Optimization of a FACTS control device using Real Time OE-EMTP technique

In Kwon Park, Paul Forsyth, A. M. Gole

Abstract — **As the power industry tries to meet the challenge of growing demands with restricted means, the value of high-power schemes using power electronics based systems in utility grids becomes higher. As more of these power electronic bases schemes are deployed, the list of their expected functionality also grows. In order to properly test and evaluate the schemes, the utilization of real time simulation becomes imperative. Many of the necessary tests cannot be executed in a real network due to either economic reasons or safety concerns.**

In this paper, the application of the real time simulation in the high-power power electronics system controller testing is extended to the purpose of tuning the control parameters. An application of OE-EMTP (Optimization Enabled EMTP) technique is proposed to optimize the real world controller parameters. A similar technique has been widely utilized in off-line simulation software, but here it is combined with the real time digital simulation. The effectiveness of the proposed technique was presented by result from tuning experiment of a FACTS controller, a DSP based STATCOM control.

Keywords: **Optimization enabled electromagnetic transient simulation (OE-EMTP), Real Time Digital Simulation (RTDS®), FACTS (Flexible AC Transmission System) device**

I. INTRODUCTION

Optimization techniques in conjunction with EMT-type simulation tools has been utilized as a mean to improve system performance. At the initial stage of the design, analytic techniques such as linear system analysis can contribute to the better understanding of the system characteristics. The understanding brought usually leads to a better system design for the given purpose. In the case of control design, the understanding can offer necessary ground for the proper selection of the controller parameters, e.g., the proportional gain and integration time constant of a PI regulator. With proper understanding of the entire system brought about by the analytical investigation, it becomes possible to design the entire system to meet the given performance criteria as well. The prerequisite for such analysis is the availability of the information regarding the system, such as parameters. If part of the information is not available, or the accuracy of the descriptive information of the system cannot be brought under a certain level required by the intended analytical method, the final results from the analysis would inevitably be compromised. As a result, the system design cannot avoid being degraded. Under these circumstances, i.e., when part of the necessary information is not available or its quality cannot be guaranteed, often alternative methods based on optimization techniques become tools to address the issue in order to improve or bring the system performance closer to the ideal. In short, the optimization techniques can offer methods for better results when the information describing a system is incomplete.

Many optimization techniques were successfully incorporated with off-line simulation software such as PSCAD™ [1, 2]. This incorporation resulted in the new terminology, OE-EMTP (Optimization Enabled EMTP) simulation. In this technique, the simulation case which represents a real system is used as an objective function evaluator. Each run of the simulation case with a given optimization candidate from the selected optimization algorithm produces the order of merit for the candidate. By taking in the evaluation result as the necessary indicator, the optimization algorithm can direct the next set of candidates in a more desirable direction in hope of terminating with a final set of candidates which lead to the better performance of the system. If the closed mathematical descriptive information of the target system is available, the application of the OE-EMTP technique is not necessary. Instead of using the optimization with the series of simulation instances, analytical methods can be applied to make the system achieve the intended purpose. However, establishing the closed mathematical description usually takes substantial amount of time and effort and is sometimes impossible. This difficulty becomes more pronounced if a power electronics device is involved in the target system. The power electronics devices depend on switching operations which are highly non-linear. The non-linearity defies easy translation of the system into a linear model required by the mathematical approaches. Furthermore, the control over such switching based devices also frequently employs non-linear elements such as signal selectors and limits, thus making the analytical investigation even more complicated.

Hence, the OE-EMTP implementation in offline simulation software tries to overcome the aforementioned difficulty by utilizing a series of simulation instances with the optimization candidate as the objective function evaluator. Therefore, it is expected that the better set of parameters will be obtained for the given performance criteria at the end of the optimization process. However another practical difficulty arises in this approach. When the simulation case involves a complex system or large scale network, the simulation speed slows down, making the evaluation process slower. Or, if the intended optimization algorithm requires large number of evaluations, the entire optimization process takes a longer amount of time. If both factors, the long simulation time for evaluation and a large number of required iterations, are combined together, the time required for optimization becomes exceedingly long, and may make the optimization attempt less viable. Another factor which limits the usability of the off-line approach is the question regarding the availability of the necessary modeling data. Frequently, the subject for the optimization is a physical device such as a real controllor. In order to optimize the physical device using the OE-EMTP technique

