CATENARY SYSTEM PARALLELING AND ITS EFFECT ON POWER CONSUMPTION AND REGENERATED ENERGY RECUPERATION

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ABSTRACT

This paper firstly gives a brief general introduction to energy consumption points in a rail system. Later, catenary system paralleling, and its effect on the power consumption and regenerated energy usage ratio will be examined with the help of a DC rail system simulation program.

I. INTRODUCTION

International Railways Association (UIC) had established a committee to investigate approaches and technologies which are applicable to rail transportation systems. This committee published its report in March 2003, which gives a detailed study of almost 100 methods for increasing energy efficiency in rail systems [1].

In this paper, one of the suggested approaches will be examined: Energy loss reduction by feeding system paralleling in DC fed mass transit systems. This could be done in Catenary or 3 rd rail systems.

First part of the paper will be dedicated to feeding system description, energy consumption points in a mass transit system. Second part covers energy saving possibilities by catenary paralleling. It is widely accepted by all engineers in the sector that paralleling of the catenary systems will lower power loss. There is another common thought that paralleling will also increase the regenerated energy usage rate. We will examine this common thought for a given line data using simulation.

II. RAIL SYSTEM ENERGY CONSUMPTION

Energy usage can be divided into two groups in a rail mass transit system: Traction power system consumption which is used for moving train sets on the line, and auxiliary power system consumption which is utilized in passenger access areas such as mezzanines, platforms, and entrance/exit tunnels etc. In addition to these, workshops and management offices' energy consumption is accounted for the auxiliary systems.

Ratio between these two groups differs depending on the system. If the system is an underground line, then it can be said that the energy consumption for auxiliary system will be somewhere between 30-50% of the total energy consumption. This depends on the operation schedule and number of escalators, elevators etc. The share of auxiliary power systems is greatly less in street tramway systems where stations on the street.

AUXILARY SERVICES ENERGY

As mentioned above, these services must be carefully observed in case of Underground systems. Some of the methods which are applicable are given below:

- Using sun light as much as possible with proper passenger station (PS) design.
- Optimization of lighting systems and using energy efficient armatures and ballasts.
- Equipping escalators with sensors to be activated when passengers approach.
- Using "soft starter" applications in escalators.
- Heat isolation of office management buildings.
- Planning maintenance.
- Using effective environmental control systems.

TRACTION ENERGY

High voltage is reduced and rectified in traction substations, and fed into the system via feeder cables and catenary wires. There have been different types and levels of voltage for the power supply system of the electric railways since the first electrified line. The most common power supply schemes are given in Table 1 below, which is specified in EN 50163 [2].

Voltage Level	U_n (V)	U_{min1} (V)	U_{max1} (V)
600 VDC	600	400	720
750 VDC	750	500	900
1500 VDC	1500	1000	1800
3000 VDC	3000	2000	3600
15 kV AC, 16 $^2/_3$ Hz	15000	12000	17250
25 kV AC, 50 Hz	25000	19000	27500

Table 1 : Voltage levels for electric railways according to EN 50163.

U_n = Nominal Voltage
U_{min1} = Lowest non-permanent voltage
U_{max1} = Highest permanent voltage

It is a well-known fact that AC systems are used in mainline applications, whereas almost all the mass transit systems in the world are DC fed systems. The voltage level used for the mass transit systems are up to 1500 VDC. In some countries, 1500 and 3000 VDC systems are also used for mainline applications. In fact, the DC fed mainline systems were forming almost half of the whole worldwide network until late 90's. But this is changing in favor of AC fed systems due to their overwhelming advantages.

Main parameters affecting traction energy consumption can be given as follows:

- **Line geometry**; gradients, passenger station locations and closeness to each other, curves, speed restrictions etc.
- **Vehicle characteristics**; control logic, weight, structure, motor, auxiliary power system etc.
- **Traction power system**; transformer substation (SS) number, locations, equipment types, feeding conductor features, feeding scheme, and SS etc.
- **Operation concept**; frequency of train dispatching (headway time - HT), train configuration, dwell time etc.

