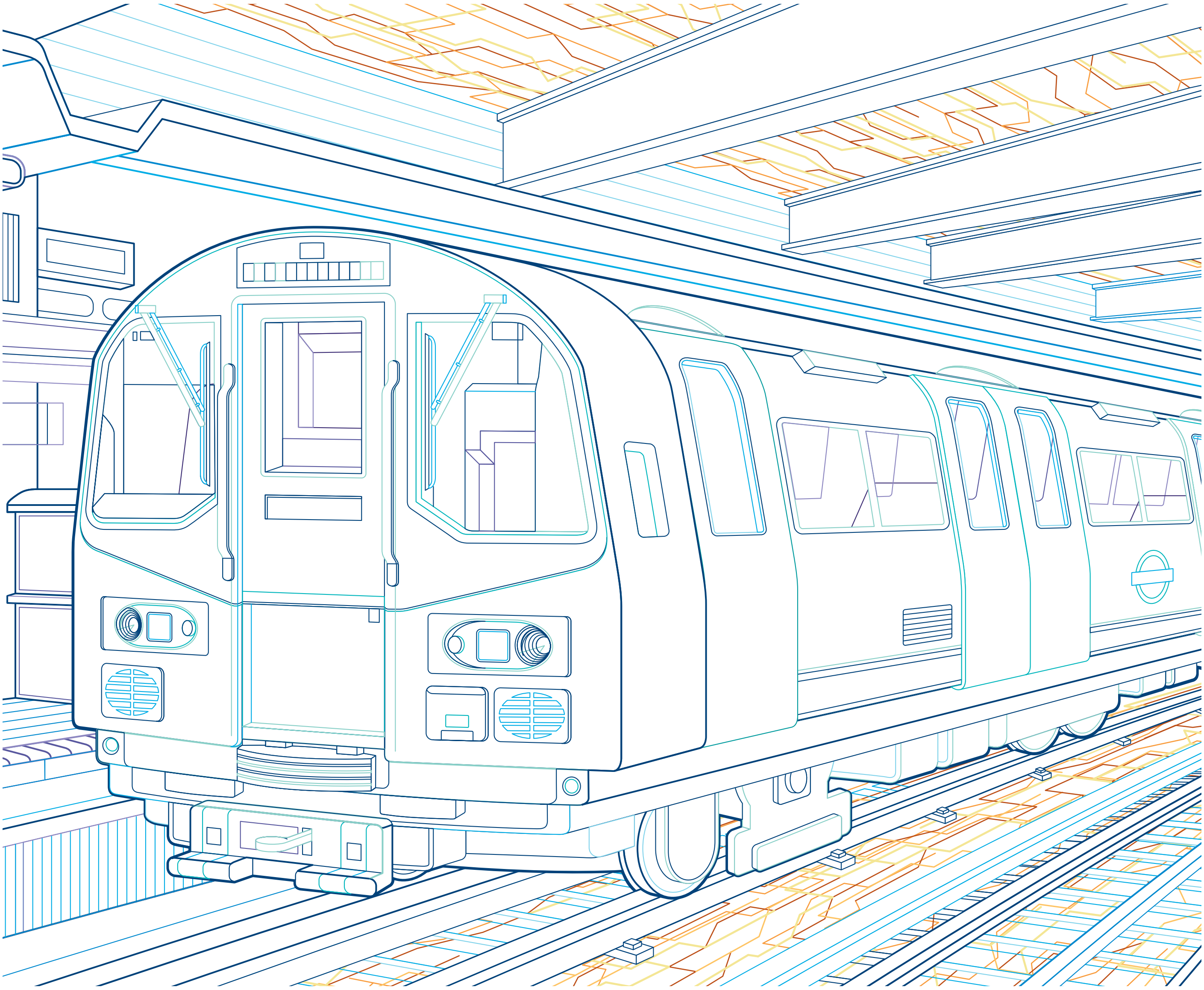
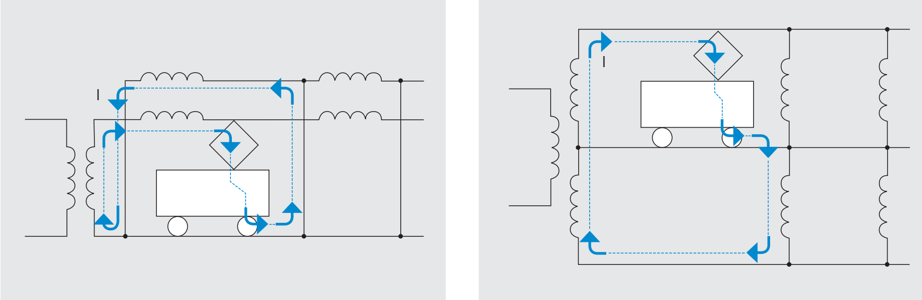


