relays or power system controllers to the real time simulator. Many different approaches have been explored in the field of power system real-time digital simulators [9-12]. The benefits derived from executing power system simulation in real-time is not confined to computational time reduction; more importantly, actual physical devices such as protective relays and control equipment can be connected to real-time simulators in a closed loop manner. Those real physical devices can be tested and evaluated as if they were interacting with real power systems. One application area in which the real time simulator (RTDS in particular) has been established as a de facto standard for testing, is the protective relay development and testing area[9]. The input into an external test subject derives from simulations in real-time. Thus, the testing subject is unable to discern whether it is connected to a real power system or to a simulated one. The output from the testing subject is reflected immediately to simulations also in real time, ensuring the validity of the effect caused by the operation of the external testing subject in the simulations. This true closed loop testing environment allows users of the real time simulators to evaluate complex power system control systems such HVDC controller[10] or multiple relays operation coordination[11].

C. *The OE-EMTP Technique with Real Time Digital Simulation*

With the reasons mentioned in the introduction, the combination of the OE-EMTP technique and the offline EMT-type program has been confined to the optimization problems with well-described conceptual models. As a measure to overcome the limitation of the combination, a real time simulation environment is utilized as the necessary objective function evaluator, thus replacing the offline EMT-program in the previous combination. The real time simulation environment can evaluate the candidate provided by an external non-linear optimization algorithm in the same way as the offline EMT-program, but, in real time. The external optimization algorithm can take the evaluation output from the real time simulation environment and proceed with executing the algorithm. This process produces the candidate for the next step or finishes its execution according to the algorithm-specific termination criteria. This new approach (combining the OE-EMTP technique with real time simulation environment) can offer two benefits to the OE-EMTP technique applications: (i) the total amount time of the optimization process can be substantially reduced because of the real time execution of the objective function evaluation in the process; (ii) the external optimization subject can be treated as a ‘black box’. The conceptual model required for the combination of the OE-EMTP technique and the offline EMT-type program necessitates detailed information, which may not be available. However, in the proposed method, the necessary information can be the input and output signal description as well as the communication method for passing candidate parameter settings from the external optimization algorithm to the optimization subject. The information is part of the manufacturer’s product specification, and is readily available from the accompanying documentation with a product (the optimization subject). Fig. 2 presents the concept of the proposed approach.

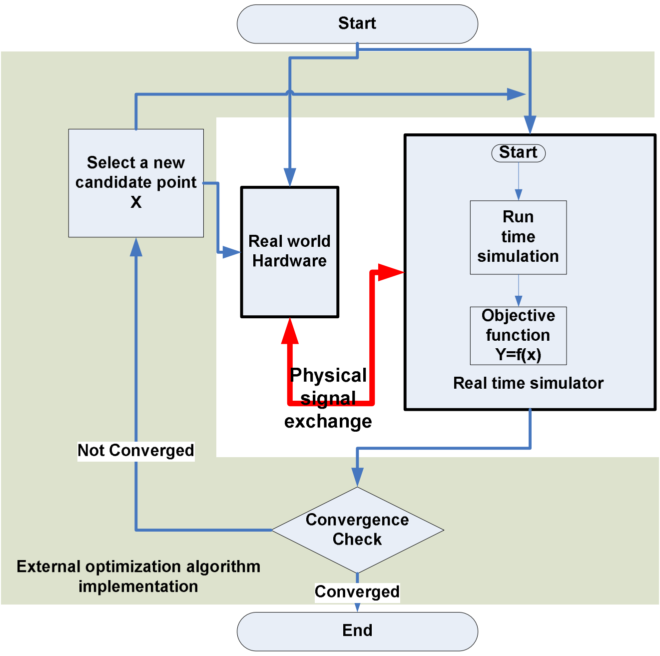

Fig. 2 OE-EMTP technique with real time simulation environment

III. A CONTROLLER PARAMETER OPTIMIZATION USING REAL TIME SIMULATION

In order to test the effectiveness of the proposed approach, an experiment setup was established. A simple DC/DC converter circuit (Buck converter) simulation case was made in a real time simulation environment. In this experiment, RTDS[12] was selected as the real time simulation environment. In the Buck converter circuit configuration, as presented in Fig. 3, a small amount of voltage drop across the storage element (an inductance in this simulation case) contributes to the decrease in the final output voltage. Thus, the voltage drop across the inductor reduces the voltage output from the Buck converter slightly less than the expected value based on the given duty ratio. In order to compensate for the voltage drop and to make the voltage output follow precisely the duty ratio command, a simple Proportional Integral regulator (PI regulator) was inserted between the duty ratio command and the final voltage output. The regulator receives the duty ratio command as a reference and the voltage output as a feedback signal. Then, the regulator tries to control the actual duty ratio being provided to the switching element in the power circuit with the aim of matching the final output voltage with the duty ratio command, as closely as possible. In this experiment, a non linear optimization algorithm, the Nelder-Mead down-hill Simplex algorithm, was selected as the optimization algorithm.

