

CHANGING FROM BOOSTER TRANSFORMER SYSTEM TO AUTO TRANSFORMER SYSTEM IN THE KIRUNA-RÅTSI-SVAPPAVAARA LINE IN SWEDEN

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Abstract

A study of the changeover from a booster transformer (BT) system to an auto transformer (AT) system has been initiated by Banverket to increase the transport capability (weight and speed) of a heavily loaded freight train lines of about 40 km situated between Råtsi and Svappavaara and fed from the Kiruna converter station.

In this paper, firstly, a survey of comparison is given on the bases of sophisticated three-conductor line simulations for the two supply schemes in the point of view of equivalent impedance, losses, power rating for actual traffic conditions, longitudinal induction to line-side telecommunication cable, rail-to-earth and rail-to-rail potential. The results of simulation calculations have provided the necessary information on the rating of the AT scheme including the required number and locations of the auto transformers.

The AT system has been installed in addition to the already existing BT without the removal of the BT system. This installation has allowed to change from one system to the other in one day period of time and thus giving the possibility of performing real scale comparison tests between the two schemes. The paper presents a survey of the results of two week time site measurements.

1. INTRODUCTION

The Kiruna -- Råtsi (Rsi) - Svappavaara (Svv) railway line North Sweden has of great importance in the transportation of the iron ore of the LKAB international ore processing company (see Fig. 1). The transportation capability of this line is limited by voltage drop occurring in the Rsi -Svv power feed supply section operated by the booster transformer. Investigations were made in close co-operation with the Technical University of Budapest (TUB) to improve the voltage stability by changing the booster transformer (BT) system with auto transformer (AT) system. The two systems have been compared both in traction supply point and induction to telecom line point of view. On the bases of the promising results it has been decided to change from the BT system to AT system, applying 4 auto transformers in the Rsi - Svv section.

The installation of the AT supply system was accomplished by the middle of 1998. The BT system remained also operable. Thus it was possible to compare the two systems on the bases of real scale measurements. The measurements have been made subsequently with both systems from 4 to 14 June 1998, in collaboration of the Banverket, Telia and TUB. Finally, it is worth mentioning that, the Rsi-Svv AT-system will be considered as a turnkey project, thus the measurements on it should, also support the Banverket in making their decision on the swaps between BT- and AT-systems in other lines.

2. ARRANGEMENT OF THE SYSTEMS

The line under study is fed from the Kiruna converter station over a 4.66 km feeder and the 39.8 km long supply feed section is situated between Råtsi and Svappavaara (see Fig. 1).

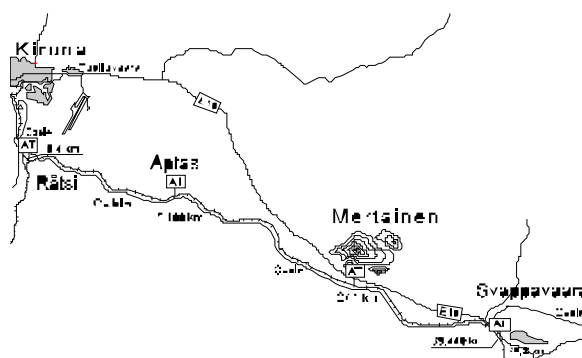


Fig. 1 Lay out of the Kiruna - Råtsi - Svappavaara railway line and telecommunication cable

The conductor arrangement of the Rsi-Svv line section is shown in Fig. 2. This corresponds to the new upgraded structure containing both the inverted feeder needed for AT and the return conductors needed for BT operation.

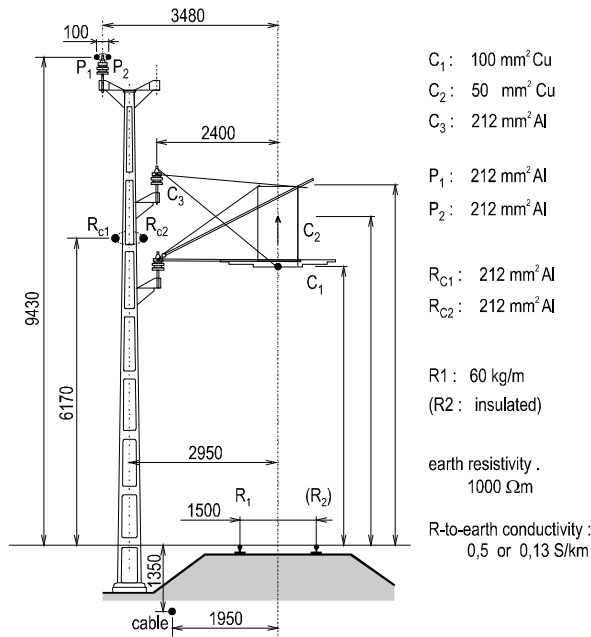


Fig. 2 Conductor configuration of the Rsi -Svv line

The *BT scheme* of the Rsi - Svv section contains 8 booster transformers resulting in practically an average BT spacing of 5 km.. The rated current of the applied BTs is 300 A.

