# A Review and Comparison of Transformer and Static Frequency Converter Traction Supply Architectures for AC Electrified Railways

Jonathan Bowdidge and Hassan Nouri

***Abstract* —Electrification of the U.K. railway network will play a critical role in achieving targets of net-zero $CO_2$ emissions while providing major benefits to train operators, passengers, and industry. In the drive to make electrification a more cost-effective prospect, this paper intends to complete a comparison of the common feeding arrangements and the novel Static Frequency Converter for use in AC electrification using PSCAD EMTDC simulations. The findings illustrate the performance of two classic architectures and autotransformer feeding compared to a proposed classic SFC arrangement and provide recommendations for SFC implementation with separations between feeder stations of up to 60 kilometres using a parallel feeding arrangement, along with demonstrating SFCs exhibiting more robust performance in the event of faults.**

***Key words* — Autotransformer (AT); Booster Transformer (BT); Coupling Transformer (CT); Overhead Line Equipment (OHLE); Static Frequency Converter (SFC).**

## I. Introduction

Electrification of railways is widely considered one of the most effective means of decarbonisation of transportation [1], as a mature technology in use for almost 150 years. The typical electric traction units are lighter, more compact, more powerful and more reliable than their diesel counterparts [2]. Beyond this, electric traction introduces a higher capacity per train, significant performance enhancements and large reduction in noise levels and air pollution, with research indicating poor air quality on diesel-powered trains at levels up to 13 times greater than a congested London Street. With the ever-increasing climate awareness and political drive to reduce $CO_2$ emissions across all industries, electrifying the remainder of the U.K.'s main-line railway network is critical to efforts. However, progress is slow, with around 40% of the network currently electrified, and only two schemes presently ongoing. The primary reason is the significant investment required to complete an electrification project, with the sourcing of power being one of the critical components in this complex project.

This paper will conduct a review and comparison of different methods of supplying traction power to the 25 kV 50 Hz AC electrification systems used on most main line railways within the U.K., in the form of common "classic" arrangements and the autotransformer method. It will also investigate the novel method utilising the Static Frequency Converter (SFC), which aims to reduce the necessary installation cost of a feeder station by up to 50% [3].

## II. Background

### A. Overview of U.K. Railway Electrification

Early electrification schemes were mostly centred around DC traction supply, with the popular use of the third rail method of interfacing between the supply and train. Examples of overhead lines were infrequent, with an early example being tried in 1908, before DC overhead lines were implemented on a selection of heavily used freight routes [4]. The 1955 Modernisation Plan would begin mainstream adoption of 25 kV 50Hz AC supply within the U.K., with the exception of the 750 V DC third rail used across the former Southern Railway routes.

The general feeding arrangements for the AC electrification are in two main categories: "classic" coupling transformer (CT) feeding and "autotransformer" (AT) feeding [5]. Within the CT format, there are multiple sub-variants designed around EMI mitigation, since signaling cables run alongside running lines. These include the "return conductor" (RC), booster transformer (BT), and screening conductors [4].

The Static Frequency Converter (SFC) is an AC-DC-AC converter, providing a large amount of flexibility within the design, with the ability to convert between different frequencies and different numbers of phases, or even as a power conditioner. Similarities can be drawn between the SFC and the STATCOM, and indeed the circuits between the two devices are nearly identical.

### B. Examples of SFC Implementation

Most examples for rail SFC use are typically found on routes using a frequency lower than the industrial frequency of 50-60 Hz. For instance, Germany and Switzerland utilise a 15 kV system at 16 2/3 Hz, and SFCs are being deployed on these networks, with one example being a 100 MW supply in Bremen, Germany [6]. The technology has also been deployed in the U.S. state of Pennsylvania [7], where routes around Philadelphia are utilising a 12 kV supply at 25Hz.

Indeed, this common use in locations where frequency conversion is taking place is the primary reason for the "frequency converter" naming convention. In these cases, the SFC is a direct succession for the traditional "rotary converters", essentially a motor-alternator, with enhancements in both reduction of installation and maintenance costs as well as up to 5% efficiency improvements.