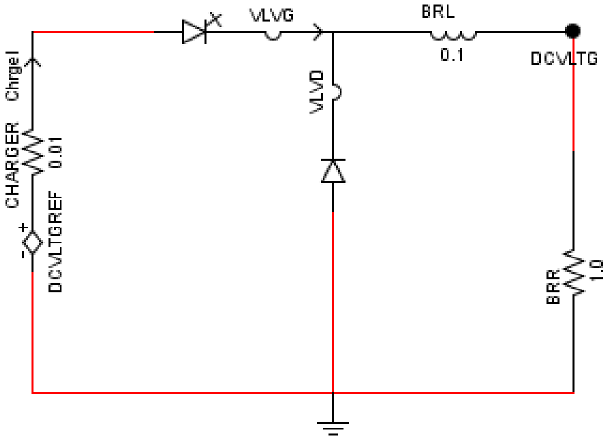

Fig. 3 Buck converter simulation in RTDS

The objective of the optimization was set to minimize the difference between the duty ratio command and the final voltage output. An evaluation function employed to produce the figure of merit is presented in (1).

$$ISE = \int (V_{REFERENCE} - V_{MEASURED})^2 \, dt \qquad (1)$$

The final figure of merit (ISE in (1)) was utilized by the optimization algorithm in order to generate a new set of candidates for the next step. Based on the objective function evaluation results, the optimization process attempted to moderate the two regulator parameters, the proportional gain and the integrator time constant, to achieve the given optimization objective.

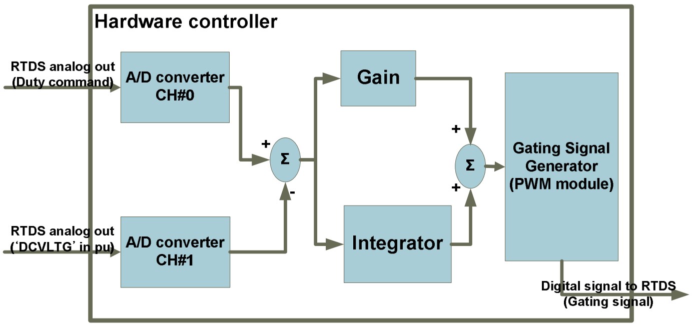

Fig. 4 Block diagram of PI controller implementation

An external hardware was employed to execute the function of the PI regulator. The regulator was implemented on a digital signal controller (DSC) based hardware[13]. The block diagram of the PI regulator implemented on the hardware is presented in Fig. 4. Two analog to digital channels on the hardware were used to import the analog signal outputs from the real time simulation environment. One was the duty ratio command signal and the other was the final voltage output from the simulated Buck converter. Both signals were properly scaled at the analog output stage in the real time simulation environment, in order to meet the signal input requirement of the hardware controller. The output of the regulator was the duty ratio which was compared with the saw tooth waveform in a PWM module in the digital signal controller. The final output from the external hardware was the gating signal which drove the switching element in the Buck converter simulation through the digital interface.

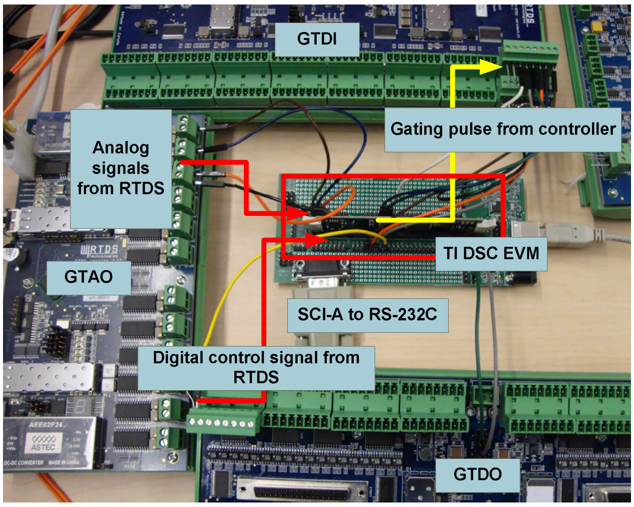

Fig. 5 Experiment set with hardware controller

Fig. 5 presents the hardware controller and the necessary signal interface between hardware controller and the real time simulation environment. The analog output from the real time simulation environment was marked as 'GTAO' and the digital input was marked as 'GTDI'.

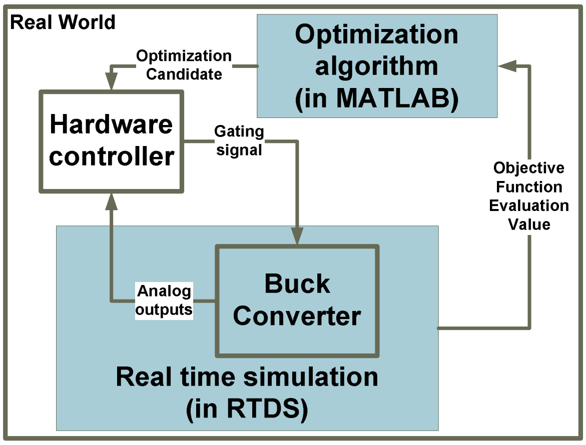

Fig. 6 Experiment setup configuration

The MATLAB® software package was utilized to implement the selected optimization algorithm. The optimization algorithm received the objective function evaluation results from the real time simulation environment through TCP/IP socket communication. Based upon the objective function evaluation results, a new set of candidates, proportional gain and integrator time constant, was generated and passed to the external hardware controller through the RS-232C serial communication channel. The performance of the candidate was evaluated in the real time simulation and the evaluation result came back to the optimization algorithm. The iteration continued on until termination criteria in the optimization algorithm was met. The configuration of the entire experiment set is presented in Fig. 6.