The *AT scheme* of the Rsi - Svv section contains 4 auto transformers resulting in practically an average AT spacing of 13 km, which is 2.6 times of the average BT spacing.

The ratings of the transformers applied in the AT system are given in **Tab. 1**.

Tab. 1 Rating of the transformers of AT system

	S_n [MVA]	ΔU [%]
auto transformer	5	0.37
main transformer	16	5.14

3.SURVEY OF THE SIMULATION STUDY

3.1 Applied modelling

The circuit model of a three conductor line for the entire power supply section is described by a differential equation system with multi-point boundary conditions. This system is solved by a special numerical method based on the multiple shooting technique [1]. The solution provides both the magnitude and phase information of all voltages and conductor currents along the line. The train load is represented by a current source of a given current injected from the contact line into the rail. The inducing current, versus length, is obtained as the phasor sum of the currents of the three conductors.

The distributed series and shunt circuit elements of the models are identified by the geometrical arrangement and conductor data (Fig. 2) with the exception of the rail-to-earth leakage G_{R0} , which is highly dependent on the condition of the track bedding. A value of 0.5 S/km (normal case) is applied in the calculations.

Calculations have also been made with $G=0,1$ S/km (dry or frozen bedding) and $G=2$ S/km (very wet bedding).

3.2 Cases and results of simulations

When comparing the different options of the AT supply system the varieties presented in **Tab. 2** were considered. The systems were investigated with the for the following train driving conditions:

- 58 railway carriages at speed of 70 km/h
- 52 railway carriages at speed of 50 km/h
- 10.000 kW uniform load.

The investigations on the first two train drive conditions were mainly used as the base of the power rating and the loss analyses, while the results for train drive with uniform load were used for the comparison of the different supply options.

Tab. 2 Varieties of the investigated AT schemes

Power factor	Rated supply voltage	AT number per section	Number of varieties
0.8	2U	5 4 (4-1) 3	4
	3U	5 4 (4-1) 3	4
1	2U	4	1
	3U	4	1
TOTAL of the varieties			10

When comparing the results obtained for different options of the power supply the following main conclusions can be made:

a) *Voltage stability* (see **Fig. 3**):

- the AT spacing (number of ATs) has no essential effect on the voltage drop
- the increase of the rated voltage from 2U to 3U would result in significant improvement.

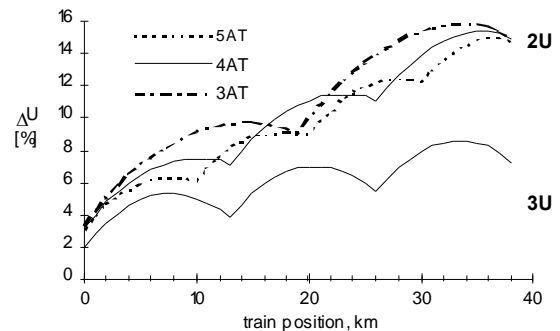


Fig. 3 Voltage drop for different AT supply options, versus train position, due to 10 MW, $\cos\phi = 0.8$

b) *System losses*:

- the AT spacing has no essential effect on losses,
- the losses of AT system - especially for 3U - are significantly lower than in BT system.

c) *Power rating* of the AT increases with the increase of the AT spacing. (The scheme with 3 ATs supply involves about 30 % higher rating than with 4 ATs.)

d) As a general indication it can be stated that the AT and BT systems result in, practically, identical induction to telecommunication lines and identical rail voltages when the half of AT spacing is closely equal to the BT (more correctly the bond) spacing [2].