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with an off line simulation software, the device must be modelled as part of the simulation case. It is obvious that the quality of the simulation result depends on the quality of the input data. However, it is usually not easy to acquire the necessary data from the physical device due to various reasons. One such reason is the device manufacturer's unwillingness in providing the data. Under such circumstance, when the necessary data is absent, the optimization approach using the off line simulation software becomes simply impossible.

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. In this paper, a realistic experimental set was established and the control parameter optimization based on the combination of real time simulation and the optimization technique was evaluated. This 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. Practical considerations necessary for the successful application of the proposed technique are explained in the section. The test results follow in section IV. Conclusion and final remark complete this paper in section V.

II. OE-EMTP TECHNIQUE WITH REAL TIME SIMULATION ENVIRONMENT

A. RTDS with power electronics simulation

In this paper, a FACTS system controller, i.e., STATCOM controller was selected as the subject of the optimization. Before going into the details of the experiment setup, the capability of the simulator where the fitness of a candidate for the optimization would be evaluated must be verified. As more and more power electronics applications such as VSC-HVDC and STATCOM systems are deployed in the field, the need to model such systems in real time has increased. Unlike the off-line simulation tools, the real time simulator where the simulation is executed and interfaced with the external device is required to meet very rigorous timing constraints.

The time between the digital simulation solutions is usually referred to as the simulation time step. A real time simulator must perform all the necessary calculations and update the I/O in a real world time equal to the simulation timestep. If the simulator violates this constraint, then it cannot be considered a real time simulator and the close-loop testing cannot be relied upon. In [3], the recommended size of time step in high power electronics application simulation is less than 5% of the fastest dynamics of the system. The fastest dynamics are usually determined by the switching frequency of the system. For instance, if the switching frequency of a voltage source converter is 10 kHz, then the period of a single switching cycle is 100 µs. This makes a simulation time step of about 5 µs suitable. However, a more widely accepted 'rule of thumb' among the power electronics engineers is more stringent than 5%. Frequently, the engineers prefer a time step size around 1% of the switching period. If this rule applies to the aforementioned example, the necessary size of time step would be around 1 µs. If this requirement has to be met in real time, the amount of calculations the real time simulator hardware platform can perform would be substantially smaller than during a conventional real time simulation where the time step size typically lies in the range of 50 µs. For example, if the processor runs with a 1GHz clock cycle, the number of instruction allowed in such a short time step such as 1 µs is only 1000. All the necessary calculation and communication must be completed within that limit.

A large part of the calculation associated with an EMTP simulation is the calculation of the network solution. In every time step of an EMTP type simulation, the models in the simulation produce the admittance values and current injections. These outputs from the models are collected and applied as input to the network solution.