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J. Bowdidge, School of Engineering, UWE Bristol, UK.
(e-mail: Jonathan2.Bowdidge@live.uwe.ac.uk)
H. Nouri, School of Engineering, UWE Bristol, UK.
(corresponding e-mail: Hassan.Nouri@uwe.ac.uk)

Despite the trend for use where differing frequencies are present, there are installations on the industrial frequency outputs, with one such example supplying the Queensland Railway 25 kV 50 Hz electrification [8]. Beyond this, the first installation within the U.K. is also operational [3], with further installations to be activated over the next few years. Generally, the consensus from industry is the use of the SFC on a 50 Hz-50 Hz grid is the ability to provide a "booster" to existing electrification, whilst providing up to 50% reduction in installation cost using lower-voltage connections. With the SFC using all 3 phases compared to a single phase, connections are simplified, and the effective load placed on the supply is balanced. To that extent, it is possible to use supplies at the level of 33-66 kV without issue, where conventional methods could not be due to the imbalance placed on the supply. An additional benefit is the ability to "parallel feed" through synchronisation of the SFC output, hence their use as boosters since these can be added into existing networks without further modification to the existing OHLE, with no requirement for phase separation by way of "neutral sections".

## III. Methodology for Simulations

Simulations demonstrated within this paper were conducted using PSCAD EMTDC software.

### A. *Feeding Architectures*

Four architectures were compared for the simulations, including the simple CT, BT, AT, and the SFC in the simple CT arrangement.

### B. *SFC Design Concept*

The SFC introduces the complexity for the simulation in this paper, requiring a custom design to be produced as part of the simulation (this is not included within PSCAD by default). With the basic architecture being an AC-DC-AC converter, this was built using an un-controlled 3-phase diode rectifier, with a single-phase full-wave IGBT inverter. The controller in use is a PI voltage-amplitude controller, which takes a reference signal $V_{Ref}$ by comparing the measured output with reference to a nominal reference voltage, $V_{o(Nom)}$ of 25 kV:

$$V_{Ref} = \frac{1}{V_{o(Nom)}} \tag{1}$$

This reference is used to obtain the error from the target to supply the PI controller linked to a first-order system with transfer function:

$$P(s) = \frac{1}{s+1} \tag{2}$$

This now provides the basis for the control system design, through obtaining an overall controller transfer function:

$$G_{SFC}(s) = \frac{K_P s + K_i}{s^2 + (1+K_P)s + K_I} \tag{3}$$

With substitution enabling the solution for controller parameters $K_P$ and $K_I$ to be found. Controller conditions were set to achieve a 95% settling time ($t_s$) around 0.05 seconds, and an overshoot allowance ($M_P$) of up to 10%, which could be substituted into equations 4-6 to obtain values of 118.989 and 10301.482 for $K_P$ and $K_I$, respectively.

$$s^2 + 2\zeta\omega_n + \omega_n^2 = s^2 + (1+K_P)s + K_I \tag{4}$$

$$\zeta = \frac{\sqrt{(\ln(M_P))^2}}{\sqrt{\pi^2 + (\ln(M_P))^2}} \tag{5}$$

$$t_s = \frac{3}{\zeta\omega_n} \tag{6}$$

At this stage, the designed controller was simulated and verified using MATLAB Simulink, before being transferred to PSCAD for the main simulations. This would be compared on a stand-alone SFC before testing on the simulated lines.

Parallel feeding was achieved through the use of the sine wave modulator within PSCAD, whereby the "phase" input was provided with the same constant, in this case, zero. Another version was created which would not use this modulator and instead measured the reference sine wave by converting the measured voltage to produce a unit reference, which could be compared to the actual measurement relative to the target voltage before supplying it to the PI controller block. From this point, the resulting waveform is compared to a 40 kHz triangular waveform to generate the PWM for the inverter IGBTs, with a delay unit for switch-through protection of the inverter H-bridge. Fig. 1 shows the resulting design and controller.