4. SURVEY OF THE SITE MEASUREMENTS

4.1 Measurement technique

The AT and BT systems were compared on the bases of the following measurements:

a) Measurements with fundamental frequency (16 2/3 Hz) “traction” current. To produce the measuring current a short circuit (see C-R bond in Fig. 4) was created between the catenary and the return rail subsequently at different locations (19

b) places for AT and 21 places for BT) and with the appropriate control of the converter voltage a current magnitude was set to a stable value in the range of 500-600 A. The following quantities were measured:

- rms value of the currents in different points of the supply feed section and the phasor value of the current and voltage in the converter station correspondingly to Fig. 4;
- longitudinal voltages induced in telecommunication line sections (see Fig. 5);
- longitudinal voltages induced in laid conductors;
- rail potential to earth, to other rail and over insulated rail joint;
- AC voltage over the relay and battery of signalling circuit.

c) Measurements with disturbing current of X.2 train standing at different locations (8 places for AT and 14 places for BT). The measured quantities are:

- longitudinal psophometric voltages induced in telecommunication line sections

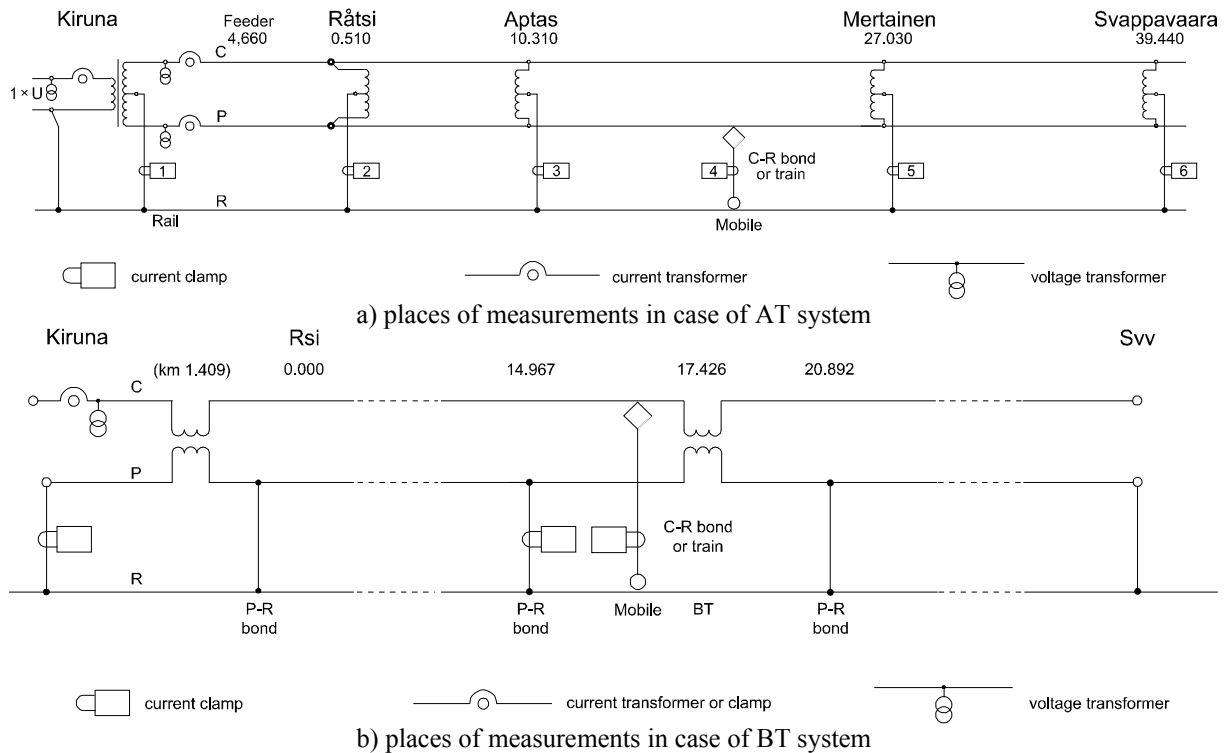


Fig. 4 Voltage and current measurements with catenary to rail bond at fundamental frequency (16 2/3 Hz)