$$[V]=[G]^{-1}\cdot[I] \qquad (1)$$

Equation (1) presents the network solution. As evident in the equation, the network admittance matrix (G) has to be inverted whenever the network topology changes. As the size of the network grows larger, the size of the admittance matrix grows proportionally. This requires more instructions and execution time for the real time simulator hardware platform. In power electronics application, the change of the network topology is mostly initiated by the change of the switching state. Therefore, whenever the power electronics circuit changes its topology due to the turn-on or turn-off of a device, the network admittance matrix needs to be re-inverted to reflect the latest network topology. In the RTDS, a technique has been developed whereby switches of a Voltage Source Converter (VSC) can be modelled by a constant admittance value approach [4]. In this approach, the ON state of a switch is described by a small inductance. Meanwhile, the OFF state of the switch is described by combination of R and small C. By judiciously selecting the amount of L, R and C, the resulting Dommel admittance can be made the same regardless of the switching state. Thus, the network admittance matrix inversion associated with the switching state is avoided. As result, the network admittance matrix can be pre-inverted before the simulation starts. By eliminating the need to invert the admittance matrix during the real time simulation a substantial reduction of the size of time step is acheived. In RTDS, this simulation capability is referred to as small time step simulation capability. The usual size of time step associated with this simulation capability is between 1.5 to 3.5 µs. Obviously, this range of time step cannot be applied to the very high switching frequency devices such as SMPS (Switching Mode Power Supply) or consumer electronics devices, where hundreds of kHz switching frequency is not uncommon. However, in the high power applications, the issue of the dead-time comes into play limiting the switching frequency applied. In [5], the size of dead-time used in the experiment was 6.3uS for a 2-level drive system of a 22 kW induction motor. The switching frequency was 5 kHz, thus the associated switching period was 200µs. From this we can see that the relative size of the dead time compared with the size of switching frequency period is 3.2% or less than 5%. As indicated by this numerical example, the size of dead time must be small in relationship with the switching frequency period. Therefore, as the rating of the power electronics system grows, the size of dead time, which has to be guaranteed by the control system, grows as well. This imposes the limit on the highest possible switching frequency. This limitation is one justification for the size of small time step in the RTDS. Evidently, as more advanced switching devices are coming into the market with faster extinction time, the required size of dead time would become smaller. However, the dead time is not the only limiting factor for the switching frequency. Hence, the switching frequency for the high power applications is not changing quickly which allows the current size of small time step in the RTDS to be justified in foreseeable future.

B. OE-EMTP with RTDS

The introduction mentioned a couple of conditions where off-line tools cannot be utilized for OE-EMTP. Those points are: first, the difficulty of executing the optimization process when the execution time required for running optimization process becomes prohibitively long. Second, the availability of necessary input parameters is not guaranteed. In such circumstances, the combination between the optimization algorithm and off-line simulation tool becomes unable to address the optimization requirement. Thus, the combination has mostly been confined to the optimization problems with well-described conceptual models. Real time digital simulators can be an attractive solution in order to overcome the limitations associated with the off-line simulator. In other words, a real time simulation environment can be utilized as the necessary objective function evaluator, replacing the offline tool in the combination previously mentioned. This replacement becomes possible because the real time simulation environment can evaluate the optimization candidate in real time. In addition, for the other side of the combination, the optimization algorithm can generate a candidate by an external non-linear optimization algorithm in the same way as the offline EMT-program or different part in the real time simulation case itself. Then the optimization algorithm can take the evaluation output from the real time simulation environment and utilize the data for the purpose of generating the next candidate with the hope of improving the system performance in regards to the given performance goal. This iterative process 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 part of the optimization subject, usually an external device connected to the real time simulator, can be treated as a ‘black box’. Therefore the need for the conceptual model required for the combination of the OE-EMTP technique and the offline EMT-type program is eliminated. 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 frequently part of the device specification, and is readily available from the accompanying information of the device.

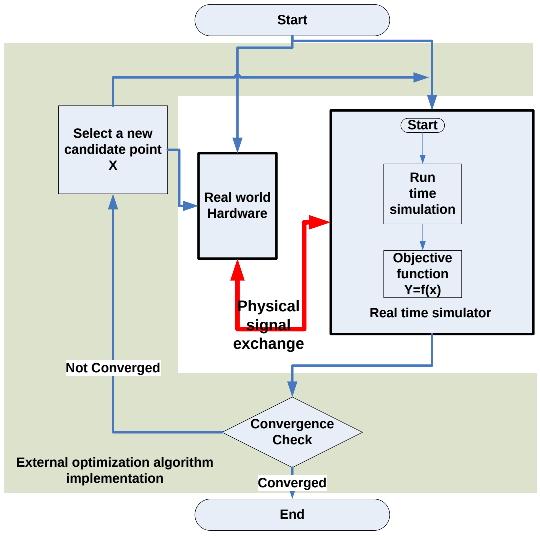

Figure 1 OE-EMTP technique with real time simulation environment

Figure 1, presents the concept of the proposed approach. Because the real time simulator can interact with the external device in real time, the external device can be seamlessly incorporated with the rest of the simulation. Thus, the optimization algorithm can regard the entire set, i.e., the real time simulation and the external device as one objective function evaluator. In other words, the optimization program can pass the optimization candidate to the simulated part of the set as well as the external device in the exactly same manner. Then, the program can receive the fitness evaluation result and continue on the iteration until the termination condition is satisfied. Modern real time simulators, including the RTDS, offer ample variety of interfacing options, including analog, digital and communication protocols, and thus different types of external devices can be interfaced with the real time digital simulator with little effort.

