Energy loss comparison between 750 VDC and 1500 VDC power supply systems using rail power simulation

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Abstract

When a new transit line is to be built, apart from many other aspects, it is also necessary to study alternatives of the traction power supply system. One aspect to be studied in calculating the operational cost is the estimated level of electricity cost.

If the line capacity exceeds 22000 pphpd (Passenger Per Hour Per Direction), i.e. medium sized transport capacity, train-set configuration will consist of more than 4 vehicles, and headway time between the trains will get narrower, which results in greater traction energy demand. Energy loss in a conductor is proportional to the square of the current drawn from it. As a result, in theory, doubling the voltage level reduces the energy losses to one quarter. This might not be correct due to regenerative braking energy.
Keywords: multi-train simulation, DC rail traction systems, 1500 VDC.

1 Introduction

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 [1] (Obviously there are other systems such as 580 VAC 3 phase, and 1200 VDC that are in use).

It is a well-known fact that AC systems are used in mainline applications, while 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

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countries, 1500 and 3000 VDC systems are also used for mainline applications. In fact, the DC fed mainline systems were 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.

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

Voltage Level	U_n (V)	U_{min2} (V)	U_{min1} (V)	U_{max1} (V)	U_{max2} (V)	U_{max3} (V)
600 VDC	600		400	720	770	1015
750 VDC	750		500	900	950	1269
1500 VDC	1500		1000	1800	1950	2538
3000 VDC	3000		2000	3600	3900	5075
15 kV AC, 16 $^2/_3$ Hz	15000	11000	12000	17250	18000	24311
25 kV AC, 50 Hz	25000	17500	19000	27500	29000	38746

In Table 1, the following symbols are used:
U_n : Nominal voltage
U_{min2} : Lowest permanent voltage
U_{min1} : Lowest non-permanent voltage
U_{max1} : Highest permanent voltage
U_{max2} : Highest non-permanent voltage
U_{max3} : Low-term over voltage with a duration more than 20 ms

A similar process has taken place in the mass transit side, too. In those early days, 19th century, 600 VDC supply system was used in rail transit systems. The state of the art technology in power electronics and electrical systems led 1500 VDC system to be chosen as power supply in the most newly constructed lines. One interesting example for this is Metrosur ring line of the Madrid Metro: The existing metro network, 176 km in total, was energized with 600 VDC. But the 1500 VDC system preferred for the new extension of the existing network [2].

The book entitled "Subways of the World" which was published by Japan Subway Association in May 2000 contains main characteristics of 117 metro systems in the world [3]. After an examination of these characterisitics, the following conclusions can be drawn:

1. The pioneering countries in mass rail transit systems such as Germany, England, and France have been using 600 ve 750 VDC systems. However, the preferred system for a new line which is not bound to any existing line is 1500 VDC system.
2. Common system in Italy and Spain is 1500 VDC.
3. Most of the Asian countries use 1500 VDC as their nominal power system. Singapore' s NE line has chosen 1500 VDC system. This is noted because catenary system has been thought as obscure and omitted in the open areas in Singapore, which is still obligatory in 1500 VDC.
4. Moreover, it would not be wrong to state that in the most cases where the train configuration exceeds five cars or pphpd > 25000, power system is chosen as 1500 VDC.

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In this paper, a case study is presented. Currently, Greater City of Istanbul Municipality is planning / designing a new metro line between Uskudar – Umraniye on Anatolian side of the city, where the line will be the first DC fed system. In section 2, advantages of the 1500 VDC system are briefly explained, and then a comparison study between the 750 and 1500 VDC systems is given in Chapter 3. Chapter 4 gives details for the simulation test runs. Conclusions are supplied in Chapter 5.

2 Advantages of the 1500 VDC system

A system must be ecomonic, modern and smoothly operated. In the following, we try to answer the question 'Why the 1500 VDC feeding system is chosen in newly constructed lines which have medium and heavy capacity?'.

2.1 Reduced traction transformer substation (SS) Number

The drawn current value for the same power demand is halved in 1500 VDC compared to 750 VDC. As a result of this fact, the voltage drop along the current carrying conductor is reduced. This will lead to an increase in the distances between the SS' s. Practical applications show that 1500-2500 m space between the neighbouring SS' s is suitable for a healthy 750 VDC power feeding scheme, whereas this distance is increased to appx. 4000 metres in 1500 VDC systems. That is why, less SS's are required for the same length of track line in 1500 VDC.

