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Optimization of Energy Consumption In Electric Traction System By Using Interior Point Method

Nilam R. Dongre[1], A. S. Sindekar[2]
PG Scholar Department of Electrical Engineering Govt. College of engineering, Amravati India
Associate Professor & Head Department of Electrical Engineering Govt. College of engineering, Amravati India
Corresponding Author: Nilam R. Dongre1

Abstract: *Increasing attention is being paid to optimization of energy consumption in electric traction system to reduce operational cost. Electric traction system requires electric power for propulsion of vehicles. One of the main objective of electric traction system is to provide better quality services which implies increasing speed and decreasing travel time. It results in increase in energy consumption. This paper deals with the optimization of energy consumption and various methods that can be used for it. Mathematical equation for energy consumption is formulated by using speed time curve. Interior point algorithm is used for optimization of energy consumption in electric traction system*

Keywords*: Energy consumption, Interior point algorithm Electric traction system, Electric locomotive, Optimization*

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I. Introduction

Electric traction system is a backbone of transportation system providing high transport capacity, lack of pollution, safe and comfortable journeys to the large number of passengers. One of the basic objective of modern railway system is to reduce the journey time which in turn increases the accelerations and corresponding high currents. As a result, energy consumption increases. It leads to increase in cost of travel. Energy resources are quite scarce and one of the most important energy resources is electricity. For this reason, optimization of energy consumption without affecting the quality of the service has become a vital need.

The evolutionary optimization techniques like interior point algorithm and genetic algorithm have been used for optimization of tractive energy consumption [1]. A speed time curve has been linearized and calculation of energy consumption for locomotives in railway electric traction system are done on the basis of linearized speed-time curve.[3]

Fig [1] shows the block diagram for locomotive supply system which represents power flow model of modern traction system. Railway traction system has dedicated traction substation. These substations receive the power from grid and feed to the catenary at suitable points. This power received from the grid is in the form of three phase power at 130/220 KV. The voltage is stepped down to 25KV by substation transformers which is received by catenary at suitable points.

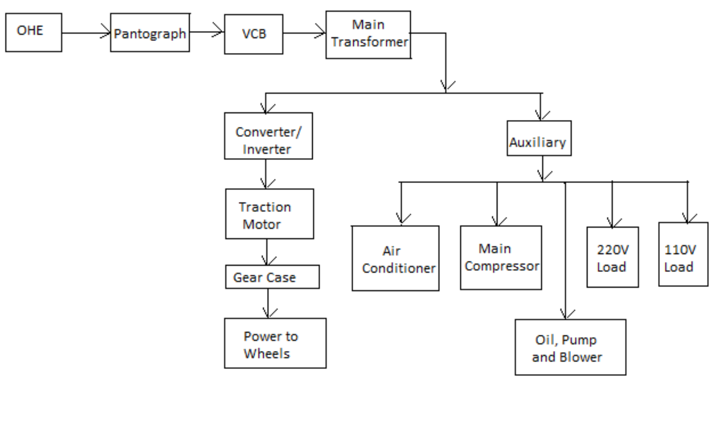

Fig 1. Block diagram for locomotive supply system

The modern traction drive system consists of locomotive transformer which has three secondary windings. The electric power collected by a pantograph from overhead catenary system is fed to the primary of the single phase locomotive transformer. This is a step down transformer usually with three secondary windings out of which traction drive are fed through converter-inverter system with two secondary windings. The auxiliaries in the locomotive i.e. air conditioners, cooling fans, lighting systems etc are fed by the third secondary winding of the locomotive transformer.

II. Mathematical Model Of Energy Consumption

Energy consumption in electric traction system can be studied with the help of speed time curve and speed distance curve. Speed time curve is a plot showing instantaneous speed of train along ordinate and time along abscissa. It represents variation of speed at different time instants after starting of the train. In speed time curve, the distance travelled during given time interval is given by the area between the curve and abscissa. Likewise acceleration and retardation is given by the slope at any point on the curve towards abscissa.