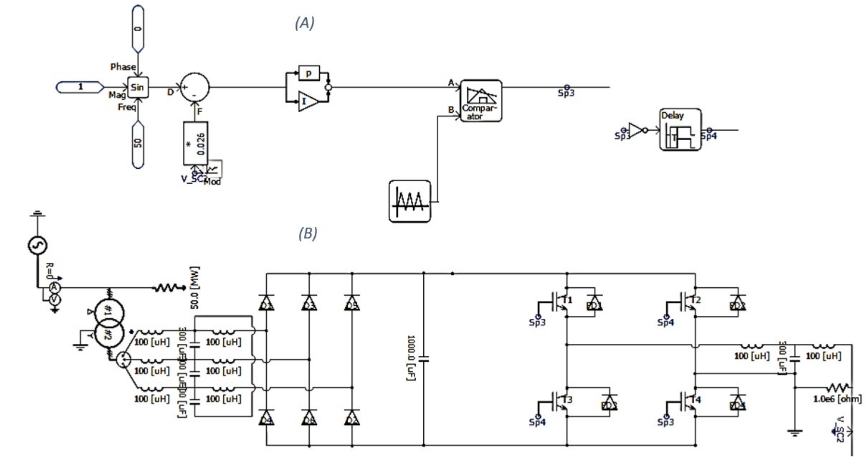


Fig. 1. SFC schematic (B) and controller (A) in PSCAD.

### C. Simulation Scenarios

The simulations cover six scenarios for the line (see Fig. 2 for three of these), which is represented by a 110 km transmission line, intended to represent the equivalent of the route between Didcot and Coventry. The four architectures detailed in subsection *A* will be run through each of the six scenarios, with three different individual load configurations.

The lines are configured such that the first configuration sees one feeder supplying the entire 110 km line. The second configuration shows two supplies, with the second of these located 50 km down the line, with the two feeder stations in phase and feeding in parallel. The third configuration uses two sources, similar to line 2, but this time, the feeders are assumed not in phase and therefore separated with a neutral section, thus acting as two independent lines. Within these, two train service patterns were simulated, one with a single train running from the initial feeder to the end of the line, and the second with two trains in opposite directions at the same speed.

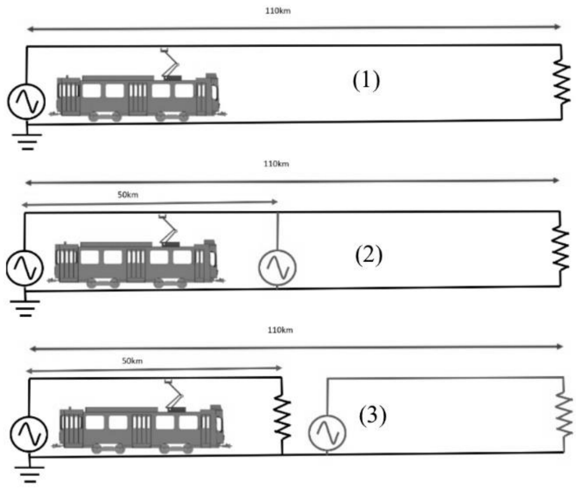


Fig. 2. Line Configurations.

Each train would be experimented with 3 different configurations for the load itself. The first load configuration sets a constant impedance, with a 0.05 H inductance and a resistor set to draw 6 MW of real power at 25 kV, which equates to approximately 105 Ω. The second load configuration measures the voltage at the location where the load is situated and adjusts the resistance to set a constant 6 MW real power draw at all voltages along the line. The third configuration would again use the measured voltage at the location to vary the resistance, this time to set a constant current draw of around 300 A per train, in accordance with U.K. railway standard GLRT1210 [9]. Varying of the resistance was achieved through manipulation and substitution of Ohm's law and the power equation. These could then be built using CMSF blocks within PSCAD, and the trains can be represented using Variable Impedance components, as demonstrated in Fig. 1.

In addition to the "normal running" simulations, a series of faults were compared, both on the 3-phase incoming supply and the single-phase railway side. All fault scenarios were simulated under no-load and load conditions.

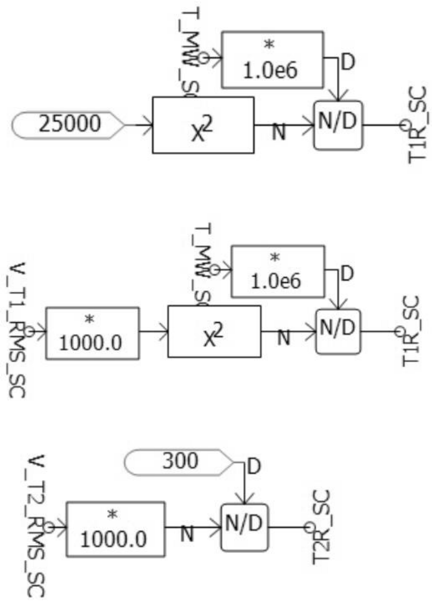


Fig. 1. Load Control methods in PSCAD.

