Power Electronics improving 3-Wire DC Railways Electrification

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«Traction application», «Power transmission», «DC power supply», «Control methods for electrical systems», «Efficiency» , «Emerging technology», «Simulation», «High Voltage power converters ».

Abstract

Urban DC railway substations are growing in size due increasing capacity demand. Several challenges associated with the increase of power demand can be met using power electronics. The proposed system is based on DC-autotransformers and active rectifiers working similarly to those in 3-wire AC railway electrification system. Conventional simulation software (Idom-REPS-DC) has been adapted to the system. A real subway line and the same line with the proposed 3-Wire DC working in the same conditions are simulated. The global performance of the system and the preliminary sizing of the converters involved are evaluated.

1. Introduction

Classical DC electrification systems use lower voltages (e.g. 1500V, 3000V) than AC systems (e.g. 15kV, 25kV). In early DC electrifications, the power consumption of trains was lower than today. Consequently, the electric size of feeding substations and the voltage drop were small, and so the distance between feeding substations could be larger.

Railway capacity can be enhanced in two ways, i.e. increasing the number of trains simultaneously in service and increasing commercial speed. More trains and with greater unitary power demand is the general short-term scenario for most railways. The natural evolution of DC railway systems had been the increase in unitary power of substations and in the number of substations, thus reducing the distance between them. But nowadays, in many cases it is very difficult to sustain this strategy. The reasons are often very different for urban and inter-urban typologies. The most common problem for inter-urban railways is the absence of sufficient electric grid power in the location of the new substation or in that of the old substation to be enlarged. In the case of urban railways, the electrical grid should support new substations or current ones should be resized. However, finding space to fit new substations or to enlarge old ones is often complicated. In both cases, the power of substations cannot increase with any limits due to limited short circuit capacity of circuit breakers. Even if the above problem is solved, the voltage drop along the line reaches unreasonable values and the efficiency of the transmission system decreases. The rules of system operation impose the N-1 fault tolerant criterion, so in case of disturbance or maintenance in one substation, the service must be maintained with case-specific pre-defined performance. This circumstance, usually named demoted operation, is especially critical in some substations both due to overload of neighbour substations and due to voltage drop in the track between them. The demoted operation performance level is usually the same as that of normal operation of urban railways. In the case of inter-urban railways, it is common to decrease the performance level to lower train frequency.

In this scenario, we focus on the solutions that power electronics can offer, especially as far as voltage drop and energy transmission efficiency are concerned. The proposed system is a 3-wire system, similar to that of High Speed railways 2x25kV AC. The core of the system incorporates autotransformers but in DC, that is, DC/DC power electronics converters.

As an example, simulations on an actual subway line are performed to illustrate the benefits that can be obtained with the proposed system. The actual installation is simulated. Real values for slope, radius, electro-mechanical train characteristics and electrical characteristics are used. The simulation is repeated with the same conditions (the same trains at the same frequency) for the proposed 3-wire system. Improvements in voltage drop and transmission efficiency are evaluated with the simulation results. Additionally, the functional requirements of the power electronics involved are estimated. The most suitable converter topology to implement the functional requirements, its characteristics and feasibility are out of scope of this paper. It is future work to evaluate in detail the most appropriate topology and power device considering restrictions in power electronic devices, like voltage, current and frequency limitations. Series and/or parallel switch arrangement, or multi-level converter topologies, are probably the best candidates due the voltage and current values required.

2. Actual main characteristics of the subway line

Tables 1 to 4 summarize the actual main characteristics of the studied line. As can be seen, the actual train frequency at peak hours is $(180s)^{-1}$ and is going to be increased up to $(158s)^{-1}$ in the near future. The main characteristics of the trains can be found in Table II.

The line has 9 substations with minimum rated power of 2500kW and maximum of 8000kW. The substations are located as described in Table III. There are 24 stations, located as described in Table IV.

Both in the conventional system and the proposed 3-Wire system train frequency $(158s)^{-1}$ must be maintained in case of demoted operation of the system. The railway company rules fix the considered demoted operations to be standard N-1 fault tolerant system. As applied to substations, this criterion means that the system must work without performance degradation in case one substation goes out of order.