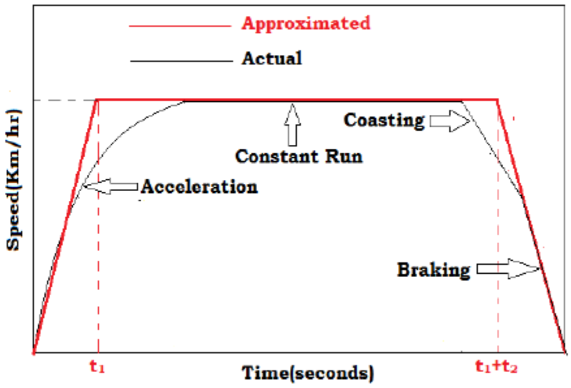

Fig 2 Typical speed- time curve

Typical speed time curve of a train is shown in Fig 2. There are four distinct periods in it, acceleration period, free running period, coasting period and braking period.

a. Acceleration period – Train is accelerated to its maximum velocity. Here, speed of train increases continuously and attains its maximum value. Maximum power is drawn during this period.
b. Free running period – Train runs at constant speed attained at the end of acceleration period. Constant power is drawn during this period.
c. Coasting period – Supply to motors is cut off at the end of free running period and train is allowed to run due to its own inertia. Here, train do not draw any power from the supply and it runs due to the kinetic energy gained by the wheels. Speed of the train gradually decreases due to train resistance.
d. Braking period – Brakes are applied at the end of coasting period to bring the train to rest.

The force developed by the traction unit at the wheel rims for moving the traction unit and its train is called tractive effort. Force exerted by the traction unit through the draw bar is draw bar pull. Thus to move the traction unit, draw bar pull is less than the tractive effort. Tractive effort exerted by the traction unit is mainly to perform following functions

a. To provide necessary acceleration to the train mass (i.e. linear and angular acceleration)
b. To overcome the gravity component of the weight of the train
c. To overcome the various resistances of the train (i.e. wind and frictional resistance)
d. To overcome curve resistance

Hence, mathematical equation of tractive effort can be developed as follows :

Motion of train is given by,

$F_e = m*a + \Sigma F$

Where, F_e = tractive effort to drive the train (Newton)

m= mass of the traction drive (Kg)

a = acceleration of the train (m/sec^2)

ΣF = summation of forces acting against the motion of the train

$\Sigma F = F_r + F_g$

F_r = tractive effort required to overcome the train resistance = mr

F_g = tractive effort required to overcome the effect of gravity

And

Fg = m*g*sinΦ

g= acceleration due to gravity (m/s^2)

sinΦ = gradient

Various calculations are done on the basis of linearized speed time curve. Considering approximated linearized curve from fig 2, constant acceleration period is upto time t_1, constant run period is from t_1 to t_2 and braking period starts from t_2.

As work done is converted into energy, energy consumed up to time t_1 i.e. for positive gradient, is represented by equation (1)

Et_1 – Energy consumed upto time t_1 (kWh)

Et_1 = Force * Displacement

$= Ft_1 * ½ * V_m * t_1$ (1)

Ft_1 is the effort required by the traction system upto time t_1 due to acceleration, gravity and tractive resistance. V_m is maximum velocity.

F_{t1} is given by equation,

$Ft_1 = [m*a \pm m*g*\sin\Phi + m*r]$ (2)

Positive sign indicates the positive slope which implies upward motion and negative sign indicates negative slope which implies downward motion.

Tractive resistance in N/Kg is denoted as r and is given by equation,

$r=K_1 + K_2*V + K_3* V^2$ (3)

K_1, K_2 and K_3 are called as Davis constants.

Fig 3 denotes tractive effort because of gravity where Φ is the angle between railway track which is rising upward or downward and horizontal level.