III. REAL TIME OE-EMTP TECHNIQUE APPLICATION – STATCOM CONTROLLER TUNING

A. *RTDS simulation case for STATCOM system*

A STATCOM (Static Synchronous Compensator) system is a shunt compensation device typically in a bulk power transmission system [6]. The STATCOM tries to regulate the reactive power exchange between itself and the AC power system where it is connected. Other devices have also been designed to serve the same purpose. A well-known example is a Static VAR Compensator (SVC). The SVC regulates the reactive power exchange by controlling the firing angle of thyristors connected in series with reactors. While the SVC system is built based on the thyristors, fast switching high capacity semiconductor devices are usually the building blocks of the STATCOM system. The switching capability, the ability of turning on and off according to the incoming command (gating signal) offers the STATCOM system a distinct advantage over the SVC system, allowing it to react to the power system dynamics in a shorter time frame.

A small time step 2-level bridge model from RTDS model library represents the power electronics converter in the system. By properly controlling the patterns of the gating signals applied to the each of the 6 switches in the bridge model, the converter can regulate the reactive power exchange. The DC side of the converter is connected to a capacitor, which supports the necessary amount of DC voltage for generating the AC voltage at the AC side of the converter. The bridge model can also receive the gating signal from an external controller. This allows the interconnection between the RTDS STATCOM simulation and an external controller. The gating signal import is made in every small time step. Thus, the high resolution of the gating signal can be preserved and more realistic simulation as well as external hardware testing becomes possible. A wye-delta transformer connects the 2-level converter to the AC power system. The converter is connected to the delta side of the transformer. The small time step portion of system is interfaced with large time step portion through interface transmission line. The size of small time step in this simulation case is 2.5µs, while the size of large time step is 50 µs. By utilizing different time steps in a single simulation case like this, more flexibility in building complex power system networks can be obtained.

B. *Hardware controller implementation*

The external hardware controller for the STATCOM system was constructed on an off-the shelf DSP development kit. It is based on a low cost DSP, TMS320F28069 from Texas Instrement [7]. The DSP is equipped with hardware floating point unit (FPU), unlike most of its predecessors. Therefore, the software developer doesn't need to be concerned with the fixed point arithmetic. However, the FPU only supports single precision floating point number, 'float' in C language. The DSP is designed for motor control applications, thus it provides most of the necessary input and output capability for such an application. The chip provides 12 A/D conversion channels with conversion time of around 325ns. The conversion resolution is 12 bits which is usually enough for power electronics application such as motor drives. The processor also provides 16 PWM channels. Certain number of PWM channels can have up to 180ps(pico second) pulse resolution with main clock speed of 90 MHz. From the available A/D channels and PWM channels, 9 A/D channels are used to import the analog measurement values from the STATCOM system and 6 PWM channel are used to drive the 6 switches in the 2-level bridge of the STATCOM system. The A/D input voltage range is between 0-3.3V, while the analog output voltage range of the real time digital simulator (RTDS) is between -10V and +10V. Ideally, the analog voltage output from RTDS must be re-conditioned at the input stage of the external controller for the purpose of full utilization of the available bit resolution, but no such attempt was made in this hardware controller implementation. Therefore, about 13 bits of resolution are available for the analog channels, which is still higher than the 12bit resolution of the hardware A/D converter. The output of the controller is the gating signals for the 2-level bridge. The ePWM modules on the processor produce the gating signals. The clock speed of the processor was 90MHz, thus the time resolution expected from the output PWM channel is around 11ns unless otherwise enhanced. However the RTDS samples the gating signal with the sampling frequency of the small time step size. For instance if the size of small time step is 2.5µs, then the incoming gating signal is sampled every 2.5µs. Therefore, the external controller provides enough resolution for the gating signals without resorting to higher precision mechanism (HRPWM). A well-known D/Q decoupled vector control algorithm [8] was implemented on the DSP. The 3-phase voltage measurement values and 3-phase current measurement values are passed to the control algorithm in DSP through the analog channels. A PLL based on the transvektor algorithm detects the phase information of the 3-phase voltage which in turn is utilized as input to the park transformation for both voltage and current signals. In the vector control implementation, D-axis was selected to regulate real power and Q-axis was selected to regulate reactive power. A PI regulator on each axis controls the current on D-axis and Q-axis. The reference of the current controller is from the higher level controller. The higher level control determines the control objective of the system. The higher level D-axis control is responsible for maintaining the DC voltage of the capacitor, while the higher level Q-axis control is in charge of the AC system voltage regulation. When the AC side voltage goes low, the STATCOM reacts with higher amount of Q production by raising the Q-axis current. If the DC capacitor begins to dissipate, then the D-axis control tries to bring it up by raising the D-axis current. The control algorithm runs every 100 µs. The frequency of execution is controlled by a hardware timer on the DSP. In order to establish the necessary communication channel between the DSP and the optimization program, SCI channel/RS-232C communication was implemented. The development kit, TMDSDOCK28069ISO, provides a USB-JTAG/SCI interface through the FTDI [9] peripheral chip, the software implementation utilizes the second serial port of the communication channel available from the peripheral chip. This communication channel allows the transfer of the necessary controller tuning information, such as PI regulator parameters.