Table I. General characteristics

Rated Voltage	1200V
Overall length	18.43km
Train frequency	$180s^{-1}$ $(158s^{-1})$
Stop time at station	20s
Commercial speed	30km/h
Contact wire	1400 mm^2 Cu eq.
Rail	UIC 54kg/m

Table II. Train characteristics

Max. braking voltage	1400V
Power reduction voltage	960V
Under-Voltage stop	840V
Max. Power Consumption	4000kW
Max. Traction effort	240kN
Max. speed	80km/h
Max. acceleration	$1m/s^2$

Table III. Actual Substation position and power

Substation	Position (km)	Rated Power (kW)
1	00.10	2500
2	02.70	8000
3	04.35	4000
4	05.82	6000
5	07.90	6000
6	10.60	8000
7	13.14	8000
8	16.33	6000
9	18.20	4000
Total Rated Installed Power: 52.5 MW		

The worst case is the demoted operation with substation 7 gone out of order, so we will focus on it and call it “Demoted 7” operation. Here the excessive voltage drop renders the system unable to meet the service requirements.

The conventional solution consists in adding one or two new substations close to substation 7. Unfortunately, the infrastructure in this area is old and it is very difficult to find space to fit new substations. Even if this problem could be solved, all the DC switches would have to be adapted to high level short circuit capabilities. The proposed system can help to solve these problems.

Table IV. Actual Stations

Station	Position (km)
1	00.10
2	00.74
3	01.38
4	02.07
5	02.74
6	03.21
7	03.68
8	04.35
9	05.08
10	05.81
11	06.66
12	07.20
13	07.90
14	08.63
15	09.28
16	10.18
17	10.65
18	11.54
19	12.33
20	13.14
21	13.77
22	14.40
23	15.32
24	16.33

3. Simulation results for conventional installation

In Figs. 1 and 2 the voltage profile at normal operation and the worst case (demoted operation) are depicted. The values are minimum, maximum and average values for each track.