## IV. Results and Discussion

The results obtained from the conducted simulations highlight a mixed overview of the different feeding architectures. The "normal running" outputs in Appendix A give a comprehensive comparison of each feeding architecture, with the BT system showing severe losses, while AT feeding remains consistent across all tests. The reasoning for these is that the BT arrangement essentially places a large inductor in series on the overhead line, adding up to around 15 Ω of impedance to the line for each BT. With the simulations conducted using half the typical number of BTs for this length of line, the losses would, in practice, be more severe, as in this example, the addition of the BTs adds the equivalent of a second train in impedance to the line. AT feeding, meanwhile, transfers power to further sections of the line at 50 kV instead of 25 kV, meaning that further sections are supplied along the line at half the current that would otherwise be measured at the feeder station, reducing losses. The CT and SFC arrangements perform in a similar manner as the general architecture for each case is the same. Where the traditional methods differ from the SFC is in the case of the second line configuration, where practically the SFC is the only system that can operate in this manner, as transformers on different connections or grid lines cannot be guaranteed in phase, so subsequent feeder stations must be separated in normal configurations, resulting in the third line configuration. However, since the SFC can be configured to synchronise and output in phase with an already present supply, the parallel feeding observed for line configuration 2 can be achieved. As a result, the data produced suggests that CT arrangements can feed for around 25-40 km, while BT systems can only allow up to 25 km and AT feeding can permit 80-120 km. SFC feeding, meanwhile, can permit 40-60 km when parallel feeding, up to 80 km for routes where traffic is expected to be lower, and will be in similar conditions to CT arrangements if using separation with neutral sections, although this is not a requirement. It should be noted, however, that typical SFCs will be rated for less than half the typical power output of similar ATs, for instance, with the AT less than twice the cost in comparison. The exact observations from the data obtained will differ in the event the line is more heavily loaded than what was simulated.

The fault simulations in Fig. 2 produce the most interesting comparison, as a 3-phase fault will typically not impact the SFC as a result of using all 3 phases and the internal DC link, while transformers connected on the phase undergoing the fault will transfer any effects of the fault in question to the railway. This is especially apparent in an unbalanced fault, where the SFC will continue to output at a steady state, where transformers on the affected phases will see a reduction in voltage output. However, in practice, protection would trip on all 3 phases, regardless of the fault, thus all outputs would ultimately have the same effect. A balanced fault will impact the SFC if the drop-in voltage is sufficient that the rectifier output leads to a limit on the maximum SFC output, but if the fault occurs at a point where this is within the input range for the SFC, the impact of the fault is not transferred to the railway, where transformers otherwise would.

Single-phase faults, however, produce the most notable differences. In the case of a fault occurring at the point of feeding the overhead lines, a large surge was observed on the transformer-based feeding methods (CT, BT, and AT), reaching a peak of up to 3.5 MV, before returning to a steady state after around 20 ms. This was the worst case observed, and a follow-up run with a surge arrester across the transformer secondary winding reduced this surge by 90%. The SFC, meanwhile, did not encounter this surge, with the output simply increasing in a controlled manner before reaching a steady state around 30 ms after the fault was cleared. The result is a longer recovery time and a controlled recovery to normal operation without a surge arrester.

## V. Conclusions

The findings of this paper bring the conclusion that SFCs can provide up to 60 km of feeder station separation under parallel feeding configurations and can provide more robust operation in the event of a fault without the necessity of surge arresters.

This paper therefore recommends consideration for the use of static frequency converters in future railway electrification schemes, where the location of the proposed feeder station means lower voltages under 132 kV have to be used. For lines proposed with SFC feeding throughout, it is proposed that SFC feeder stations are separated by up to 60km depending on route traffic and geographical considerations.

