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Optimization of Railroad Electrical Systems with the Integrated Smart Grid

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Abstract
This paper proposes an optimization model for the railroad transportation electrical systems with the integrated smart grid. The proposed railroad smart grid consists of distributed generation (wind and solar power generations) and the hybrid energy storage system. The hybrid storage considered in this paper includes the supercapacitors and the batteries, and they are used to provide the storage flexibility. The proposed optimization problem is formulated as a mixed integer nonlinear optimization problem and it is solved using the micro genetic algorithms. The simulation studies are performed on a actual electricity price data using with and without considering the smart grid components.

Keywords: Utility grid, railroad power system, distributed generation, electrical smart grid, energy storage.

NOMENCLATURE

T	Scheduling Period.
P_{Grid}	Power to/from to the utility grid.
P_{Excess}	Excess power.
$P_{Battery}$	Power to/from to the storage battery.
P_{Train}	Train traction power.
P_W	Power output from the wind farm.
P_S	Power output from the solar photovoltaic plant.
P_{SC}	Power to/from to the supercapacitor.
I(t)	Charge (+)/discharge (-) current.
Δt	Scheduling interval.
C^{min}	Aggregated lower capacity of the battery.
C^{max}	Aggregated capacity of the battery.
$C_{initial}$	Initial SoC of the battery.
C_{final}	Final SoC of the battery.
$I(t)^{min}$	Aggregated charging current limit (-) for all batteries.
$I(t)^{max}$	Aggregated discharging current limit (+) for all batteries.

INTRODUCTION

Railroad transportation systems are one of the largest energy consumers in the electrical power systems. Railroad accounts for 2% of overall energy consumption and 7 million tons of CO_2 emission. The target of European Union Climate and Energy by 2020 is that to improve the energy efficiency of railroad systems and to create the "green image" to the railroad [1]. In the recent years, the utilization of renewable energy and advanced energy technologies has increased the insertion of distributed generation into the utility grid. The operation, planning and control strategy of distribution system changes because of the power injection from the distributed generators. Some of the utility grids may have their own distributed generators or buy power from the owners of distributed generators. The insertion of power from the distributed generators significantly reduces the power losses and improves the voltage profile of the system.

There is a requirement for improving the energy efficiency of railroad power systems by incorporating the smart grid components. References [1]-[7] have made an attempt to improve the energy efficiency of railroad power systems by utilization and efficiency of braking trains regenerative energy. During the breaking, the electric trains convert the mechanical energy to the electrical energy and feed it back to the catenary. This electrical energy can be used by the accelerating trains or stored in the energy storage devices or dissipated using the resistors. Nowadays, with the incorporation of smart grid concept, the grid optimization can be performed dynamically. The smart grid system balances the energy produced from the decelerating trains, energy consumption by the accelerating trains, energy storage and the energy exchange from the main electrical utility grid. By using the integrated smart grid, the railway system operator becomes less dependent on the main electrical grid, increased efficiency can be obtained, it encourages the stability and reliability of the system with less operating cost.
An energy flow optimization of a railway system microgrid is proposed in [3]. The proposed optimization problem is formulated as a linear program that takes into account the energy storage systems with corresponding charge and discharge efficiencies, actual electricity prices and simulated daily train consumption profiles. Reference [4] proposes the stability of a DC Micro-grid integrated in urban railway systems in order to recover trains braking energy. An energy optimization tool for the interconnected railway-MG system using the Artificial Bee Colony algorithm is applied for achieving the economical cost during the operation is proposed in Reference [5]. A new green solution to recover trains braking energy by integrating Smart DC micro-grid concept in railway systems is proposed in [6]. A fuzzy logic supervision strategy is developed in [7] to achieve the renewable energy sources and storage units' coordination in the railway power substation. Reference [8] proposes an approach to modify the power supply systems currently used in ac-fed railways with neutral zones (NZs), in order to allow power-flow routing.
The proposed railroad smart grid consists of distributed generation (wind and solar power generations) and the hybrid energy storage system. The hybrid storage considered in this paper includes the supercapacitors and the batteries, and they are used to provide the storage flexibility. The proposed

optimization problem is formulated as a mixed integer nonlinear optimization problem and it is solved using the micro genetic algorithms. The simulation studies are performed on a actual electricity price data using with and without considering the smart grid components.

PROPOSED RAILROAD ELECTRICAL SYSTEM WITH INTEGRATED SMART GRID

The proposed electrical smart grid system balances the energy produced from the decelerating trains, energy consumption by the accelerating trains, energy storage from the battery storage and the supercapacitors and the energy exchange from the main electrical utility grid. The proposed railroad electrical power system with an integrated smart grid is depicted in Figure 1.