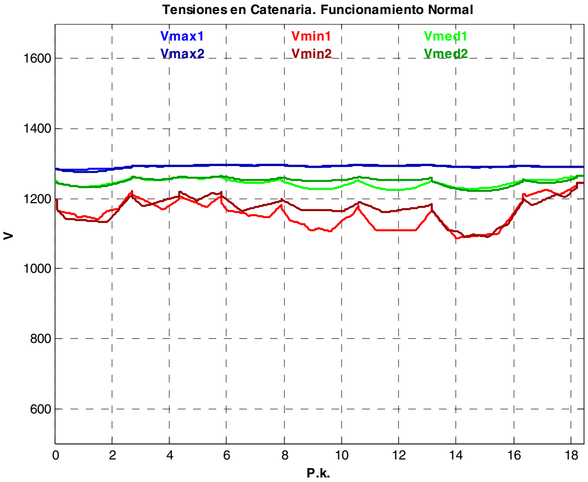


Fig. 1: Pantograph voltage at Normal operation

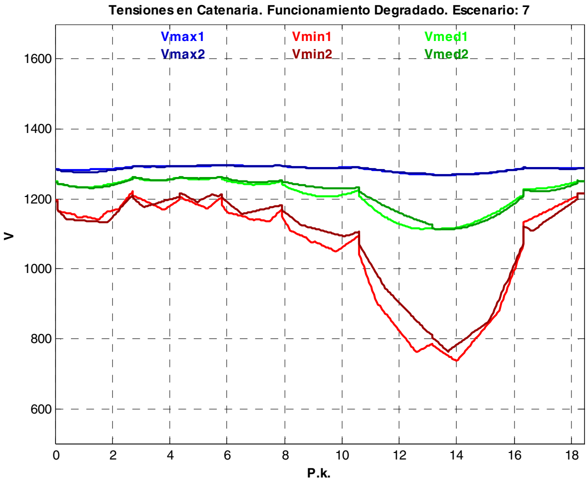
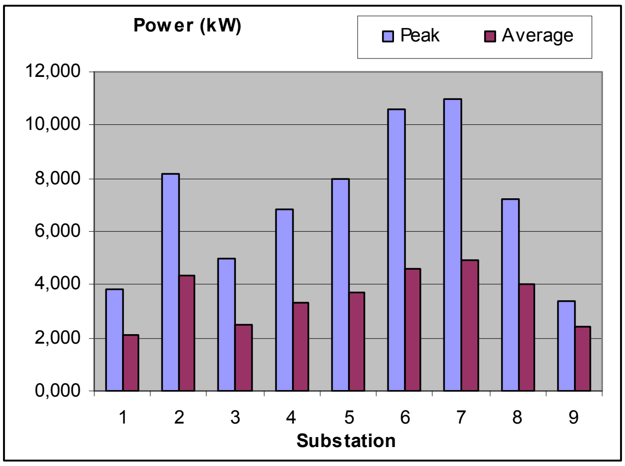


Fig. 2: Pantograph voltage at Demoted 7 operation

In Figs. 3 and 4 the corresponding average and peak values for power are depicted. The substations have no power problems in the Demoted 7 case, but the voltage drop is excessive.



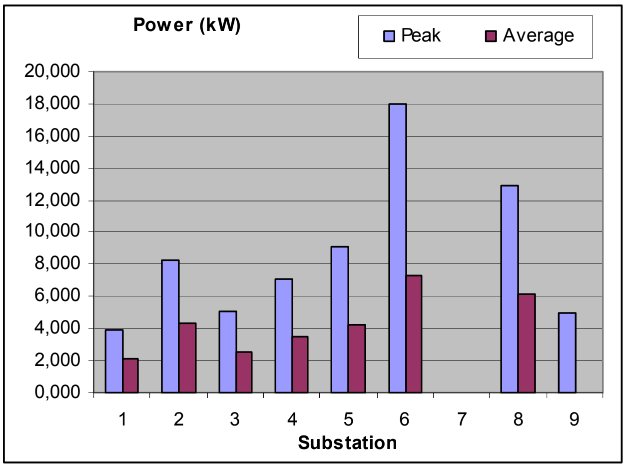


Fig. 3: Power demand at Normal operation

Fig. 4: Power demand at Demoted 7 operation

4. Proposed system

Several 3-wire systems have been proposed in the literature. [1] provides a general overview and a list of advantages offered by different systems. In this paper we propose the 3-wire symmetric-voltage negative feeder system for multiple reasons: it has the safest behaviour in case of short circuit, the isolation level is the same as that in the original installation and, as in our case, the resistance of catenaries is similar to the resistance of rails. Thus, there is no substantial difference in transmission loss compared with positive feeder systems.

The main part of the actual installation remains unchanged. The rated voltage catenaries-rails remain at 1200V. One new conductor, named negative feeder, is added to the system. The rated voltage negative feeder to rail is -1200V. This feeder needs a new rectifying group in each substation to provide this voltage. There is at least one DC autotransformer between substations in each track linking the contact line, the rails and the negative feeder. Fig. 5 illustrates the additional installation (red), the conventional installation (black), and the new currents distribution.