Knowing the FACTS

FACTS that enhance power quality in rail feeder systems

ROLF GRÜNBAUM, PER HALVARSSON, BJÖRN THORVALDSSON – The increase in traffic on existing tracks combined with new high-speed rail projects mean rail traction is fast becoming an important load on electric supply grids. This in turn is focusing a lot of attention on voltage stability as well as the power quality of the surrounding grids. Trains taking power from the catenary need to be sure the supply voltages are stable and do not sag. Voltage and current imbalances between phases of AC supply systems must also be confined in magnitude and prevented from spreading through the grid to other parts of the system. Voltage fluctuations and harmonics need to be controlled if they are to stay within the stipulated limits.

1 Two transformer schemes are used to supply high and efficient power



1a Booster transformer scheme

1b Auto-transformer scheme

There are several ways to feed traction systems with electric power. One scheme used in many traditional electrification systems is to supply it directly using the fundamental frequency main power, ie, 50/60 Hz. The transmission or sub-transmission voltages are then directly transformed by a power transformer to the traction voltage.

On the traction side any one of two transformer schemes can be used to supply high and efficient power: the booster transformer and auto-transformer schemes ➔ 1. In the booster transformer scheme, the main voltage is transformed into a single-phase catenary voltage. One end of the power transformer traction winding is grounded and the other is connected to the catenary wire. In the auto-transformer scheme, the traction winding is grounded at its midpoint. One end of the winding is connected to the catenary wire while the other end is linked to the feeder wire. In both schemes the grounded points are connected to the rail.

On the transmission network side the power transformer is connected between two phases. Frequently, two isolated rail sections are fed from the same feeder station, and in this case the power transformers are then connected between different phases.

Nowadays, the traction load, P_{load}, tends to be relatively large, often with power ratings between 50 MW and 100 MW per feeding transformer. These loads will create imbalances in the supply system voltage if they are connected between two mains phases. As a rule of thumb, if the fault level of the grid is represented by S_{ssc}, the imbalance, $U_{imbalance}$, is equal to

$$U_{imbalance} = \frac{P_{load}}{S_{ssc}}$$

A common requirement is that the negative phase sequence voltage resulting from an unbalanced load should not exceed one percent. Assuming loads of between 50 MW and 100 MW, the feeding system must have a short-circuit level of at least 5,000 MVA to 10,000 MVA if it is to stay within the imbalance requirements. In many cases the traction system is relatively far from strong high-voltage transmission lines. Weaker sub-transmission lines, however, normally run somewhere in the vicinity of the rail and can therefore be used to supply the rail in cases where an imbalance caused by the traction load can be mitigated.

Flexible AC transmission systems

Flexible AC transmission systems (FACTS) is a family composed of static devices that are controlled using state of the art computerized control systems in conjunction with high power electronics. One such device, the conventional static var compensator (SVC) as well as the more recently developed SVC Light® (STATCOM) can be used for imbalance compensation, ie, they serve as load balancers when used with special control algorithms. Load balancing is concerned with transferring active and reactive power between different phases ➔ 2.

SVC and SVC Light devices can also be used to dynamically support sagging catenary voltages and mitigate harmonics emanating from thyristor locomotives. In the case of SVC Light, a certain number of these harmonics can be removed by active filtering.

FACTS in rail traction

Power grids feeding railway systems and rail traction loads benefit enormously by using SVC and STATCOM. These benefits, listed in ➔ 3, reduce, if not eliminate, the investments needed to upgrade [1] the railway power feeding infrastructure.

FACTS devices in a system also enable adequate power quality to be achieved with in-feed at lower voltages than would otherwise be possible. This means, for example, that it may be sufficient to feed a railway system at 132 kV rather than at 220 kV or even 400 kV.