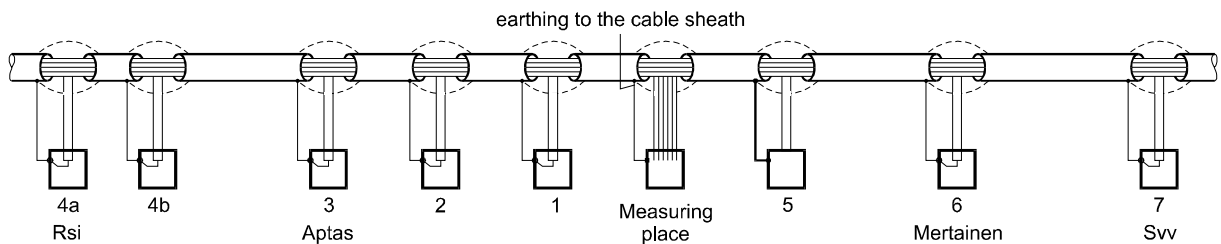


Fig. 5 Sections of telecommunication cable for longitudinal voltage measurements

- longitudinal psophometric voltages induced in laid conductors.
- c) Measurement *with inrush current* of the transformer of Rc 4 locomotive equipped with synchronised breaker control. The synchronised breaker control was set for maximum inrush current. The induced transient dc voltages were checked over the relay of two signalling circuit in critical locations.
- d) Detailed current distribution measurements at the auto transformers in Aptas and Mertainen.

4.2 Measurement results

4.2.1 Voltage stability, equivalent impedance

The voltage stability of a supply system can be characterised by the equivalent impedance or the voltage drop occurring in this impedance due to a given (i.e. 500 A) traction current. These values have been identified by voltage and current measurements (as phasor values) in the Kiruna converter station.

The comparison of the equivalent impedance values, versus train location, (see Fig. 6) clearly shows that the AT system involves significantly lower values than the BT system. The measured and the calculated values are -- in the accuracy of the measurements -- identical.

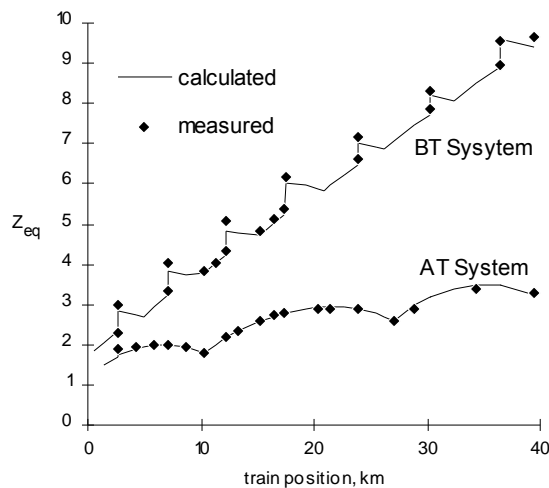


Fig. 6 Comparison of the equivalent impedance

The voltage drop due to 500 A and the equivalent impedance are plotted for three characteristic locations in Tab. 3. (Note: The voltage drop values in the table are the modulus of the voltage drop. The voltage magnitude is actually reduced only by the longitudinal component of the voltage drop.) The reduction in the equivalent impedance can be characterised by the ratio of the maximum values relevant to AT and BT systems, (marked by shading in Tab. 3) which is 0.36. The impedance values relevant only to the supply feed sections between Rsi and SvV are about 2 Ω and 7 Ω for the AT the BT systems, respectively. It means an even lower (30 %) value. It can be observed that, the impedance up to Rsi (1.51 Ω) causes a significant contribution (44 %) to the total impedance

(1.51 Ω) of the AT system. More than half of this 1.51 Ω is resulted by the stray impedance of the substation transformer, which is 0.85 Ω at 16 kV voltage level. Further reduction can be reached by use of transformer with low zero sequence impedance.

Tab. 3 Comparison of the voltage drop due to 500 A and equivalent impedance

Quantity	AT system		BT system	
	km from Rsi, 1+329	36+500 (39+450)	km from Rsi 2+630	36+510 (39+430)
Voltage drop, per 500 A, [V]	755	1735	1160	4805
Equivalent impedance [Ω]	1.51	3.47 (3.27)	2.32	9.61 (9.42)

4.2.2 Induction to telecommunication lines

For comparison purposes a measuring site has been set up at the location of the junction box B10-10 at km 15+205. At this junction there were access to 7 pairs of the telecommunication cable thus allowing the measurements of the induced longitudinal voltages in 7 basic sections and their combinations.

a) Longitudinal voltages at 16 2/3 Hz

The longitudinal voltages induced at fundamental frequency have been measured for both systems under the same short circuit locations and with currents around 500 A, as applied to the equivalent impedance measurements. The results are the longitudinal voltages versus train location for both systems. The induction level of a given section of the telecom cable is characterised by maximum induced voltage. With the comparison these measured maximum values the following conclusions can be made:

- (1) The longitudinal voltages induced by AT system at a given traction current are smaller for each line section than that induced by BT system.
- (2) The maximum longitudinal voltage occurred, in case of booth systems, when the train (short circuit) was located at the SvV end of the line. It has been proven by the simulation calculations that the majority of the maximum voltage is the consequence of following two kinds of line unbalances:
 - the unbalance in the self impedance of the catenary system and the inverted feeder. This is the dominating effect in case of AT system.
 - the unbalance in the mutual impedance values of catenary system to rail and the inverted feeder or return conductor system to rail. This is the dominating effect in case of BT system.