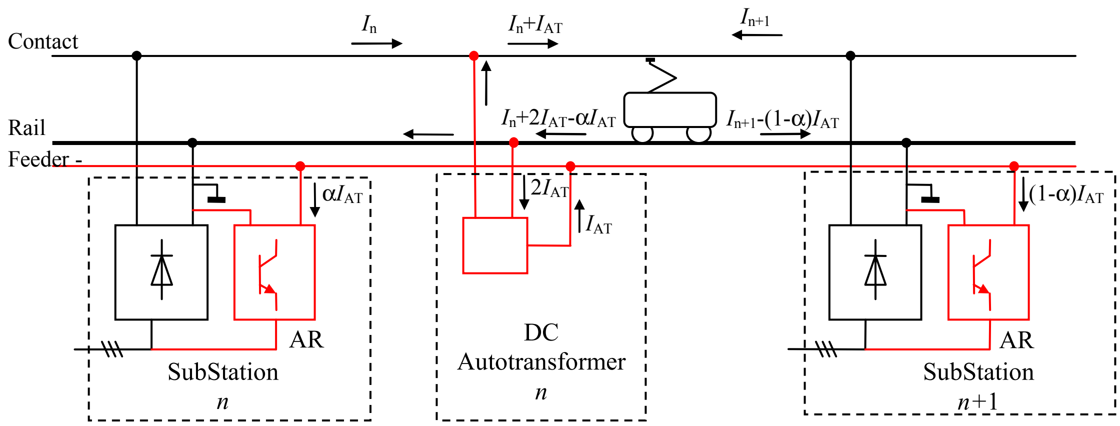


Fig 5. Proposed system

The core of the system is the DC autotransformer. Fig. 5 shows the currents for motoring trains. The negative rectifier (AR) of the substations energizes the negative feeder and the autotransformers supply power to the positive circuit. When trains are (regenerative) braking, the autotransformers reverse the power flux. In order to use the braking power by re-injection on the AC grid, the negative rectifiers must be active.

The DC autotransformers must be power electronic devices and can have different control laws:

1. **Symmetric control**: The regulation system tries to equal the positive and negative voltage, limiting the currents if necessary (short circuits, abnormal surcharges).
2. **Asymmetric control**: The regulation system tries to maintain the targeted positive voltage. The voltage target can be close to rated or to maximum brake voltage.

The symmetric control acts like in the 3-wire AC system while no current limiting area is reached. The asymmetric control acts like a variable transformation ratio transformer, so more voltage stability is reached at the positive circuit. But transmission losses in the negative circuit are larger than in symmetric control. For this reason, the presented simulation is conducted with symmetric control.

With symmetric control and no current limiting area, the current and the power at each autotransformer is the result of the load flow from power demand of trains and the resistance of wires. As usual, the contact wire section is greater than the negative feeder section, and less power flows through the negative feeder than the positive feeder. Therefore, negative rectifiers in substations can be smaller than positive rectifiers, as opposed to AC systems, where the two circuits are the same size. The small size of the negative rectifier allows using an active rectifier in terms of cost. System simulations are used to determine the sizes of autotransformers and negative rectifiers. The simulation software used is Idom-REPS, developed by CITCEA-UPC for Idom Company. The software has been modified in order to support both the conventional system and the 3-Wire DC system.

The diode rectifiers have been modeled with a maximum efficiency of 99.6%, and a maximum voltage drop (overlap) of 8%, values corresponding to the real system. The maximum efficiency values of the active rectifiers and DC autotransformers have been set to 98%. These values must be revised with real values when converters exist.

5. Simulation results for the 3-wire system

The voltage profile obtained with the same installation and conditions but with the 3-wire system is depicted in Figs. 6 and 7. The voltage drop is smaller than that of the actual installation (Figs. 1 and 2), especially in the worst case of demoted operation. Now the minimum voltage is greater than the minimum required by trains. The negative feeder has a 90mm^2 Cu equivalent section.

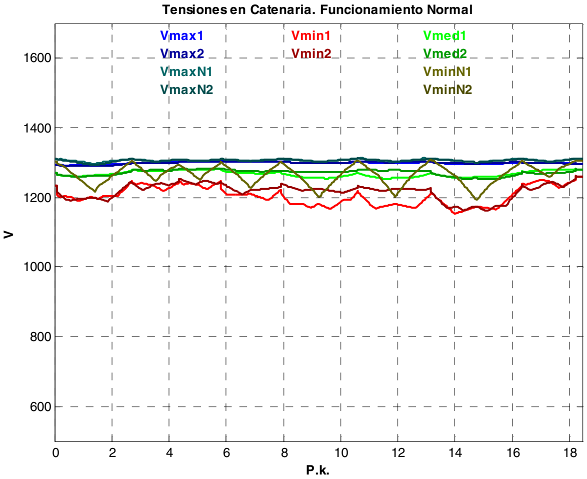


Fig.6: DC-3Wire pantograph voltage at Normal operation.

