Optimisation of the DC railway power feeding system using the embedded simulation technique

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Abstract

Generally, numerical optimisation is a process that requires significant computing resources. It requires either the iteration of evaluation of the simulation model on which the optimisation is performed or the integration of the analytical model in the optimisation algorithm itself. The former is the basic concept of "embedded simulation". However, because of the constraint in the available computing resources, even when the "embedded simulation" approach is taken, the simulation model used in the optimisation process is somewhat simplified, which may make the optimisation results unreliable. If there is a proven, reliable simulation model or tool, and if there is no constraint on the available computing resources, it is preferable to use it without simplification in the optimisation process. In the optimisation of the DC railway power feeding network, there are a number of well-proven and reliable simulation programs; among them is RTSS, the simulator developed by the author. In this paper, the attempts made within the author's research group at Kogakuin University, Tokyo, in the past few years are reviewed, together with a new result.
Keywords: optimisation, DC power feeding networks for electric railways, multi-train power feeding network simulator, energy-saving operation, electric railways.

1 Introduction

Generally, numerical optimisation is a process that requires a significant amount of computing resources. It requires either the iteration of evaluation of the simulation model on which the optimisation is performed or the integration of

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the analytical model in the optimisation algorithm itself. The former is the basic concept of “embedded simulation”.

However, because of the constraint in the available computing resources, even when the “embedded simulation” approach is taken, the simulation model used in the optimisation process is somewhat simplified, which may make the optimisation results unreliable. If there is a proven, reliable simulation model or tool, and if there is no constraint on the available computing resources, it is preferable to use it without simplification in the optimisation process. Thanks to the recent developments in the optimisation algorithms and the improvements in computer hardware, this approach is quickly becoming more realistic.

The author’s research group at Kogakuin University has been maintaining an open-source object-oriented simulator of the power feeding network for DC electric railways, called RTSS [1]. RTSS is a full-scale simulation software first developed in the early 1990s and is now very reliable and well-proven. Using this tool, the group has conducted a number of research projects on the optimisation of power feeding network for DC electric railways using this approach [2–5].

In this paper, the author presents the basic concept of “embedded simulation” using a full-scale simulation software, and discuss its advantages and disadvantages. Then the author presents the latest results from one of such optimisation attempts.

2 Embedded simulation using a full-scale simulation model

2.1 The concept

The numerical optimisation using the embedded simulation approach generally takes a longer time to complete than the optimisation using the “analytical model” approach due to longer computing time required to calculate the model. However, in complex systems, it is difficult or even impossible to derive an analytical model. For example, Miyatake and Matsuda [6] have extended the previous successful attempt by Ko *et al.* [7] of optimising the speed profile of a train between adjacent stations using dynamic programming to obtain optimal charge/discharge power of an onboard energy storage system (ESS). This approach, however, has not been successful for the optimisation of charge/discharge power of the stationary ESS. While it is necessary to consider the speed profile of only one train, i.e. the train carrying the ESS itself, in the optimisation of the charge/discharge power of onboard ESS, it is necessary to consider basically all trains in the feeding network to conduct the optimisation of stationary ESS using the same approach. This will make the application of dynamic programming very difficult.

The idea of embedded simulation is to use the simulation model, established elsewhere, in the optimisation process. Suppose there is a group of different design instances in a set S_D. If the evaluation function $E(D_i)$ can be calculated for each design instance $D_i \in S_D$, then it is possible to select the best design from among the elements of S_D. The optimisation algorithm helps this process by reducing the number of actual calculation of $E(D_i)$ below $|S_D|$.

It is important to note that, whatever the system is to be optimised and whatever the evaluation function is, the numerical optimisation can be theoretically carried out if S_D can be specified and $E(D_i)$ can be calculated for all $D_i \in S_D$. Even when S_D is unknown or has large, if not infinite, number of elements, optimisation may be carried out it using an efficient optimisation algorithm if it is possible to create a new design candidate $D_i \in S_D$.

2.2 The advantages

This optimisation approach can be used for all optimisation problems as long as $E(D_i)$ can be calculated for any design instance $D_i \in S_D$. For example, suppose there is a group of input data, $x_1, x_2, \ldots, x_n$, to be given to a simulation program, and the simulation program can output an evaluation index for any combination of these input data. Then it is possible to conduct optimisation by embedding the simulation program in the optimisation process. It is possible to define a design instance in a number of different ways. For example, a design instance can be a combination of all variables $x_1, x_2, \ldots, x_n$ as an n-tuple $(x_1, x_2, \ldots, x_n)$; or, alternatively, it can be just x_1, in which case other variables $x_2, \ldots, x_n$ are given as the assumed condition. Basically the same algorithm or principle can be used for any definition of design instance, although the required calculation time greatly depends on it.