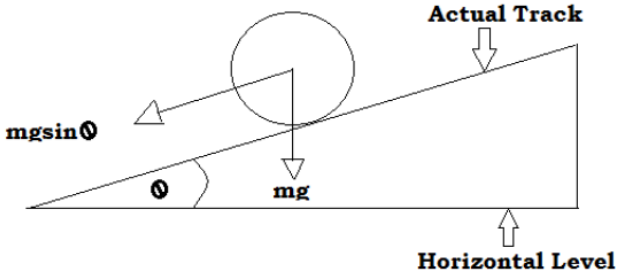

Fig 3. Tractive effort because of gravity

Energy consumption from time t_1 to t_2 is denoted as E_{t2} and is given by equation,

$E_{t2} = F_{t2} * V_m * t_2$ (4)

During constant velocity, acceleration a = 0

Therefore, Energy consumption occurs during constant velocity,

$E_{t2} = [m*g*\sin\Phi + m*r]* V_m * t_2$ (5)

Where, t_2 is free running period

Total energy consumption can be calculated as

$E= E_{t1} + E_{t2}$ (6)

$E = m*V_m [(\frac{\alpha \pm g*\sin\Phi + r}{2})* t_1+ (\pm g*\sin\Phi+r)*t_2]$ (7)

Since $V_m = \alpha * t_1$

$E = m* (\alpha*t_1)*[(\frac{\alpha \pm g*\sin\Phi + r}{2})* t_1] + (\pm g*\sin\Phi+r)* t_2\}$ (8)

Equation [7] and [8] denotes the total energy consumption where positive sign is for positive gradient and negative sign is for negative gradient In order to calculate the tractive energy consumption, realistic values for various parameters are considered. Data for positive, negative and zero gradient is given in Table-I.

Table 1: Data used for calculations

Parameter	Value
M	213 Tonnes
V_m	50 m/s
SinΦ	$2 * 10^{-3}$
R	$8.736 * 10^{-2}$ N/kg

Considering the data from table-1, the corresponding equations for energy consumption are,

$E = 10^4 *(\alpha *t_1)[10.65* \alpha *t_1+1.14*t_1+2.28*t_2]$ (9)

$E = 10^4 *(\alpha *t_1)[10.65* \alpha *t_1+0.72*t_1+1.44*t_2]$ (10)

$E = 10^4 *(\alpha *t_1)[10.65* \alpha *t_1+0.93*t_1+1.86*t_2]$ (11)

III. Problem Formulation

The equation of total energy consumption as defined in (9), (10) and (11) is considered as a function to optimize with respect to some constraints.

Optimization of tractive energy is done under following two constraints

a. Maximum velocity (V_m); attained by the train should not exceed beyond specified value
b. Distance travelled by the train (S); should remain constant

Mathematically, the objective function of the optimal control problem is defined as

$$\text{Min } F(X) = E = m*V_m \left[\left(\frac{\alpha \pm g*\sin\Phi + r}{2}\right)* t_1+ (\pm g*\sin\Phi+r)*t_2\right]$$

Constraints can be defined mathematically as,

$\alpha * t_1 \leq V_m;\ V_m = 50$ m/s (12)

$0.5* \alpha * t_1^{\ 2} +\alpha * t_1 * t_2 = S;\ S=100$km (13)

IV. Various Methods For Optimization

Mathematical model of tractive energy consumption which is denoted by equations (9) – (11) has to be optimized under constraints. Various optimization techniques can be used to optimize the above mentioned energy equation. Some of these methods are

A. Interior point algorithm

Interior point methods are barrier methods that can solve linear and non linear convex optimization problems. It can optimize large, sparse and small dense problems. The basic approach is to solve a sequence of approximate minimization problems.

Considering a generalized problem defined in equation,

Min $F(X) = 0$ subject to $G(X) \leq 0$ and $H(X) = 0$ (14)

Where G(X) denotes inequality and H(X) denotes equality constraints.

The original problem which has the inequality constraints can be converted into a problem with equality constraints which is easier to solve.

Considering λ as a parameter which changes after every iteration and pi is number of slack variables and is equal to number of inequality constraints ‘G’ in the optimization problem,

for each $\lambda > 0$; the approximate problem is given by,

$\min F_\lambda (x,p) = (\min F(x) - \lambda\ \Sigma i \ln p_i)$ (15)

subject to $G(x) + p = 0$ and $H(x) = 0$

To keep ln(pi) bounded, slack variables are restricted to be positive. The minimum value of f_λ should correspond to the minimum of F. This algorithm uses one of two main type of steps which includes direct step and conjugate step at each iteration to solve the approximate problem. Initially, the direct step is taken in this algorithm. If it is not possible to take direct step due to some reasons, it attempts conjugate step.