This reduction in SS number to be built will lower the construction cost. When the SS equipment producers contacted, such as BBRail, they state that most of the equipments in the SS cost almost the same except DC Switchgear and Transformers which give a increase of 5% in overall cost of a SS [4]. The total cost reduction to be gained in overall Traction Transformer Substation System is to be expected somewhere between %25 - %35 compared to the 750 VDC system.

It is obvious that lesser the current, smaller the cross-section of DC feeder cables and MV cables will be. Moreover, the OHL system construction cost would also be affected. Pham, et. al. [4] gives ideas about this matter. The rigid catenary system has been chosen as current carrying conductor for the Uskudar – Umraniye line due to its advantages over normal catenary system in deep tunnel applications.

2.2 Maintenance man-hour reduction

The point discussed above has a direct reflection on the maintenance cost of the Traction Transformer Substations. In a SS, there are app. 25 items, which need periodical inspection and maintenance. So, decrease in the number of SS results in reduction of maintenance costs. It should also be noted that the lesser the equipment, the lesser the potential fault source.

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2.3 Increased regenerated energy usage

Regenerated energy usage is a factor depending on trains and SS locations. With the increased space between the SS' s, the possibility of existance of more than one train in the same feeding section is higher, especially in short headway time operation. This causes an increase in the regenerated energy usage.

2.4 Less energy loss

In a rail transit system, an energy loss occurs in the process of transmission. The current carrying conductor and SS equipments are the inevitable sources of this wasted energy. It should not be forgotten that rails are also contributing to this energy loss. According to $P_{loss} = R \times I^2$ formula, energy loss is proportional to the square of the current.

As a result of this formula doubling the voltage level reduces the energy losses to one quarter. But, this might not be exactly correct due to the existence of regenerative braking energy. Moreover, increased SS distances also affects energy loss.

Actually, these values can be quantified by only a detailed multi-train, multi-line simulation software. The next chapter deals with this issue.

3 Comparison study

The comparison study is carried out using a newly developed multi-train, multi-line rail system simulation program [5]. The tests are done for a given train-set characteristics, and geographical conditions, and the results are provided in a comparison table.

3.1 Uskudar – Umraniye metro line

The metro line is planned to be 16 km in length. It will consist of 13 passenger stations. The line is originally studied and planned by an international company. Later on, Istanbul Ulasim Co. (ITC) established a project team, and changed alignment of the line. The project planners shortened the route length by removing some curves. This is achieved by increasing the maximum gradient of the line. There is a 4 % gradient at the beginning of the line for app. 2200 m.

Voltage level of the power feeding system is also discussed during this study. For this reason a report is prepared and submitted. In that report 1500 VDC / 750 VDC voltage level and Catenary / 3rd Rail systems are compared, and it is concluded that 1500 VDC + Rigid Catenary system would be more appropriate for the line.

Data supplied by the ITC for the simulation study covers the first 9300 meters of the line where eight passenger stations will be built. The estimated pphpd is 25000 for the year 2010, but it is projected that the capacity will raise to 35000 pphpd in the year 2025. Headway time is calculated as 210 sec. for the start. For the final pphpd, it will be reduced to 150 sec. Train sets will be configured as 6 cars (all motored).

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The cars to be used in the line is assumed to have the same characteristics with the currently used ones in Aksaray – Havalimani LRT line. A detailed data set is provided by Istanbul Ulasim Co. covers all aspects to model a train for the simulation purpose.

3.2 SimuX software

The comparison study is done with a multi – line, multi – train simulator called SimuX [5]. The SimuX enables the users simulate DC fed rail systems in a user-friendly environment. It takes the regenerative braking and under-voltage behavior of the vehicles into consideration.

3.3 Simulation test runs

The line is modelled with its geometrical data such as curves, gradients, P/S locations, and speed limits etc. (See Figure 1). Terminus stations, Uskudar and Cakmak, are assumed as train dispatching points. All stations have a standart 20 sec dwell time.

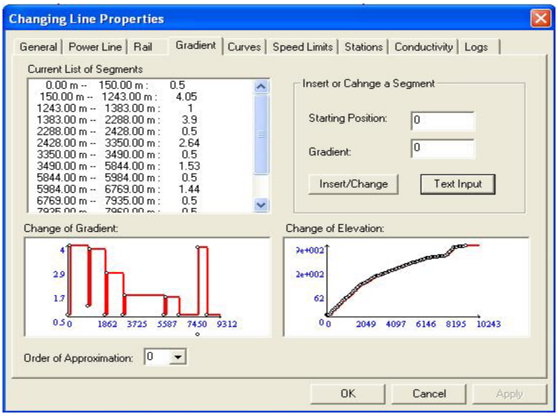

Figure 1: Gradient data of the metro line.