Load balancing by means of SVC

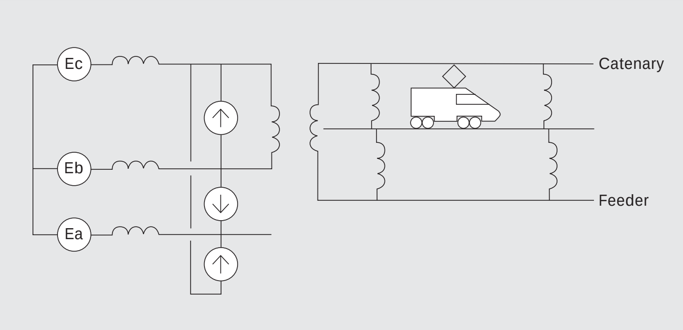
An SVC is a device that provides variable impedance, which is achieved by combining elements with fixed impedances (eg, capacitors) with controllable reactors. Surprisingly, this combination is capable of balancing active power flows ➔ 4. The reactors also have fixed impedances but the fundamental frequency component of the current flowing through them is controlled by thyristor valves, which results in apparent variable impedance. In ➔ 4, this type of reactor is known as a thyristor controlled reactor (TCR).

A TCR is a shunt (parallel) branch consisting of a reactor in series with a thyristor valve ➔ 5. The branch current is controlled by the phase angle of the firing

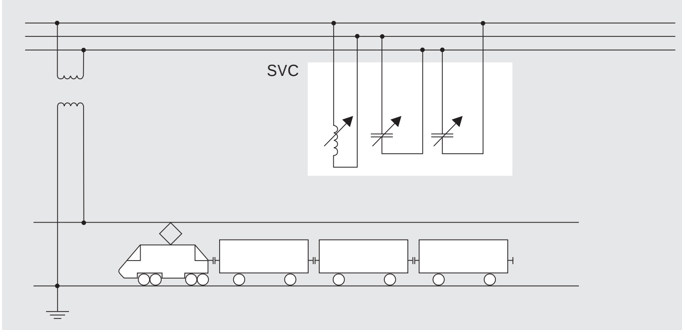
Footnote

1 Reinforcing would involve building new transmission or sub-transmission lines, substations and feeder points.

2 FACTS for load balancing



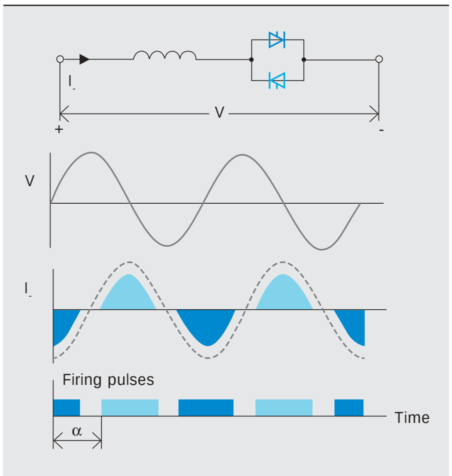
4 Load balancing and reactive power compensation by SVC



3 Benefits of using SVC and STATCOM

- Non-symmetrical loads fed from two phases of three-phase supplying grids are dynamically balanced.
- Voltage fluctuations in the feeding grids caused by heavy fluctuations of the railway loads can be dynamically mitigated.
- Harmonics injected into supply grids from traction devices can be eliminated.
- Regardless of load changes and fluctuations, power factor correction occurs at the point of common coupling. This means the power factor is high and stable at all times.
- SVC and STATCOM provide dynamic voltage support of catenaries feeding high power locomotives. This in turn prevents harmful voltage drops along the catenary and allows heavy traction capability to be maintained despite weak feeding. If an outage happens to occur at a feeding point, the locomotives will still receive adequate power. In fact the use of SVC and STATCOM may help reduce the number of feeding points required.
- From a power quality point of view, the feeding grid can be chosen with a lower voltage with FACTS, for example, 132 kV instead of 220 kV or higher.
- And finally, FACTS devices provide dynamic voltage control and harmonic mitigation of AC supply systems for DC converter fed traction (typically underground and suburban trains).