The algorithm decreases a merit function in every iteration. The algorithm rejects the iterate k_i if either a objective function or nonlinear constraint function returns a complex value, infinite value or an error. It is equivalent to the case as if the merit function did not decrease sufficiently and in this case algorithm attempts a different step.

B. Genetic algorithm

Genetic algorithm is an optimization technique which is inspired by the principles of natural evolution and natural selection. It is an exploratory method which locates a near optimal solution to complex problems. As there are no slopes or derivatives required in genetic algorithm, there are very less chances to get trapped to a local optima. It can provide better results when search space is very large. It generates solution on the basis of inheritance, selection, crossover and mutation which are the techniques inspired by natural evolution.

Initially a representation of possible solutions is developed. A random population is used to start the optimization process and best fit function is selected based on the Darwin’s theory of ‘survival of the fittest’. It is selected to move towards optimal solution. The process includes the step as evaluation, reproduction, recombination and mutation.

V. Optimization By Conventional Method

Optimization of tractive energy consumption which is defined by equation of total energy is done using the constraints defined in section III by using conventional method of MATLAB programming.

Basic equation of objective function (for energy consumption) and two constraints are plotted on a single graph so that the region of optimal point can be obtained. Table 2 shows the optimized energy and corresponding parameters obtained by conventional programming method.

Table 2: Optimized parameters by conventional method

Parameter	Value
Acceleration 'a' (m/s^2)	0.2
Acceleration time 't_1' (s)	250
Free run period 't_2'(s)	1875
Energy consumption (kWh)	680.6667

To initially get the idea about where the minimum point of energy consumption lies the graph is plotted as shown in Fig.4. It shows a plot of train energy, error in train distance and error in train velocity with respect to variable time events. It includes

a. Sub graph 1 – It shows the variation in train energy corresponding to variable time instants.
b. Sub graph 2 – Error in train distance is plotted against the variable time events. It is one of the constraint i.e. distance travelled by the train should remain constant for minimum energy consumption. The point at which error is minimum i.e. zero is the optimal point. Therefore, optimal point lies in the region where error in train distance is zero.
c. Sub graph 3 – Error in train velocity is plotted against variable time events. It is also one of the constraints i.e. Maximum velocity of the train should not exceed beyond specified value. When train velocity is greater than 50 m/s , error is positive and vice versa. So the optimal point lies in the region where velocity is less than 50 m/s.