The highest measured longitudinal voltages are: for BT system 127.5 V and for AT system 112.6 V. The ITU-T limit for the permissible value: 60 Vrms.

b) Longitudinal psophometric voltages

With the comparison of the measured maximum of the psophometric voltages, it can be stated that in case of AT system they are smaller in sections to Rsi direc-

tion, but the values are *higher* for in line sections to the SvV direction from the measuring place and also in the total line length.

The highest measured longitudinal psophometric voltages are: for BT system 118 mV and for AT system 231 mV. The limit value used by Telia is 200 mV.

c) Longitudinal voltages in laid conductors

Along the railway line at kilometre point 15+120 Telia had laid three conductors at the distances 30 m, 100 m, and 300 m from and parallel with the line towards Svappavaara. Each conductor was 400 m long. Due to the effect of the earth potential rise of the return (S) rail the voltages measured in the laid conductors were the expected one's and were in good agreement with the calculated values only for current injection applied at the vicinity of the SvV end.

4.2.3 Rail voltages in different relations

The so called personnel safety measurements were performed by staff of Banverket in advance to the main measurements with the aim of measuring the different type of rail related voltages. Parts of these measurements were performed also during the main measurements and provided the following main results.

a) Rail to earth voltage

The rail to earth voltage was measured and also it was checked at the AT locations of Aptas and Mertainen, but only with AT supply system. The highest measured rail potential of 176 V occurred at the km 15+174 point, due to 590 A at that point. Accordingly to the simulation calculation the maximum rail voltage occurs around the middle of the largest auto transformer pacing. Its value can be slightly above 200 V due to 600 A traction current.

b) Voltage over insulated rail joint

It was measured on joint of three different signalling circuit. The highest measured values were:

- for AT system: 184 V
- for BT system: 211 V

The measured values show that the voltage over the rail joint in BT system is higher than in AT system.

c) AC voltages in signalling circuit

The voltages were ranging up to 6 V over the relay and battery of the measured three signalling circuits.

4.2.4 Transient DC due to inrush current

Accordingly to the records of the inrush current, the transients have shown peak currents ranging up to 824 A with time duration of 10 -15 ms. The transient voltages recorded over the coil of the signalling relay have had peak values ranging up to 3 V and they were attenuated with a time constant of about 2 s.

Non of the signalling relays was affected by the transients of the inrush current of Rc4 locomotive transformer.

The transient inrush current resulted in bit error detection on a modem connection operated on telecommunication cable pairs between Rsi and SvV.

5. CONCLUSIONS

The comparisons of the results obtained from both simulation calculations and site measurements on the Rsi-SvV railway line changing from BT to AT system show that:

- a) The equivalent impedance between the feeding converter and a train, versus length, is significantly (about 3 times) less for the AT system than that for the BT system. Thus, the *voltage stability* is much better in AT system or consequently the AT supply is capable to provide more power to trains.
- b) In point of view of electromagnetic *compatibility with telecommunication lines* the two systems are, practically, identical. The maximum longitudinal voltage occurred in the whole line length when the current injection (short circuit) was located at the SvV end of the line. This could significantly be reduced for AT system by the improvement of the balance in the self inductance of the catenary system and the inverted feeder.
- c) In point of view of electromagnetic *compatibility with signalling* circuits the two systems are, also practically, equivalent.
- d) Concerning the *rail potentials* in personnel safety point of view, they are also similar in AT and BT supply systems with the following remark:
 - (1) In case of AT supply the rail-to-earth voltage can reach higher value in the middle of the Aptas - Mertainen section due to the relatively big AT spacing.
 - (2) In case of BT supply, the voltages over insulated joints are higher in certain places.

6. LITERATURE

- [1] Sollerkvist, F.J, Varju, Gy.: A general model and numerical method for multiconductor simulations in frequency domain. *Proceedings of the IEEE/KTH Stockholm Power Tech Conference*. Stockholm, Sweden, 1995, pp. 227-232.
- [2] Sollerkvist, F.J, Varju, Gy.: Comparison of the AT and BT railway system from an induction point of view, using a multiconductor system, *EMC'98 Int. Symposium on Electromagnetic Compatibility*, Rome, Italy 1998, pp. 139-144.