Total consumed energy by the system can be reduced by changing some these parameters. Some of the methods are given below:

- Reducing energy loss by catenary system paralleling.
- "Energy-wise" driving approach.
- Increasing regenerated energy usage rate.
- Re-arranging speed limits on the line.
- Revising operation concept. Short trains with higher frequency are expected to reduce energy consumption.

III. DC FED RAIL SYSTEM SIMULATION PROGRAM: SimuX

A DC fed rail mass transit system power network solution involves solving of numerous non-linear equations. Iterative solution of sparse matrices whose size depend on length of line and selected parameters for examination is required in such calculations. This can only be achieved by help of simulation programs.

The comparison study is done with a multi – line, multi – train simulator called SimuX [3,4]. SimuX enables the users to simulate DC fed rail systems in a user-friendly environment. It takes the regenerative braking and under-voltage behavior of the vehicles into consideration. Below given characteristics of the line are taken into account by SimuX:

1. Geometry of lines
2. Transformer Substations
3. Trains (Different types possible)
4. Passenger stations
5. Depots
6. Isolation points (Section Insulators)
7. Jumpers (Conductive connection between catenary wires or rails)
8. Traffic lights
9. Rail Potential Control Devices – RPCD

Some of the usage areas of the SimuX are given below:

1. Performance assessment of trains under different operation conditions
2. SS equipment size determination
3. Catenary system capacity adequacy verification
4. Determination of minimum pantograph voltage
5. Energy consumption and loss calculations
6. Regenerative energy usage
7. Rail potential – stray current calculations [5]
8. DC side short circuit current calculations
9. Comparison of different feeding schemes
10. Controlling of relay settings.

Simulator was used in two projects which are carried out for Istanbul Transportation Co. (ITC).

First project studied the effect of vehicle replacement in Istanbul Street Tramway Line. Results of the study are applied to existing system and compared to real world data which showed very close approximation to simulation results [6]. This project enabled ITC to postpone its investment in traction power system.

Preliminary study of Üsküdar - Ümraniye metro line traction power system was completed, and a study using the line data showed that there would be 10 % energy saving when 1500 VDC used instead of 750 VDC [7].

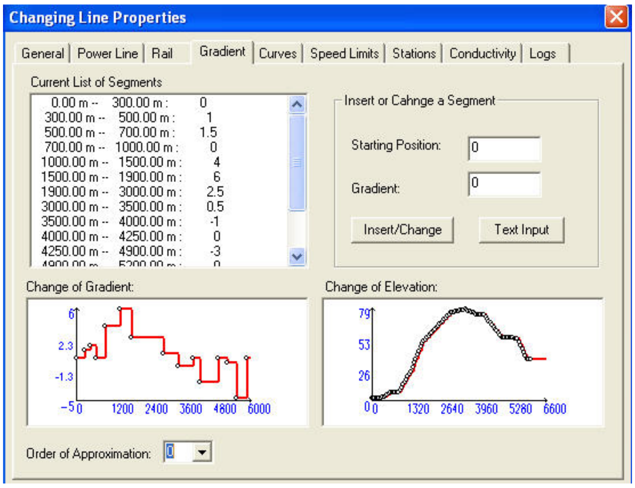
IV. TEST SYSTEM

Several simulation tests were carried out to investigate the effect of paralleling of two track catenary systems on power consumption and regenerative energy usage.

TEST LINE

A test line is introduced to SimuX to carry out simulations. Main characteristics of this line are given below:
Length = 6000 m
Number of SS = 3
Number of PS = 12
Voltage = 750 VDC
Catenary system resistance = $9.34\ 10^{-5}\ \Omega/m$
Rail resistance = $2.06\ 10^{-5}\ \Omega/m$
V_{max} = 50 km/h

Gradient profile for the line is shown in Figure 1. This is quite realistic for a Tramway system in Istanbul.