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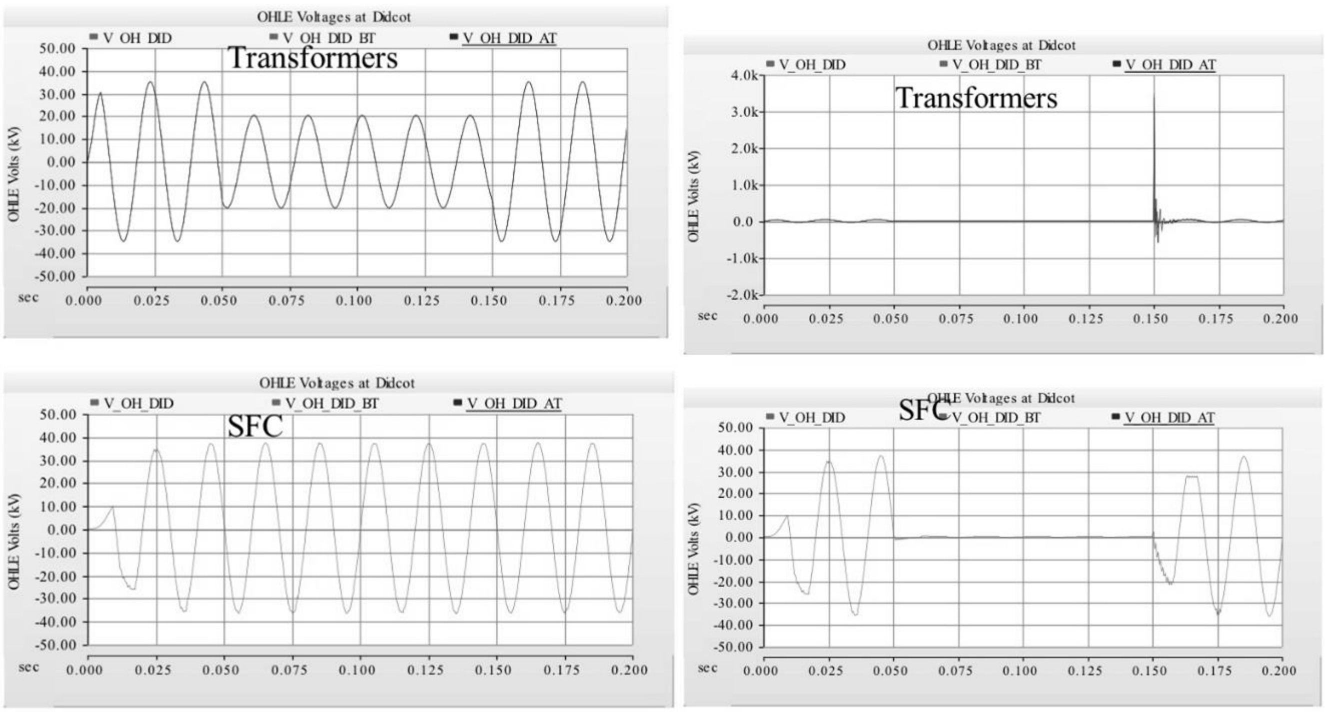


A B

Fig. 2. OHLE Voltages at the feeding stations for feeding architectures during (A) three-phase fault and (B) single-phase fault.