It can also be said that, depending on the maturity of the simulation model to be embedded, the optimisation result becomes more reliable than the result using any "simplified" simulation models.

2.3 The disadvantages

The most significant problem of this approach is the requirement on the computing resources. It is not uncommon that the simulation is repeated for more than 10,000 times, and if this is the case and one single simulation takes 1 second, then the total optimisation will take three hours. Full scale simulation models generally require more computing resources, and repeating the simulation very many times is limiting the possibility of application of this approach.

It must also be pointed out that, although the simulation model may be proven and reliable, the assumption to be made on the part of the design not to be optimised may have a significant impact on the optimisation result. For example, in the optimisation of a DC railway power feeding system, very large number of data must be input, such as the voltage-current characteristics of the feeding substation, topology and parameters (e.g. resistance per length) of the feeding circuit, train performance, train timetable, etc. Out of these, optimisation of the characteristics of the feeding substation to minimise energy consumption of the railway system as a whole can be considered; however, in doing that, the impact the assumptions on train timetable causes to the optimisation results may be far larger than the minute difference caused by the change in substation characteristics.

The relevance of the setting of any particular parameter(s) to be optimised must also be examined. For example, the charge/discharge characteristics of an ESS can be optimised using the embedded simulation, as presented in references [4] and [5]. However, the characteristics must be defined in its entire possible region. Taking the ESS control scheme in which line voltage is used to determine the charge/discharge current, as shown in Fig. 1, for example: all parameters Va, Vb, …, Vf in the Figure must be determined to perform a simulation. Let us assume that Vb, Vc, Vd and Ve are the parameters to be optimised. If the lowest line voltage observed during the simulated period is above the optimised value of Vc, then the optimised values for Vb and Vc would probably contain no meaningful information.

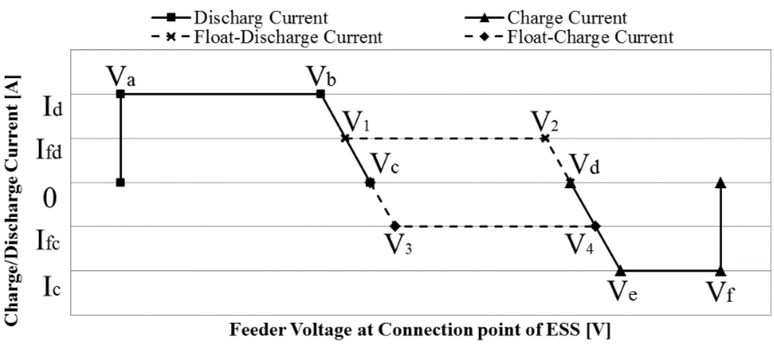

Figure 1: Current-Voltage characteristics of an ESS [4].

3 Multi-train railway power network simulator “RTSS”

In the examples shown in this paper, the multi-train DC railway power network simulator RTSS [1] is used as the simulation tool.

First developed in 1990, RTSS has been maintained and used extensively within the author’s research group. This program incorporates the detailed simulation model, including the voltage-dependent train performance model. Inclusion of the voltage-dependency of train performance, however, would generally mean that the start-to-stop times of trains may fluctuate when other parameters such as substation output voltages change, resulting in unreliable evaluation of energy consumption. RTSS resolves this issue by implementing a small subprogram that auto-calculates the time at which any train in the simulation ceases acceleration, enabling the simulation with precise start-to-stop time of any inter-station run in the simulation. This program has actually been used for evaluation of a number of DC railway related projects.

It is important to note that RTSS is not the only tool that can be used for the embedded simulation. The idea of embedding a full-scale simulation model in the optimisation process appears, for example, in reference [8], in which the simulation tool OOMTS with the object-oriented signalling system model developed by the University of Birmingham was embedded in a genetic algorithm (GA) to obtain optimal train order at a junction. Any other simulation tools can theoretically be embedded in the optimisation process in completely the same way.

4 Optimisation algorithms

There are a number of optimisation algorithms that can be used in the embedded simulation.