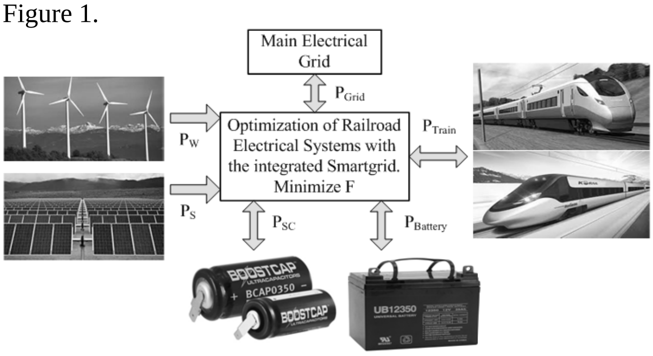

Figure 1: Railroad electrical power system with an integrated smart grid.

The objective of the proposed optimization model is to minimize the total cost of operation utility grid and smart grid considering the forecasted consumption profiles of trains, wind and solar power and state of charge (SoC) of batteries considering various equality and inequality constraints. The objective function is formulated as,

Minimize,

$$F = \sum_{i=1}^{T} \left[C_G(P_{Grid}^t) + C_W(P_W^t) + C_S(P_S^t) + C_{SC}(P_{SC}^t) + C_B\left(P_{Battery}^t\right) \right] \quad (1)$$

subjected to the following equality and inequality constraints.
The power balance equation is expressed as,

$$P_{Train}^t + P_{Excess}^t = P_{Grid}^t + P_{SC}^t + P_{Battery}^t \qquad t = 1,2,3,\dots,T \quad (2)$$

P_{Train}^t is positive for the power consumption and P_{Train}^t is negative for the power production by accelerating/decelerating trains.

Constraint on the power from the utility power grid is given by,

$$P_{Grid}^{min} \le P_{Grid}^t \le P_{Grid}^{max} \quad (3)$$

Constraint on excess power is expressed as,

$$P_{Excess}^t \ge 0 \quad (4)$$

Battery state of charge (SoC) balance equation is given by,

$$C(t) = C(t-1) + I(t)\Delta t \qquad t = 1,2,3,\dots,T \quad (5)$$

The battery SoC limits are expressed as,

$$C^{min} \le C(t) \le C^{max} \qquad t = 1,2,3,\dots,T-1 \quad (6)$$

$$C(0) = C_{initial} \quad (7)$$

$$C(T) = C_{final} \quad (8)$$

The charge/discharge current limits of the battery are expressed as,

$$I(t)^{min} \le I(t) \le I(t)^{max} \qquad t = 1,2,3,\dots,T \quad (9)$$

The charging and discharging power limits of supercapacitors are expressed as,

$$P_{SC}^{ch,min} \le P_{SC}^{ch} \le P_{SC}^{ch,max} \quad (10)$$

$$P_{SC}^{dch,min} \le P_{SC}^{ch} \le P_{SC}^{dch,max} \quad (11)$$

The above optimization problem is solved using the micro genetic algorithm (MGA) and it is described next:

MICRO GENETIC ALGORITHM (MGA)

The optimization problem proposed in this paper is solved using the micro genetic algorithm (MGA). Genetic algorithms are simple, robust, flexible, and able to find the global optimal solution. They are especially useful in finding solution to problems for which other optimization techniques encounter difficulties. The disadvantage of GAs is the high processing time associated. That is due to their evolutionary concept, based on the random processes that make the algorithm quite slow. However, different methods for reducing processing time have already been proposed, such as more appropriate choice of solution coding and reduction of search space using the specialist knowledge. One alternative method known as micro genetic algorithms (MGAs), whose processing time is considerably smaller, and it is shown in Reference [9] .

Most GAs produce poor results when populations are small, because insufficient information is processed about the problem and, as a consequence, premature convergence to a local optimum occurs. Population size generally varies from 30 to 300 individuals. In contrast, MGAs explore the possibility to work with small populations (from five to 20 individuals usually) in order to reduce the processing time. From a genetic point of view, it is known that frequent reproductions inside a small population may disseminate hereditary diseases rarely found in large populations. On the other hand, small populations can act as natural laboratories where desirable genetic characteristics quickly can emerge. In MGAs, mutations are unnecessary because after a certain number of generations, the best chromosome is maintained and the rest are substituted by randomly generated ones. It requires adoption of some preventive strategy against the loss of diversity in population.

Basically, two mechanisms are used to prevent loss of diversity in population [10]. First, the individuals are selected (only once) for a tournament where couples are randomly formed to compete between themselves. The most adapted individual of each couple wins. Then, the tournament is repeated and the selected individuals form couples to begin crossover. In this way, not only do the most developed individuals have an opportunity to participate in the reproduction but all of them do. The second mechanism is to insert new individuals each time the population becomes homogeneous. Each time the population reaches a homogeneous degree previously chosen, the best individual is kept and inserted into a new population randomly created. When it occurs, a generation has occurred. If the same individual is the best one along a certain number of generations, the algorithm stops and this individual represents the solution.

The MGA implemented in the present paper is described next:
Step 1: Select a population of n randomly generated individuals. Alternatively, n-1 individuals may be generated randomly together with one good individual obtained from previous search.

Step 2: Evaluate the fitness and determine the best individual which is always transferred to the next generation. This "elitist" strategy guarantees against the loss of good information embedded in the best individual produced thus far.

Step 3: Select individuals for reproduction with the tournament selection strategy.