IV. TEST RESULTS

A test was designed and executed to evaluate the proposed optimization method using the experiment set which is explained in the previous section. The selected optimization algorithm began with an initial simplex. The members in the initial simplex were as follows: (0.1, 0.1), (100.0, 0.1) and (0.1, 100.0). The optimization process terminated after 31 iterations. The termination condition associated with this experiment was that the execution would terminate when the difference between the best objective function evaluation result and the worst in the simplex (with 3 vertices) is less than the given tolerance (0.2). Table 1 presents the candidates in each of those iterations and corresponding objective function evaluation results.

Table 1 Hardware in the loop optimization test result

Iteration Number	Pgain	Iconst	ISE
1	25.075	50.05	14406.3
2	37.5625	25.075	13928.8
⋮	⋮	⋮	⋮
14	54.7328	3.2219	17714.7
⋮	⋮	⋮	⋮
25	51.5622	0.1976	4.533
26	51.6597	0.0024	2.87689
27	48.5378	0.0024	2.96279
28	50.0744	0.0512	3.22339
29	50.0866	0.0268	3.21241
30	50.0927	0.0146	3.12868
31	50.0957	0.0085	3.07578

It can be observed from the experiment result in Table 1 that some of the candidates were not successful in controlling the PWM (Pulse Width Modulation) duty ratio, resulting in a large ISE (Integrated Squared Error) value. It was also noticed that the simplex came close to the minimum ISE, which is

2.8769, before the optimization algorithm met with the given convergence criteria and terminated at iteration number 31.

The same experiment was repeated to evaluate whether the experiment outcome was from the operation of the selected optimization algorithm, and not by a random search. The second experiment terminated after 36 iterations. The best candidate produced during the iteration was (53.2206, 0.0024) which resulted in the ISE value of 2.7513. The best candidate in both the experiments matches one another in less than 5% of difference (both in the parameter values and the ISE values), thus demonstrating that the experiment results were not from a random search. The performance difference between the best candidate and the worst candidate can be observed from the following two waveforms (Fig. 7 and Fig. 8). Fig. 7 is the per-unitized DC voltage output and duty ratio command waveforms plot when the best candidate, (51.6587, 0.0024), was applied to the hardware controller as parameters. Fig. 8 is the same waveforms plot as the Fig. 7 when the worst candidate, (54.7328, 3.2219), was applied.

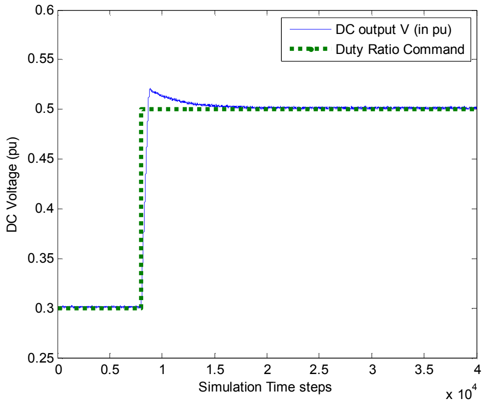

Fig. 7 Controller performance with the best candidate

As presented in the Fig. 7, the best candidate obtained from the proposed OE-EMTP technique was able to make the controller closely follow the given command (the duty ratio). In contrast to the best candidate performance, Fig. 8 clearly presents that the controller failed to follow the command when the worst candidate was applied as the controller parameters.

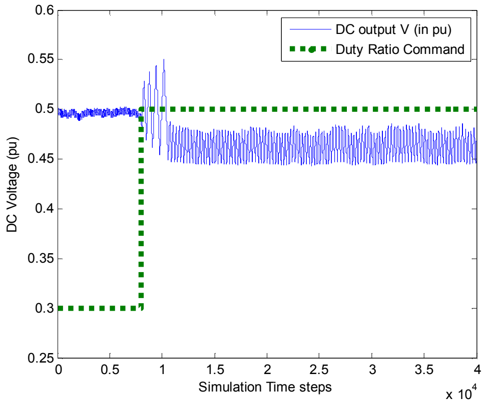

Fig. 8 Controller performance with the worst candidate

V. CONCLUSIONS

The improvement of the OE-EMTP technique was proposed by replacing the offline simulation software as an objective function evaluator with a real time simulation environment. The usefulness of the proposed improvement was demonstrated with hardware in the loop optimization using a simple controller in real world and a power electronics circuit simulation in a real time simulation environment.

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