5 The fundamental principle of a thyristor controlled reactor (TCR)



pulses (firing angle control) to the thyristors, ie, the voltage across the reactor equals the full system voltage at a firing angle of 90 degrees and is zero at a firing angle of 180 degrees. The current through the reactor is the integral of the voltage; thus it is fully controllable between the natural value given by the reactor impedance and zero.

To address the issue of space as well as benefiting from advanced semiconductor technology, the thyristor valves make use of a bi-directional device, a semiconductor component which allows the integration of two anti-parallel thyristors in one silicon wafer. Using these thyristors reduces the amount of units needed in the valves by 50 percent ➔ 6. The thyristor is a five-inch device with a current handling capability of about 2,000 A (rms).

In the conventional SVC, load balancing is achieved when, by controlling the reactive elements, active power is transmitted between the phases. In its simplest form the load balancer consists of a TCR connected between two power supply phases and a fixed capacitor bank in parallel with a TCR connected between two other phases. Power factor correction is obtained by a fixed capacitor bank in parallel with a controlled reactor between the remaining two phases. Harmonics are normally suppressed by the addition of filters. These can be connected either in a wye (Y) formation or directly in parallel with the reactors.

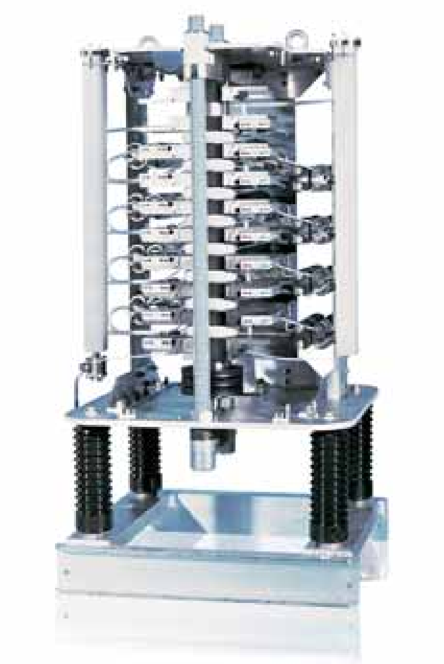
The control of the load balancer may be based either on the fact that three line-to-line voltages with the same magnitude cannot contain a negative phase sequence voltage or on a more sophisticated system that derives the different phase sequence components and acts to counteract the negative one. The control of the positive sequence voltage normally has a lower priority compared with that of the negative, ie, it is only fully controlled when the load balancer rating is large enough to allow for both balancing and voltage control.

SVC and the HS 1 rail link

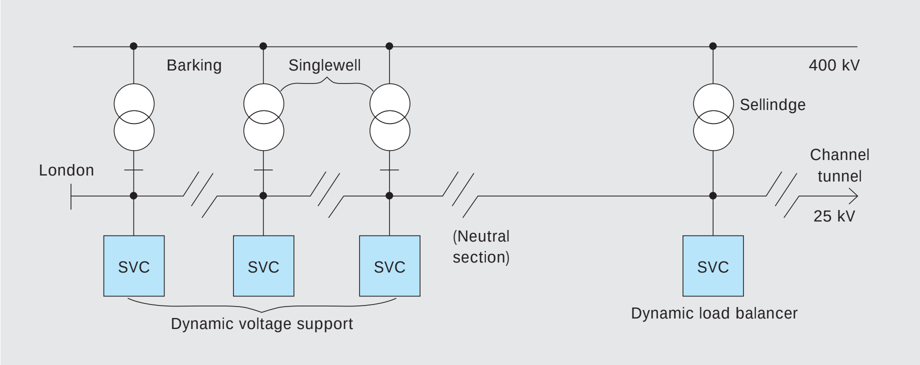
A total of seven SVCs were supplied to High-Speed 1 (HS 1), a 108 km high-speed rail line between London and the channel tunnel at Dover which was formerly known as the channel tunnel rail

The increase in traffic on existing tracks combined with new high-speed rail projects mean rail traction is fast becoming an important load on electrical supply grids.