Catenary system and the transformer substations are defined. For 750 VDC feeding schemes 6 SS are considered to be built, while 4 SS will be sufficient for the case of 1500 VDC system. (See Table 2.) These numbers are chosen with the following points in mind: rail potential should not rise over a threshold, and operation schedule of the system should be undisturbed as much as possible under one faulty transformer in one of the SS (that is there should be no change in the timetable under this situation).

All the substations are considered having two rectifier-transformer sets, except the first and the last ones which are equipped with one set. Rigid catenary resistance is taken as 1.5E-5 Ω/m. Two parallel rail resistance is assumed as 2.06E-5 Ω/m. Each track is fed seperately, which means that there is no

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parallelling posts for catenary system. Running rails are used for carrying return currents, and to minimize stray currents a floating earth strategy is adopted [6]. In all test runs, sampling time is chosen as 25 msec.

Table 2: Transformer substation locations for the both feeding schemes.

	Trf1	Trf2	Trf3	Trf4	Trf5	Trf6
750 VDC	0+000	1+300	3+350	5+850	7+850	9+300
1500 VDC	0+000	2+400	5+950	9+300		

Several simulation tests are carried out for both of the 750 and 1500 VDC cases. Each test runs cover 2 hours of operation. Trains are considered first fully loaded and then half loaded. For all cases, headway times of 150 and 300 sec. are used.

4 Results

The whole system data entered to the simulator, and abovementioned tests are carried out. The SimuX representation of the Uskudar – Umraniye metro line with 6 SS, 8 PS, and trains running on the lines can be seen in Figure 2.

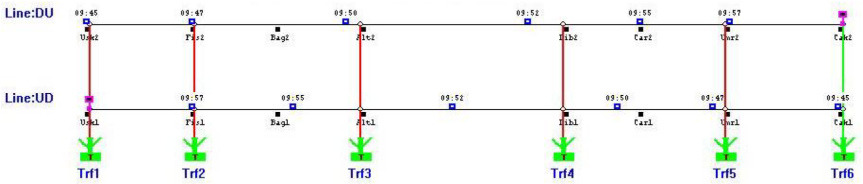

Figure 2: Graphic representation of the metro line.

4.1 Simulation test of 750 VDC system

Numerical values of the main variables such as feeders currents, min. train voltage, and max. rail voltage are shown in a table during the simulation run. See Figure 3.

From the Figure 3, it is seen that min. train voltage is 662 V. Energy consumption for one vehicle per km is 3.18 kWh.

SimuX was set to log all the variables relating to trains, which means 22 different logs for each one of the trains (there were 96 trains dispatched in two hours), transformer substations, which means 16 different logs for each Substation, and 8 general variables such as total energy consumption. Some sample graphs are shown in Figure 4.

From these graphs commercial speed is calculated as 38 km/h for the metro line. Gradient's effect on the current of a train is clearly seen from the graph on the right in Figure 4 as the current drawn by a train in between stations varying around 3100 A. for the first three passenger stations where a 4% gradient exists, whereas the current drops to lower values for the rest of the track.

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Lines	: 2	Min. train Voltage [V]	:	662.03	Current time	:	10:00:00
Transformers	: 6	Max. rail Voltage [V]	:	84.07	Time to simulate	:	00:46:51
Depots	: 2	Total vehicle kms	:	5065.36			
Trains	: 12	Max. Power [kW]	:	16779.82			
Jumpers	: 0	Total Energy [kWh]	:	16086.57	Energy per vhc/km	:	3.18

Transformers:	Max. Iw1:	Max. Ie1:	Max. Iw2:	Max. Ie2:	Max. power	Energy
Transformer1	0.00	3260.11	0.00	4299.38	4540.72	2024.09
Transformer2	3498.22	2513.82	2338.98	5264.51	5768.01	3026.27
Transformer3	3293.09	4618.76	3348.49	4324.39	5082.00	3609.48
Transformer4	3934.52	4363.64	1991.91	4593.06	4951.99	3065.61
Transformer5	3875.47	4209.72	4961.62	4546.44	4461.82	2484.90
Transformer6	4227.09	0.00	2323.31	0.00	4073.30	1876.20

Figure 3: Summary table of the test for 750 VDC.