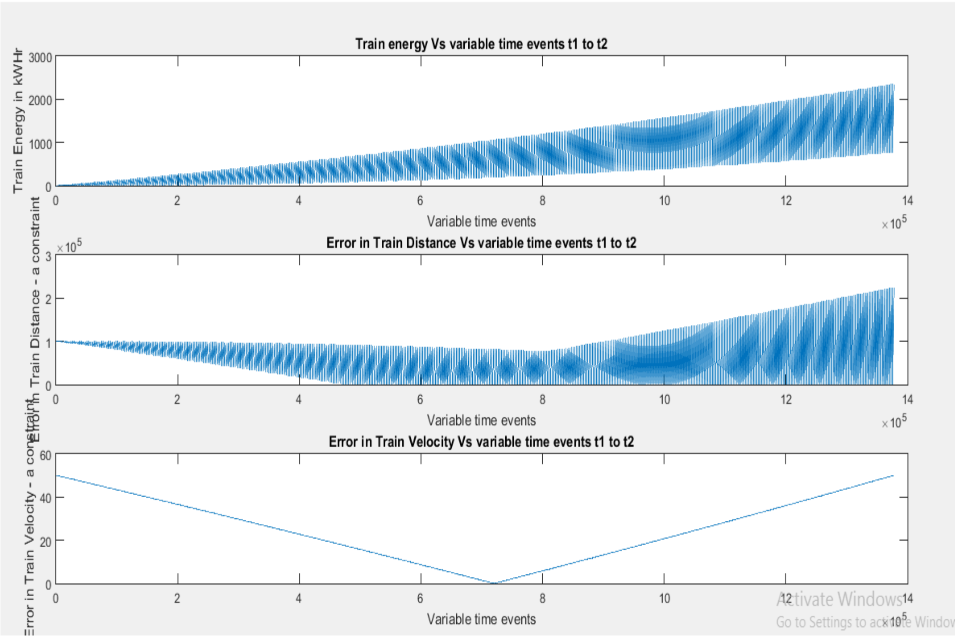

Fig 4. Plot of energy and constraints corresponding to variable time events

Error in train velocity is plotted against the error in train distance so that the actual region where the optimal point lies can be obtained which is shown in Fig 5. The point at which error is minimum i.e. zero, is considered as an optimal region.

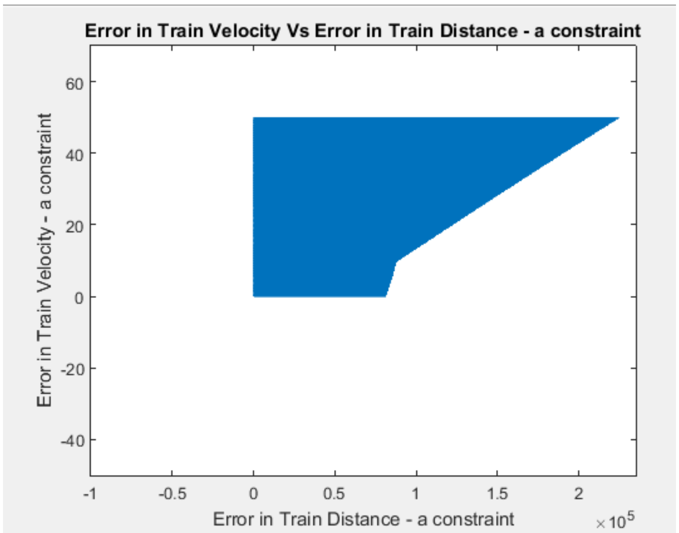

Fig 5. Plot of error in train velocity with respect to error in train distance

VI. Optimization By Interior Point Method

Energy consumption in electric traction system as referred by equations (9) – (11) are optimized using interior point algorithm in MATLAB with the constraints defined in section II. Fmincon function is used with lower and upper bounds for a, t_1 and t_2 . Rosenbrock function which is a non convex function is used as a performance test problem for optimization algorithm. Rosenbrock function has its minimum objective value of zero at point (1,1).`The optimized parameters are given in table 3.

Table 3: Optimized parameters by interior point method

Parameter	Positive gradient	Negative gradient	Zero gradient
Acceleration ‘a’	0.2	0.3	0.1
Energy consumption	664.4953	444.9655	546.3243
Velocity	32.4555	38.9867	31.8625

Implementation of interior point method in practical system can optimize energy consumption which can reduce cost of energy. In order to implement this method, a MATLAB program designed which will ask the value of acceleration, maximum velocity limit, upper limit of acceleration time (t_1) and free run period (t_2) to the user. Optimal value of energy consumption and velocity is calculated and displayed.

VII. Comparison Of Results

It has been observed that energy consumption for positive gradient is maximum and it is minimum for negative gradient. Results obtained by conventional method and interior point method are shown in table 4. It has been observed that energy consumption is reduced by 2.375% using interior point method as compared to conventional method.

Table 4. Comparison of results

Parameters	Conventional method	Interior point method
Energy consumption (kWh) (For positive gradient)	680.6667 (minimum value) 707.2917 (maximum value)	664.4953
Velocity (m/s)	50	32.4555

It has been observed that energy consumption is reduced by 2.375% using interior point method as compared to conventional method.

VIII. Conclusion

Optimized value of tractive energy consumption and corresponding parameters have been obtained by conventional method and interior point algorithm. Further the results have been compared and it has been observed that implementation of interior point algorithm can save the energy consumption in railway traction system and hence the energy cost. These studies will be very helpful for designer of the system to decide the parameters of the system, so that the energy consumption is minimized.

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