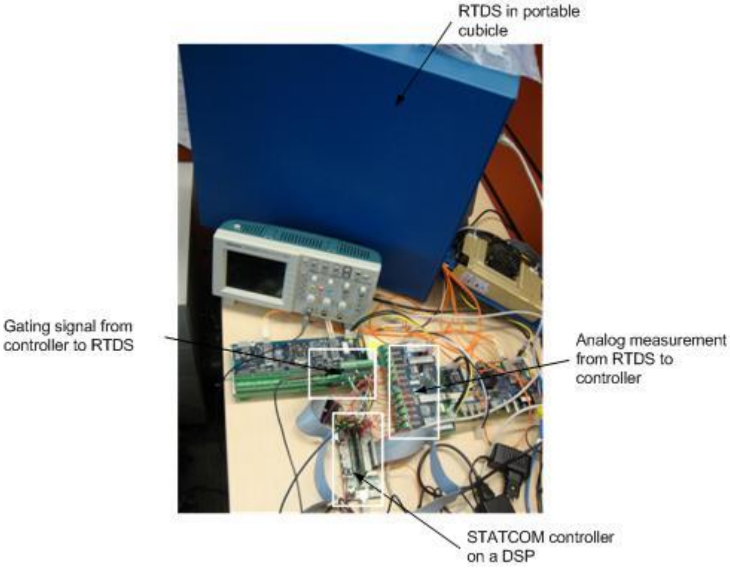

Figure 2 Interconnection between real time simulator and external controller

C. Overall experiment configuration

The Nelder-Mead downhill Simplex method [10] was selected as the optimization algorithm for the experiment. The Simplex algorithm was found to be suitable for small number of subject parameters [2]. When the external hardware becomes involved in the optimization, the necessary optimization parameters need to be transferred to the external hardware through communication, thus the number of parameters cannot be too large. In addition, the algorithm presents a good convergence characteristic with a small number of iterations. Many of the Heuristics based optimization algorithms require a large number of iterations, which dictates that time required for the experiment to verify the proposed concept will be long. However, this characteristic does not prevent the proposed concept from being used. Reference [11] reported an application using PSO (Particle Swarm Optimization) algorithm with a quite long evaluation time. The selected optimization algorithm was implemented in MATLAB^{TM} software platform. The objective function evaluation part of the algorithm interacts with the external hardware and real time simulation. The interaction is made between the implementation, external controller and real time simulation simultaneously. RTDS and its simulation are controlled by TCP communication between the RTDS user interface software, RSCAD and the MATLAB software where the optimization implementation runs. At the same time, the implementation communicates with the external hardware through RS-232C serial communication channel. The execution of real time simulation is controlled through the TCP channel. The final ISE (Integrated Squared Error) value from RTDS is brought back to the implementation through the same channel. The optimization candidate is transmitted to the external hardware through the RS-232C channel. The hardware controller receives the optimization candidate and applies those parameters to the corresponding regulators. In this experiment, the transient response of voltage control loop in the STATCOM system was selected as the target for the optimization. The control involves two PI regulators, one is at the higher level and the other is at the lower current controller level. The higher level PI regulator receives the AC RMS voltage and the AC voltage command as input. The output of this PI regulator is the reference value Q-axis current controller. The Q-axis current controller is composed of another PI regulator. It receives the output from the higher level PI regulator