## APPENDIX

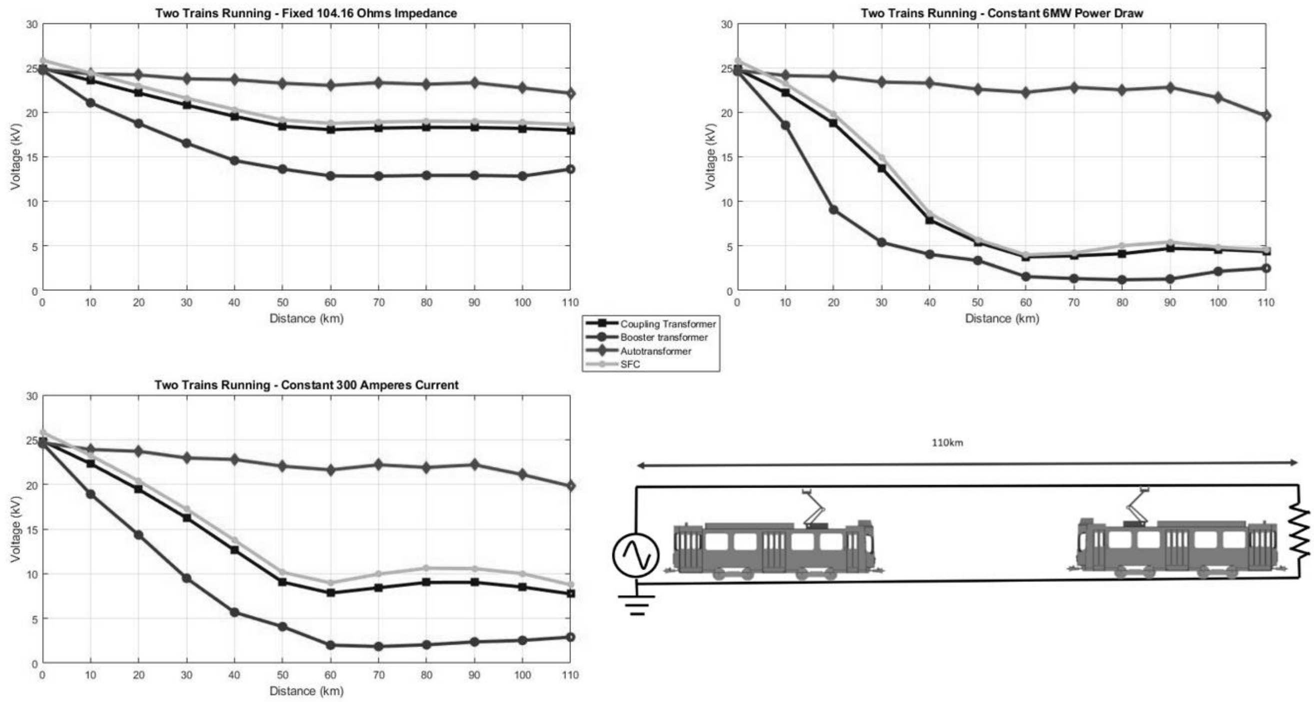


Fig. 3. OHLE Voltage profiles for one feeder station with two trains in section.