Current List of Segments

0.00 m --	300.00 m :	0
300.00 m --	500.00 m :	1
500.00 m --	700.00 m :	1.5
700.00 m --	1000.00 m :	0
1000.00 m --	1500.00 m :	4
1500.00 m --	1900.00 m :	6
1900.00 m --	3000.00 m :	2.5
3000.00 m --	3500.00 m :	0.5
3500.00 m --	4000.00 m :	-1
4000.00 m --	4250.00 m :	0
4250.00 m --	4900.00 m :	-3

Insert or Cahnge a Segment

Starting Position: 0

Gradient: 0

Order of Approximation: 0

Figure 1. Test line gradient profile.

SimuX representation of the line is given in Figure 2. SSs are 2000 m apart from each other.

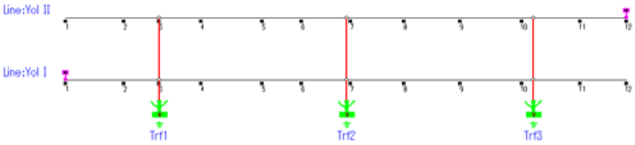


Figure 2. SimuX representation of the line

Line representation with jumpers every 100 m is given in Figure 3.

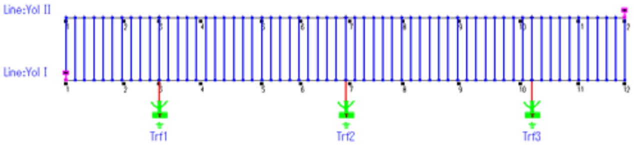
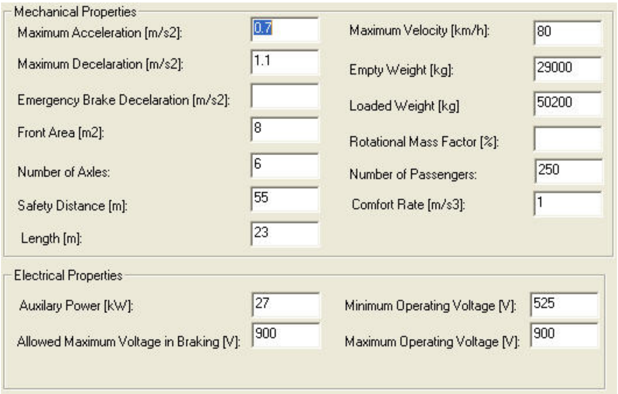


Figure 3. SimuX representation of jumpered line

VEHICLE CHARACTERISTICS

Main mechanical and electrical characteristics of the vehicle used in simulations are given in Table 2.



Mechanical Properties

Maximum Acceleration [m/s2]: 0.7

Maximum Decelaration [m/s2]: 1.1

Emergency Brake Decelaration [m/s2]:

Front Area [m2]: 8

Number of Axles: 6

Safety Distance [m]: 55

Length [m]: 23

Maximum Velocity [km/h]: 80

Empty Weight [kg]: 29000

Loaded Weight [kg] 50200

Rotational Mass Factor [%]:

Number of Passengers: 250

Comfort Rate [m/s3]: 1

Electrical Properties

Auxilary Power [kW]: 27

Allowed Maximum Voltage in Braking [V]: 900

Minimum Operating Voltage [V]: 525

Maximum Operating Voltage [V]: 900

Table 2: Vehicle characteristics

Tractive effort produced by one vehicle versus speed diagram is given in Figure 4.