Step 4: Apply crossover with probability equal to 1 to favor exchange of genetic information among the population.

Step 5: Check for convergence by measuring the amount of diversity left in the population (by counting the total number of bits which are unlike those possessed by the best individual). If population diversity has fallen under a preselected threshold, the go to Step 1; otherwise, go to Step 2.

Changes compared to basic GA
In micro genetic algorithm (MGA) approach the problem formulation remains the same. The steps involved in solving the problem are briefly described below.

i. For optimal power dispatch using MGA parents are selected using the tournament selection technique.
ii. The crossover probability is made 1 to favor exchange of genetic information among the population.
iii. Mutation is not needed, since enough genetic diversity is introduced after every convergence when all the population (with the exception of the best individual) is randomly recreated afresh.
iv. Convergence is checked by measuring the amount of diversity left in the population.

RESULTS AND DISCUSSION
In micro genetic algorithm (MGA), the selected population size is 5, the best fit chromosome is copied in elitism operation, the crossover probability is 1. In MGAs, the mutations are unnecessary because after a certain number of generations, the best chromosome is maintained and the rest are substituted by randomly generated ones.
The effectiveness of the proposed optimization approach is tested on a actual electricity price data obtained from the Power Exchange India Limited (PXIL) [11], train consumption profiles are taken from [1,12]. The train data and various Microgrid components data are taken from [4]. The maximum wind energy generator capacity considered in this paper is 3MW and the forecasted wind velocity is 11m/sec. For a given wind speed, the output of wind energy generator is calculated using [13, 14],

$$P_W = \begin{cases} 0 & for\ v < v_i\ and\ v > v_o \\ P_r\left(\frac{v-v_i}{v_r-v_i}\right) & for\ v_i \le v \le v_r \\ P_r & for\ v_r \le v \le v_o \end{cases} \quad (12)$$

The considered maximum power limit of solar PV unit is 3MW and the solar irradiation is 800W/m^2. For a given solar irradiation, the power output is expressed as [15, 16],

$$P_{PV}(G) = \begin{cases} P_{sr}\left(\frac{G^2}{G_{std}G_c}\right) & for\ 0 < G < R_c \\ P_{sr}\left(\frac{G}{G_{std}}\right) & for\ G > R_c \end{cases} \quad (13)$$

The lower and upper limits of SOC of storage battery are considered as 10kAh and 15kAh, respectively. The maximum power considered from the grid is 20MW, the maximum capacity of battery and supercapacitor are 1MW and 2 MW, respectively. The proposed optimization problem is solved using the MGA and the optimization program is coded in MATLAB R2016a and implemented with Intel Core i7 processor of 3.66GHz, 8GB of RAM.
In the present paper, two case studies are performed and they are,

- **Case Study 1**: Operation of railroad electrical system without considering the MG components.
- **Case Study 2:** Operation of railroad electrical system considering the MG components.

Case Study 1
In this case, the simulation is performed without considering the MG components, i.e., wind energy generator, solar energy generator, battery storage and the supercapacitor. The obtained objective function values are presented in Table 1. Here, the energy consumed by the train is 21.8126MWh and the energy returned to the electrical grid is 2.6403MWh. The total energy cost obtained in this case is 173,921.35 Rs/hr.

Table 1. Optimum objective function values for Case Studies 1 and 2.

Objective function/variables values	**Case Study 1**	**Case Study 2**
Energy consumed by the train (in MWh)	21.8126	21.7859
Energy returned to the electrical grid (in MWh)	2.6403	5.1132
Wind power generation (in MW)	---	2.820
Solar power generation (in MW)	---	1.536
Storage battery power (in MW)	---	0.865
Supercapacitor power (in MW)	---	1.324
Total energy cost (in Rs/hr)	173,921.35	160,250.72
Savings (in Percentage)	---	7.86

Case Study 2

In this Case Study, the simulation is performed by considering the MG components, i.e., wind energy generator, solar energy generator, battery storage and the supercapacitor. Table 1 also presents the objective function values for Case 2. The amount of energy consumed by the train is 21.7859 MWh and the energy returned to the electrical grid is 5.1132 MWh. The amount of power generation in the MG has the wind power generation of 2.82MW, solar power generation of 1.536MW, storage battery power of 0.865MW and the supercapacitor power of 1.324MW. From this, it can be observed that the amount of power returned to the grid has increased in this case, compared to Case Study 1. The total energy cost obtained in this case is 160,250.72 Rs/hr. Therefore, the net savings obtained in this Case is 7.86%.

From the above simulation studies, it can be observed that by including the MG components the amount of energy returned to the grid has increased and there is a considerable savings in the total energy cost.

CONCLUSIONS

Micro genetic algorithms (MGAs) are more efficient to solve this kind of problems, as they are faster and converge to better optimal solutions. The micro genetic algorithms become even more efficient when specialist's knowledge (Eg. Fuzzy Logic) about the problem is included. In this way, it is possible to reduce search space and, consequently, decrease the execution time, increasing the chances to reach global optimal solution. The simulation studies indicates that by including the MG components the amount of energy returned to the grid has increased and there is a considerable savings in the total energy cost.

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