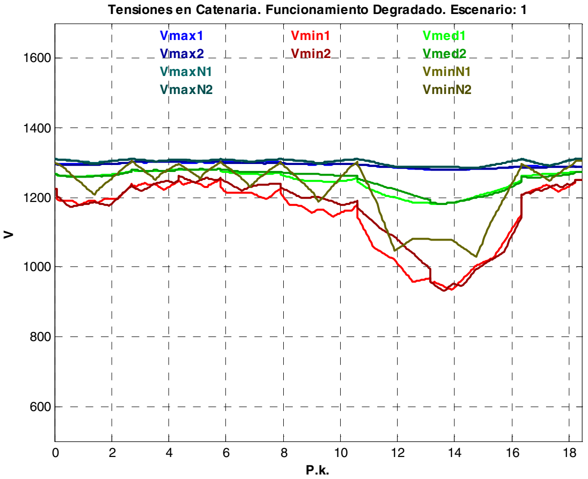


Fig. 7: DC-3Wire pantograph voltage at Demoted 7 operation

The new power demand on substations can be seen in Figs. 8 and 9. The higher the number of circuits power flows through, the lower the energy transmission losses, as shown in Table V. The great improvement in demoted operation is due to the voltage collapse of the system in the case of the actual installation. This result has no special relevance because the operation time in demoted modes should be much shorter than in normal mode.

The traction converters on the train can obtain the power demanded for traction while the pantograph voltage is within the limits. Thus, the train is acting like a power source. If the voltage drop increases, the traction converter gets more current to maintain the demanded power. But increased current implies a greater voltage drop. If there were no voltage limits, the system would reach very low voltage levels, that is, it would have a collapse. This behaviour is the so called voltage collapse. In the real system, if the voltage is below the limit, the converter reduces the traction power, eventually reaching a zero value or stopping. Indeed, this is a consequence of the well-known principle of maximum power delivery capability of electrical power systems.

Table V. Total Power Demand in Substations (kW)

		Normal	Demoted
Actual	Total	31879	33192
Proposed	Positive	25401	25487
	Negative	5971	6527
	Total	31375	32012
	Energy improvement	504	1180

For system sizing purposes, the peak and average power for autotransformers and negative rectifiers was calculated during simulation. The results can be found in Figs. 8 to 11. The reasonable size of the autotransformers for the proposed configuration (1 autotransformer per track between two consecutive substations) is 500kW average and 1000 kW peak. Other configurations like doubling the number of autotransformers or resizing the negative feeder in some parts of the installation are under study. The reasonable size of the active rectifier for the proposed configuration is 1500kW average and 3000 kW peak. These sizes are within the normal range of power electronics based electrification systems [2], [4]. By collecting the voltage requirements, power requirements, and current requirements, a set of basic characteristics for power electronic devices was found. The next step is to analyze whether there exist any structures and power semiconductors that can meet these requirements at a reasonable cost.