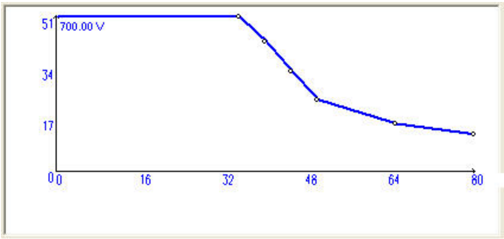


Figure 4. Tractive effort (kN) – Speed (km/h)

V. SIMULATION TESTS

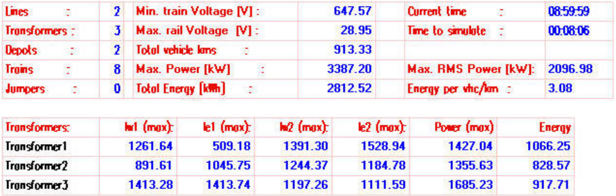
Total energy consumed by the system depends on all the parameters given above. One of the parameters affecting consumed energy is HT. Two different HTs are used during the simulation to show its effect: 3 min (180 sec) and 5 min (300 sec). Reducing HT increases regenerative energy usage rate [8].

Firstly normal case, with no paralleling, is simulated, then jumpers are applied to catenary systems. Different distances are used between the jumpers to assess the effectiveness of the jumpering.

6 different tests were done for each HT. As a result, 12 test results are obtained. Simulations cover 2 hours of peak time operation.

NORMAL CASE TEST

Table 3 shows summary of the results for 180 sec HT. The first part of the Table gives system-wide information such as minimum pantograph voltage (647 V). Lower part of the Table summarizes power network values.



Lines :	2	Min. train Voltage [V] :	647.57	Current time :	08:59:59
Transformers :	3	Max. rail Voltage [V] :	28.95	Time to simulate :	00:08:06
Depots :	2	Total vehicle kms :	913.33		
Trains :	8	Max. Power [kW] :	3387.20	Max. RMS Power [kW]:	2096.98
Jumpers :	0	Total Energy [kWh] :	2812.52	Energy per vhc/km :	3.08

Transformers:	Iw1 (max):	Ie1 (max):	Iw2 (max):	Ie2 (max):	Power (max)	Energy
Transformer1	1261.64	509.18	1391.30	1528.94	1427.04	1066.25
Transformer2	891.61	1045.75	1244.37	1184.78	1355.63	828.57
Transformer3	1413.28	1413.74	1197.26	1111.59	1685.23	917.71

Table 3: HT=180 sec normal case results

Figure 5 and 6 gives speed-displacement and voltage-time graphics for a typical train on the line.

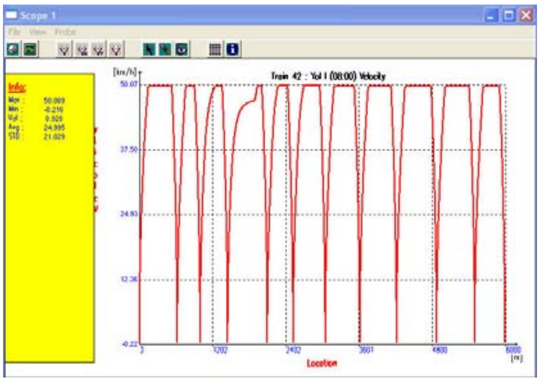


Figure 5. Speed vs. Displacement for a train

Effect of the steep gradient shows itself in Figure 5. Moreover, this figure tells us that commercial speed for this imaginary line would be 25 km/h. Figure 6 shows that maximum voltage drop will occur at the end of the line as it is expected.

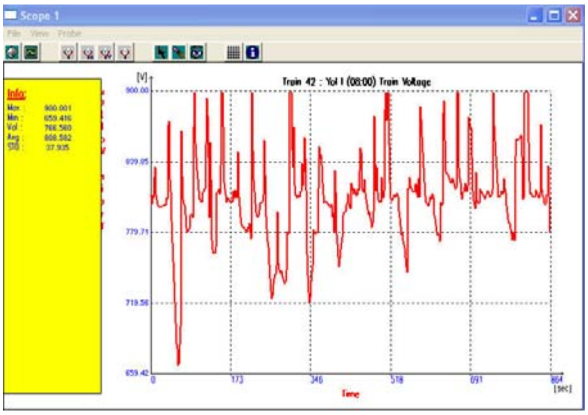


Figure 6. Voltage-Time graphic for a train

OTHER TESTS and COMPARISON TABLES

Two catenary systems are jumpered in every 2000, 1000, 500, 250 and 100 m, and simulations were repeated. Simulation results (HT = 180 seconds case) relating to energy consumption and regenerated energy values are summarized in Table 4. HT = 300 sec cases are not presented here, instead, comparison charts will be given.