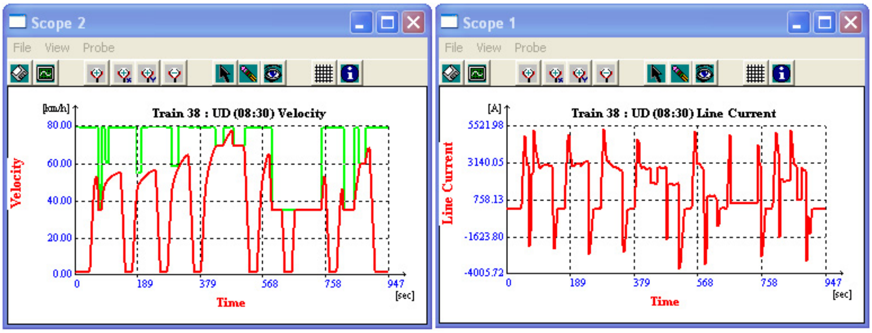

Figure 4: Velocity/speed limits and line current vs. time for a train.

"Total energy consumption", and "Energy loss" general variable data can be shown in graphic with the help of the Scope module of SimuX. See Figure 5.

Total energy consumption is the energy amount drawn by the whole system. The Line loss value is a calculated value. From these graphs, it can be seen that for a two hours run of the system 16086 kWh energy consumed, 1744 kWh of which is lost on the system. Energy loss percentage can be calculated from formula (1):

$$E_{loss}\ (\%) = E_{loss} / E_{consumed} \times 100 \qquad (1)$$

For this case, energy loss percentage is calculated as 10.84 %. This number states that approximately every 10 kWh out of 100 kWh of traction energy cost is lost. If this is taken as basis for Istanbul Aksaray – Havalimani LRT line, which consumes app. 2 GWh per month, it can be said that 200,000 kWh energy is lost on the system. Energy cost is quite high in Turkey; 8.3 cent/kWh. When

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this is taken into consideration, app. 200,000 $/year is spent for the line loss.

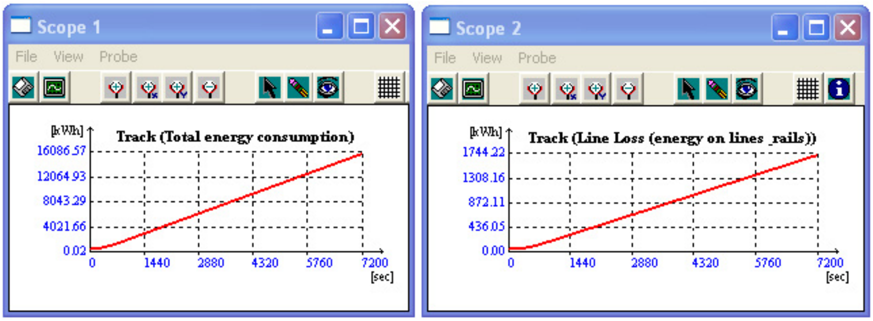

Figure 5: Total energy consumption and loss for two hours of simulation.

4.2 Simulation test of 1500 VDC system

A similar test is carried out for 1500 VDC fed system. Energy loss percentage is calculated as 4.82 %. Energy consumption and line loss curves can be seen in Figure 6.

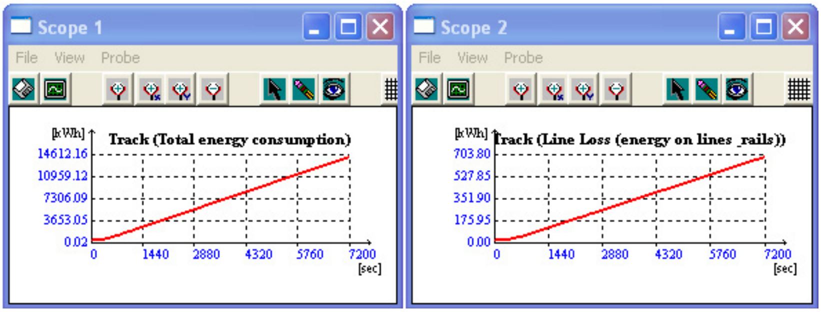

Figure 6: Energy graphics for 1500 VDC system.

These graphs state that 703.8 kWh of the 14612 kWh energy is lost on the traction line. Figure 7. shows the main screen of the SimuX after the simulation.