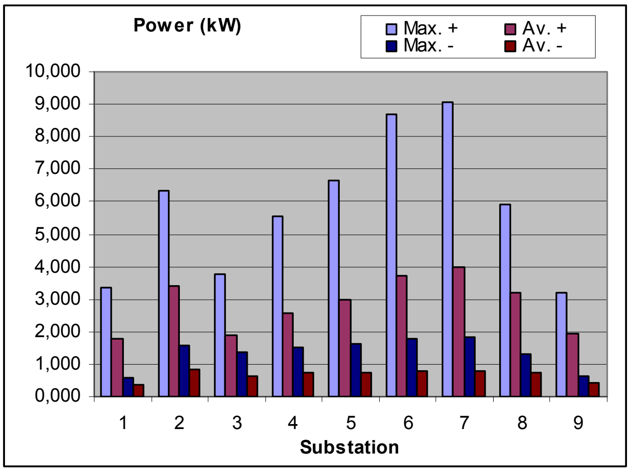


Fig.8: Substation power demand at Normal operation

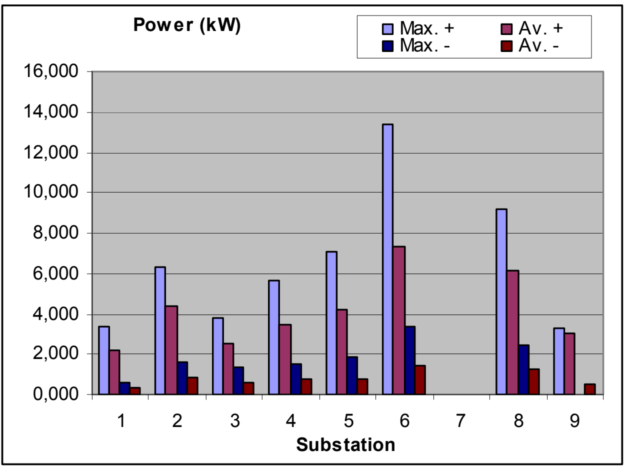


Fig. 9: Substation power demand at Demoted 7 operation

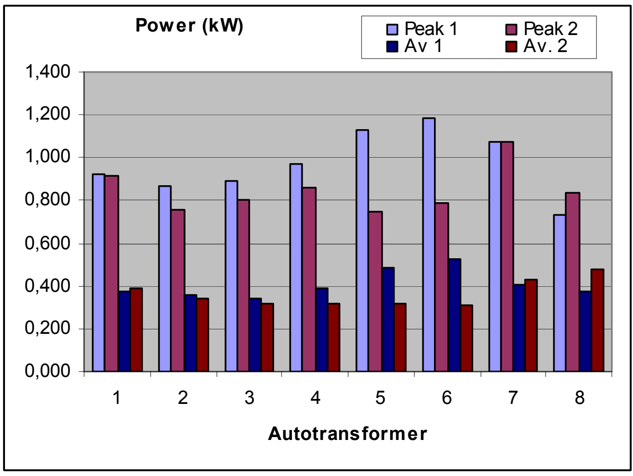


Fig.10 Autotransformer power demand at Normal Operation

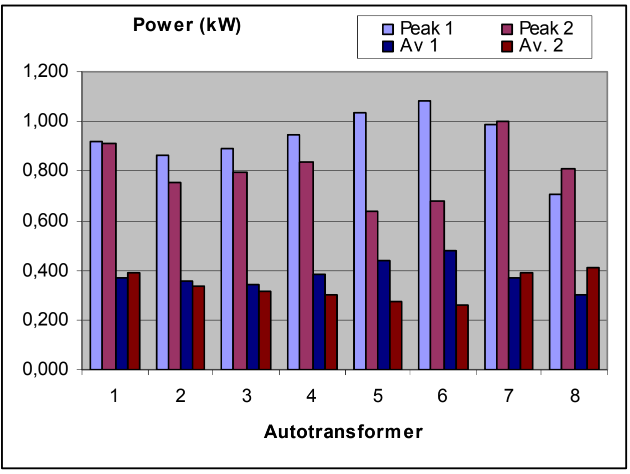


Fig. 11 Autotransformer power demand at Demoted 7 operation

6. Conclusions

The application of a 3-Wire DC electrification system was studied in a real-case subway line. The system can solve the challenges associated with growing transportation demand and improve the energy efficiency of the transmission system. This system needs the application of power electronics like DC autotransformers, and optionally active rectifiers. The size of power electronics equipment was found using specific simulation tools.

The proposed system is fully compatible with conventional electrification schemes. Therefore, in case of failure it is possible to come back to the conventional system, of course, in demoted operation. This is a key point because of the traditionally conservative behaviour of railway companies due to the feasibility required by this kind of installations.

New equipment is smaller in size than current equipment on board of trains. Consequently, there are objective technical reasons to think that this size of DC-autotransformers and active rectifiers is actually affordable. The best technical and economical option to implement is under study.

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