In reference [4], the author used the multi-dimensional downhill simplex method (also called the Nelder-Mead method or the amoeba method) [9]. This algorithm utilises a polyhedron (simplex) with the $n+1$ vertices in n-th dimensional space, when n variables are in the parameter set to be optimised. The position of any one vertex of the simplex corresponds to a set of values for the parameter set, and therefore a simplex as a whole represents a set of candidates of the optimal solution. During the optimisation process, the shape of the simplex is transformed according to the evaluation of the vertices until all the vertices are brought very close to the vertex with the best evaluation. The simplicity of this optimisation method makes it easy to embed any detailed simulation tool in the process. However, the optimisation attempts using this algorithm with RTSS as embedded simulator did not produce satisfactory results. Some results clearly suggested that the optimisation algorithm was trapped in the so-called local minimum. This can frequently happen when a full-scale simulation program like RTSS is embedded, because the evaluation function calculated through such a simulation program tends to be badly behaving, i.e. has many small peaks and bottoms scattered about in its domain of definition.

Recently, GA is extensively used in the author's research group with better results compared to the amoeba method, mainly due to its ability to avoid local minimum. The main disadvantage of GA is the tendency that the computing time becomes even longer than the amoeba method in our trials – it must be noted that the amoeba method is not believed to be the efficient optimisation algorithm.

5 Recent attempts

In references [2–5], the author intended to use the embedded simulation approach to optimise various parameters related to the control of ESS in the DC railway feeding network.

In references [4] and [5], the control parameters of the stationary ESS was the target of the optimisation. In this attempt, it was assumed that the charge/discharge current of the ESS was determined using the line voltage, as shown in the example presented in 2.3. There were only a few parameters necessary to be optimised to determine a charge/discharge characteristics as shown in Figure 1. This model was then used to investigate the relationship between the storage capacity of ESS and the optimal characteristics so that "optimal" storage capacity can be derived [10].

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In references [2] and [3], the reference data for the "feed-forward" control of the onboard ESS was the target of the optimisation. However, the reference data, which is the state of charge (SOC) value (in %) of the ESS onboard a train at any position, is very difficult to derive directly using the numerical optimisation algorithm, because the number of variables to be optimised may become too large. Therefore, a technique was introduced to reduce significantly the number of variables to be optimised [3].

The embedded simulation technique has the advantage that the set of parameters to be optimised can be easily altered without modifying the program significantly. As an example, the tool developed for the optimisation of the control parameters of the ESS was quickly modified to optimise the parameters for the "main circuit power control", as proposed by the author in 1992 [11, 12]. The optimisation was attempted as part of the discussion for the possibility to adopt this control to the power saving train operations, which was imposed in the wake of the 2011 Tohoku Earthquake and Tsunami that badly damaged the electrical power supply system of Japan [13].

6 Discussions

Through a number of attempts of adopting the embedded simulation technique, the following were found on the technique through experience:-

- The time required for computing is very long. In an example shown in reference [10], it took a few days to complete an optimisation case using a computer with the latest Intel Xeon microprocessor with eight cores and running as many parallel runs of RTSS simulation program as the cores in the processor (RTSS is currently a single-threaded application).
- For this reason, it is currently not realistic to use embedded simulation technique to generate a function, which means a large number of variables need to be optimised.
- The possibility of shortening the calculation time should be seriously investigated. Better use of parallel computing (currently RTSS is a single-threaded application, i.e. no parallelism is used in it), improvement in computing time of the simulator itself (apart from the introduction of parallel computing, poorly designed, inefficient codes exist in many parts of the RTSS source), and quicker invocation of any individual run of the simulator (currently, because of the fear of encountering the "memory leak" bugs, each RTSS run is invoked using the "system()" library function of C programming language, i.e. the optimisation program asks the operating system to start the RTSS program, which is a slow way of starting the simulation) are among the possible measures.
- A full-scale simulator of a large scale system such as the DC railway power feeding system is generally complex. Therefore, using the result of this simulator to calculate the evaluation function makes it more probable that the search for optimal solution using the optimisation

algorithm ends up being caught in a “local minimum”. This requires the use of an algorithm less likely to be caught in a local minimum – for example, the GA is preferable to the amoeba method for this reason. This may also result in the situation in which the interpretation of the optimal solution is difficult.

7 Conclusion

The experience by the author’s research group to conduct research using the embedded simulation and the full-scale DC railway power network simulation program RTSS has been reviewed in this paper.

From the experience, it seems clear that the most serious issue in the research using this technique is the long calculation time. This prevents the repetitive trials of many optimisation attempts necessary to adjust input data, optimisation algorithm parameters, evaluation functions, etc. to obtain better results. Shortening of the calculation time through various measures, including but not limited to the use of more efficient optimisation algorithms, should be considered in the future studies.

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