As it can be seen from Figure 7, for the same total vehicle kms, the total energy consumption is reduced from 16086 kWh in 750 VDC to 14612 kWh in 1500 VDC system. This gives a 1474 kWh reduction in the total consumption, which is equal to 9.16 % reduction in traction energy consumption.

The numbers also suggest that regenerated energy usage is increased in 1500 VDC system as expected. This can be explained with the two values of the energy lost: 1744 kWh is lost in the 750 VDC case, while 704 kWh is lost in the case of 1500 VDC system. This means that 1040 kWh is gained from energy

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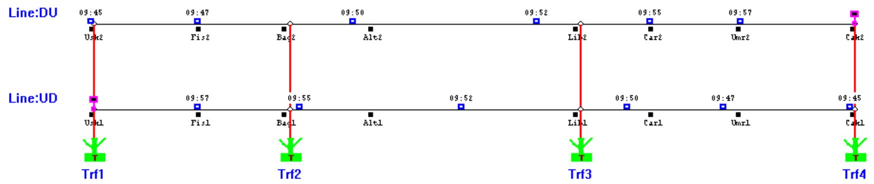
loss amount. Whereas, the real energy saving value given in the above paragraph is 1474 kWh. Difference between 1474 and 1040 is 434 kWh, and is the energy recovered from regenerative braking. The topic of regenerative braking energy usage rate is left for a future detailed discussion.



Lines :	2	Min. train Voltage [V] :	1468.63	Current time :	10:00:00
Transformers :	4	Max. rail Voltage [V] :	71.79	Time to simulate :	00:40:41
Depots :	2	Total vehicle kms :	5065.48		
Trains :	12	Max. Power [kW] :	15605.67		
Jumpers :	0	Total Energy [kWh] :	14612.16	Energy per vhc/km :	2.88

Transformers:	Max. Iw1:	Max. Ie1:	Max. Iw2:	Max. Ie2:	Max. power	Energy
Transformer1	0.00	1564.64	0.00	2487.42	4557.87	2507.25
Transformer2	2422.92	1844.01	2802.39	2687.36	6915.16	4876.88
Transformer3	2313.78	2577.77	2625.21	2808.86	6252.29	4558.43
Transformer4	2426.87	0.00	1692.94	0.00	5028.67	2669.60

Figure 7: Main screen for 1500 VDC system.

4.3 Comparison table for tests

Other tests, as mentioned in Chapter 3.3, are done with the SimuX. After using the fully loaded trains (FL = 271 tonnes), the trains are assumed as half loaded (HL = 219 tonnes). These four tests are repeated for an increased headway time of 300 sec. This means that eight different simulation test runs carried out. The total consumed and lost energies for these tests are summarized in Table 3.

Table 3: Summary of the simulation runs.

Power Feeding System	Train Load Mode	Head way Time	Total Energy (kWh)	Energy Loss (kWh)	Energy Loss %	Difference in Total Energies (%)
750 VDC	FL	150 s.	16087	1744	10.84	9.17
1500 VDC	FL	150 s.	14612	704	4.82	
750 VDC	HL	150 s.	13978	1412	10.10	10.13
1500 VDC	HL	150 s.	12562	570	4.54	
750 VDC	FL	300 s.	8995	857	9.53	12.87
1500 VDC	FL	300 s.	7837	363	4.63	
750 VDC	HL	300 s.	7901	674	8.53	11.78
1500VDC	HL	300 s.	6970	280	4.02	

The energy loss percentage is between 4.02 and 4.82 for 1500 VDC, whereas, it is between 8.53 and 10.84 for 750 VDC system.

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The last column of the Table 3 shows energy gain by choosing the 1500 VDC feeding scheme over 750 VDC. This shows an approximately 10 % reduction in the traction energy cost for the same operation conditions in favour of the 1500 VDC feeding scheme.

5 Conclusion

During the design and planning phase for a rail mass transit system, it is essential to study power system. 1500 VDC system has many advantages over 750 VDC system. One of the advantages considered is the energy saving characteristic of the 1500 VDC system.

In this paper, advantages of the 1500 VDC power system over the 750 VDC power system are given in summary. In particular, simulation tests are carried out for a given metro line and it has been observed that 1500 VDC power system gives approximately 10 % saving in traction energy cost of the system. The tests showed that traction energy loss percentage is halved in 1500 VDC system compared to the 750 VDC system.

These arguments encourage us to recommend 1500 VDC system over the 750 VDC system for the Uskudar – Umraniye metro line.

Acknowledgement

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