EXPLANATION	Distance Between Jumpers (m)					
	Normal	**2000**	**1000**	**500**	**250**	**100**
Total Consumed Energy (kWh)	2812.5	2722.7	2720.5	2692.5	2679.7	2671.1
Saving compared to normal condition (%)		**3.19**	**3.27**	**4.27**	**4.72**	**5.03**
Energy per vehicle-km (kWh)	3.08	2.98	2.98	2.95	2.93	2.92
Reduction compared to normal condition (%)		**3.25**	**3.25**	**4.22**	**4.87**	**5.19**
Energy Loss (kWh)	309.61	230.1	228.07	201.19	188.13	179.6
Regenerated Energy (kWh)	1830.8	1830.8	1830.8	1830.8	1830.8	1830.8
Burned Energy (kWh)	113.45	102.8	102.54	101.37	101.62	101.57
Cumulative Regeneration Ratio (%)	93.8	94.39	94.4	94.45	94.45	94.45
Regenerated Energy Usage (kWh)	1717.4	1728	1728.3	1729.4	1729.2	1729.2
System Energy Demand (kWh)	4529.9	4450.7	4448.7	4421.9	4408.9	4400.3
Percentage of Regenerated Energy Usage (%)	37.91	38.83	38.85	39.11	39.22	39.30

Table 4: Energy related values for HT = 180 sec

Table 4 gives values for “Energy drawn from the public network” under “Total Consumed Energy” caption, “Recuperated energy amount out of regenerated energy by the trains” under “Regenerated Energy Usage” caption.

Key parameters in Table 4 are shown in Figures 7, 8, and 9 for HT = 180 and 300 seconds cases. Jumpering at the terminus points and between SS, test case of 2000 m will give 3% energy saving in total consumed energy. This saving is highly increased in 100 m jumpering case; 5%.

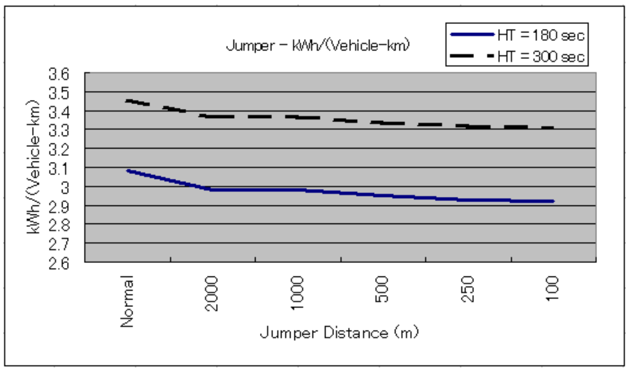


Figure 7: Energy consumption per vehicle-km for different jumper spacing.

It can be seen from Figure 7 that the effect of jumpering each 1000 m and 200 m will have similar effects on power consumption. In the same manner increasing jumpers from every 250 meters to every 100 meters will have a slight impact on the power consumption. This graphic also implies the importance of operation with higher frequency of trains. Decreasing the HT from 5 minutes to 3 minutes will decrease energy consumption per vehicle-km by 10%.