and Q-axis current measurement as input. Then, finally it produces the Q-axis voltage command. The proportional gain and integrator time constant of those two PI regulators were selected as the candidate for the optimization. Therefore, a single candidate contains four numbers, the proportional gain and the integrator time constant of both the voltage control PI regulator and the Q-axis current control PI regulator. Therefore, the dimension of Simplex becomes 5, the size of candidate plus one. As explained those parameters which compose the candidate are transmitted to the external controller and applied to the PI regulators before the evaluation of the candidate starts.

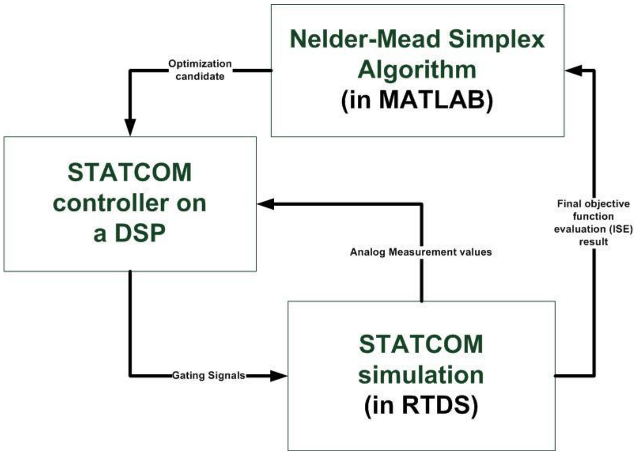

Figure 3 Overall experiment configuration

IV. TEST RESULTS

The experiment based on the configuration explained in the previous chapter, chapter III.-C., was attempted to verify the usefulness of the proposed idea in a more complex and realistic circumstance. During the first experiment, the iteration of the optimization process converged after 116 iterations. Each iteration took about 30 seconds. The total amount of time from the start of the experiment to the end was about 56 minutes. However, because the entire process was fully automatic, there was no manual engagement during that time. The candidate which was outside of the feasible boundary for the PI regulator parameters were automatically excluded from the evaluation. For example, a negative value to the integration time constant is not feasible, thus such candidate was excluded from the objective function evaluation. Therefore the number of iterations for the experiment indicates the true evaluation conducted with the real time simulator as well as the external controller. The best ISE value found during the iterations was 3.0270 at 104th iteration. The convergence criterion given to the optimization implementation was 0.2. In other words, once evaluation results of every vertex of Simplex comes within this distance, the convergence criterion becomes satisfied and the iterations stop. Figure 4 compares the STATCOM system dynamic response when the AC voltage reference was changed from 1.0 pu to 1.1 pu, from the best candidate and the worst candidate, found during the iterations in the experiment.

The best candidate was 0.0235, 0.0243 (AC voltage PI regulator parameters) 0.0092, 0.0019 (Id current controller PI regulator parameters) and the corresponding ISE value was 3.0270. The slight offset between the offset and the measurement is due to the analog output channel offset. The channel was used to transfer the reference from real time simulator to the controller.