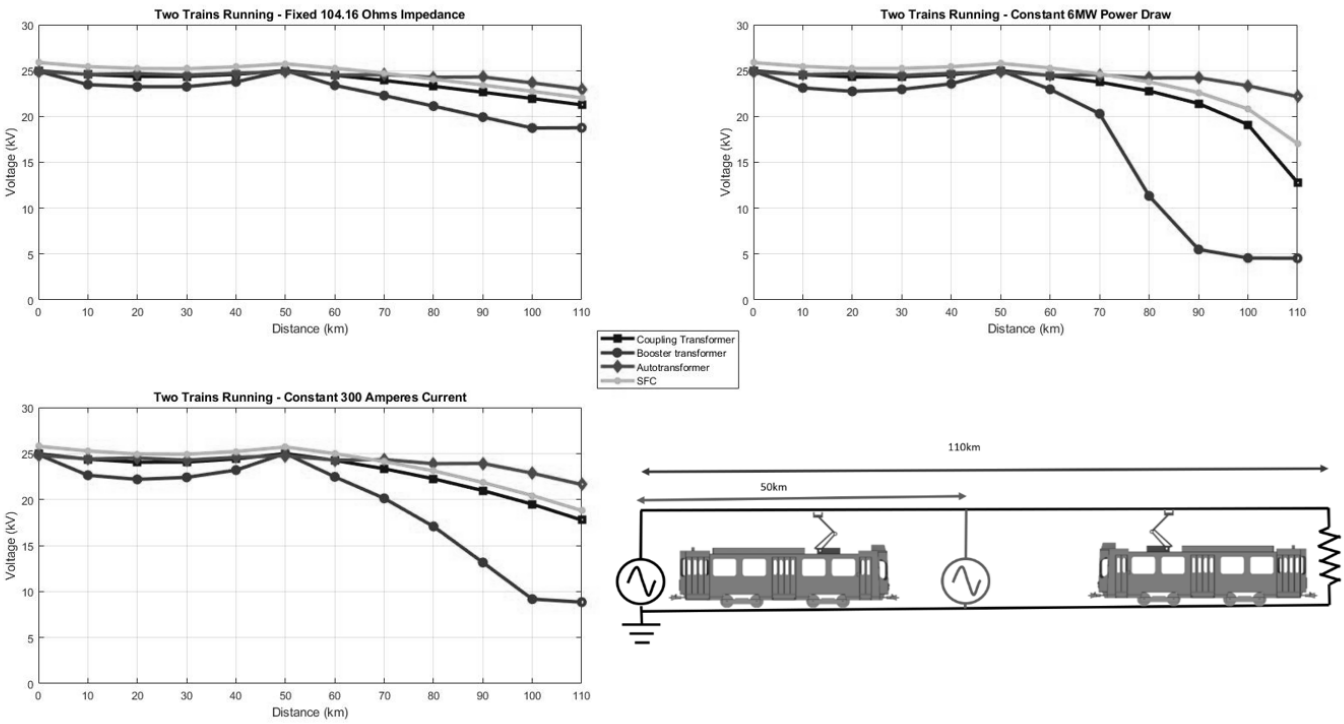


Fig. 4. OHLE Voltage profiles with two parallel-feeding stations and two trains in section.

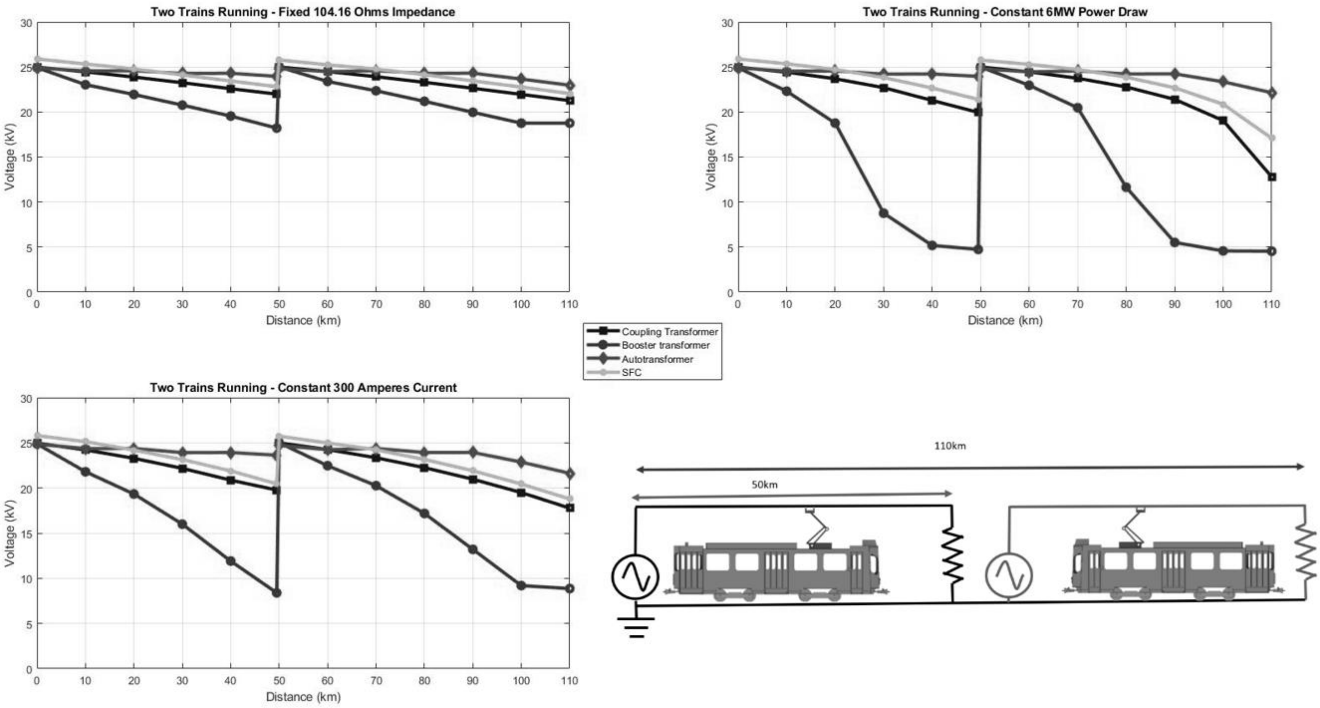


Fig. 5. OHLE Voltage profiles for two independent feeder stations (separated by a neutral section) and two trains in section.

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