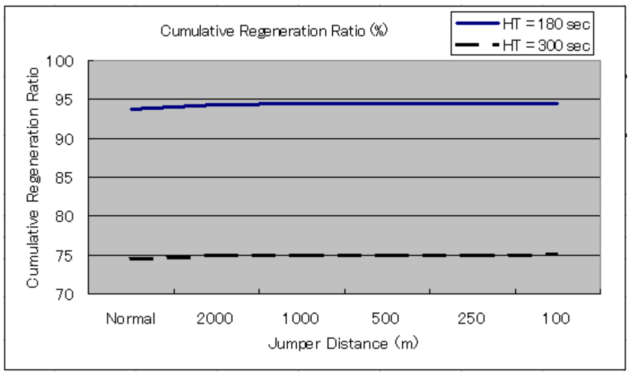


Figure 8: Change of cumulative regeneration ratio with different jumper spacing.

Figure 8 shows cumulative regeneration ratio in percentage. This means how much percentile of regenerated energy is used by the system. The remaining part of the regenerated energy is burned on the braking resistors mounted on the vehicles. Explanation of regenerative braking methodology is considered to be out of scope of the paper.

This graphics shows once again that frequent operation has great impact on the recuperation rate. There is another important characteristic to be noted in this graphic: Jumpering of the two catenary systems does not have any significant impact on recuperation rate for this given imaginary line. This is on the contrary of the common thoughts, which implies an increase on the regenerated energy usage with increased number of jumpering.

Some more extra simulation tests were carried out to examine this point. Dwell time in passenger station were fixed to 15 seconds in these tests. Dwell time set to be chosen as randomly between 5-35 seconds for every pasenger stations. Related values are given in Table 5.

EXPLANATION	**Distance Between Jumpers (m)**					
	HT = 180 sec			**HT = 300 sec**		
	Normal	**2000**	**100**	**Normal**	**2000**	**100**
Total Consumed Energy (kWh)	3090,8	3008,2	2952,1	2025,1	1981,8	1935,7
Saving compared to normal condition (%)		**2,67**	**4,49**	--	**2,14**	**4,41**
Cumulative Regeneration Ratio (%)	81,15	81,14	84,21	65,3	65,8	65,8
Percentage of Regenerated Energy Usage (%)	32,34	32,94	31,67	26,2	26,6	27,2

Table 5: Random dwell time test results

Similar results can be observed from above given Table 5 for randomized tests. It can be noticed that cumulative regeneration ratio is reduced 10 %. Moreover, there is still no significant increase by adding jumpers on the catenary lines.

Figure 9 shows the percentage of regenerated energy in the total system energy demand for different jumper spacing and HT. It states that around 40 % of the system energy demand is supplied by braking vehicles in 180 sec HT case. This rate is reduced to 30 % in case of 300 sec HT. Measuring this in real life systems is a painstaking job, and there is study done by Adinolfi et. al. [9].

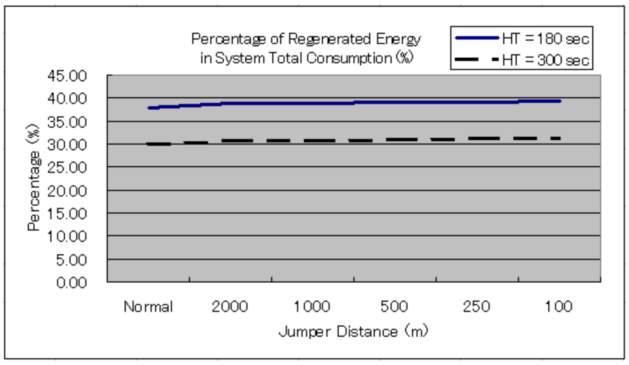


Figure 9: Percentage of regenerated energy

VI. SUMMARY and RECOMMENDATIONS

Simulation tests showed that jumpering of catenary systems has a potential of 5 % energy saving in the total energy consumption. This can be done in street tramway systems with frequent jumpering.

In a similar manner, with safety constraints in mind, jumpering between the SSs and line ends on LRT catenary systems will save energy between 2 – 3 %. This can be done with motorized isolators.

Study also showed that jumpering of catenary systems does not increase much regenerated energy recuperation rate as it is expected.

VII. REFERENCES

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