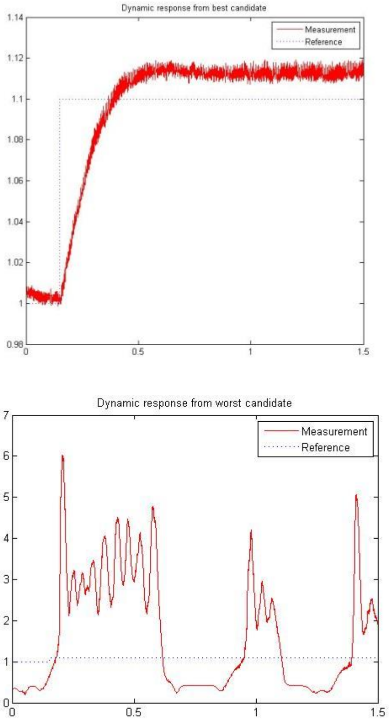

Figure 4 Performance comparison

The worst candidate was 1.0000, 1.5000 (AC voltage PI regulator parameters) 2.0000, 2.5000 (Id current controller PI regulator parameters) and the corresponding ISE value was 31390.00. As obviously attested in the comparison between the best candidate and the worst candidate, the performance of the best candidate from the optimization process was far superior to the performance of the worst candidate, proving the effectiveness of the proposed idea.

The experiment was repeated for 10 times to check the statistical characteristic of the proposed idea. At the same time, this series of tests were intended to demonstrate the usefulness of the proposed technique, the possibility of automated testing within reasonable amount of time. Table 1 presents the results.

Number of experiment	Number of iterations	Total amount of time	The best ISE result
1	72	35 minutes	9.5260
2	752	374 minutes	6.2140
3	77	37 minutes	4.3880
4	169	75 minutes	11.920
5	102	50 minutes	4.4630
6	387	192 minutes	7.7860
7	85	42 minutes	8.3630
8	72	37 minutes	4.3300
9	123	61 minutes	2.3420
10	70	35 minutes	8.7190

Table 1 Results of experiment repetition

An interesting point noticeable from the table is the fluctuation of the total number of iterations and corresponding duration time of experiment. The fastest experiment took 35 minutes with 70 iterations, while the longest experiment took 374 minutes with 752 iterations. If the off-line simulation was used as the objective function evaluation, every attempt of experiment would have been finished at the same number of iterations and the same amount of total execution time, regardless of the number of repetition. Besides, every experiment would have been produced the same best candidate with the same fitness value. However, once the external hardware becomes involved, certain level of uncertainty affected the experiment result, thus every repetition of the experiment finished with different number of iteration and different results. One external factor affected the outcome of the experiment would have been the noise on the analog signal interface. As we can see in the Figure 2, the wiring between the real time simulator analog output and the input of the external controller is less than ideal, probably prone to the external noise. In addition, no attempt was made on either real time simulation side or the external device side to suppress the adverse effect of the noise upon the analog measurement value. One possible approach would have been a signal conditioning circuitry at the input stage of the A/D converter in the external controller. The output voltage range of the analog output card at the real time simulator is +/-10V while the input voltage range of the A/D converter at the DSP is 0-3.3V, thus if the full range of the voltage output at the real time simulator would have been available towards the A/D converter stage of the DSP, probably the portion of the noise upon the analog signal would have been reduced, thus allowing higher quality in analog measurement value transfer from the simulator to the external controller.

V. CONCLUSIONS

The OE-EMTP technique with real time simulation was extended for the purpose of application in more complex environments. A STATCOM system based on 2-level power electronics based bridge was implemented and utilized as a subject for the proposed optimization technique. The experiment results presents that the proposed algorithm can improve the system performance under more realistic circumstances.

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VII. BIOGRAPHIES

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A. M. Gole received the B.Tech. (E.E.) degree in electrical engineering from the Indian Institute of Technology, Bombay, India, in 1978 and the Ph.D. degree in electrical engineering from the University of Manitoba, Winnipeg, MB, Canada, in 1982. He holds the NSERC Industrial Research Chair in Power Systems Simulation at the University of Manitoba. As an original member of the design team, he has made significant contributions to the PSCAD/EMTDC transient simulation program. Prof. Gole is the 2007 recipient of the IEEE Power Engineering Society's Nari Hingorani FACTS Award.