6 A bi-directional control thyristor (BCT) valve

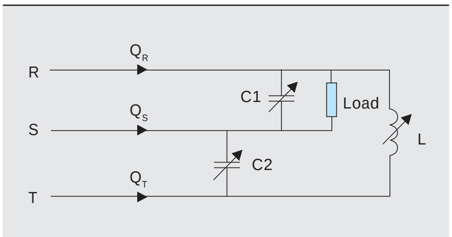


7 High-Speed 1 (HS 1) SVCs



8 HS 1 dynamic load balancer

9 Balancing an asymmetrical load



FACTs devices such as the conventional static var compensator (SVC) and SVC Light® (STATCOM) can be used for imbalance compensation, as well as for the dynamic support of sagging catenary voltages.

link (CTRL). With this link in operation, it is possible to travel between London and Paris in just over two hours at a maximum speed of 300 km/h.

Even though it is primarily designed for high-speed trains, HS 1 also accommodates slower freight traffic. As modern trains have power ratings in the range of 10 MW, the power feeding system must be designed to cope with large fluctuating loads. The HS 1 traction feeding system is a modern direct supply of 25 kV with a mains frequency of 50 Hz, and each of the three traction feeding points between London and the channel tunnel is supported by SVCs → 7. Direct transformation from the power grid via transformers connected between two phases is used, and the auto-transformer scheme is implemented to ensure a low voltage drop along the traction lines.

Dynamic voltage support

Six of the SVCs are used mainly for dynamic voltage support and are connected on the traction side of the power transformers. A seventh SVC is needed for load balancing. At three of the feeding points, one of two identical single-phase SVCs is connected between the feeder and earth and the other is connected between the catenary and earth.

There were three main reasons for investing in SVCs. The first and primary reason is to support the railway voltage in case of a feeder station trip. When this happens, two sections have to be fed from one station. It then becomes essential to keep the voltage up in order to maintain traction efficiency.

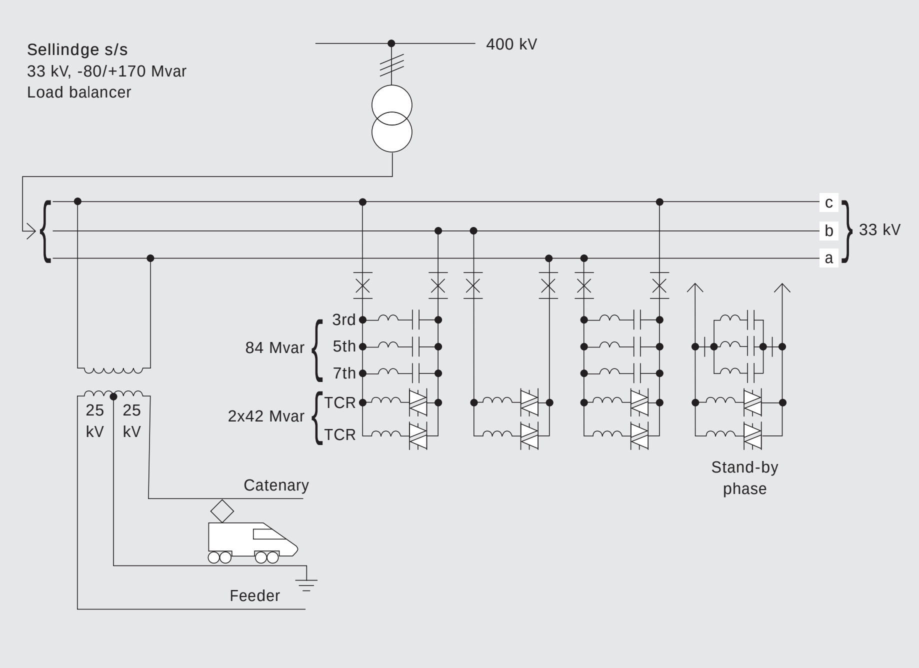
The second reason is to maintain unity power factor seen from the super grid transformers during normal operation. This ensures a low tariff for the active power consumed. And finally, the SVCs are installed to mitigate harmonic pollution. SVC filters are designed not only to accommodate the harmonics generated by the SVC but also those created by the traction load. There are stringent requirements on the allowed contribution from the traction system to the harmonic level at the connection points to the supergrid.

The SVCs operate in a closed-loop power factor control; an outage at a feeder station automatically changes operation to closed-loop voltage control.

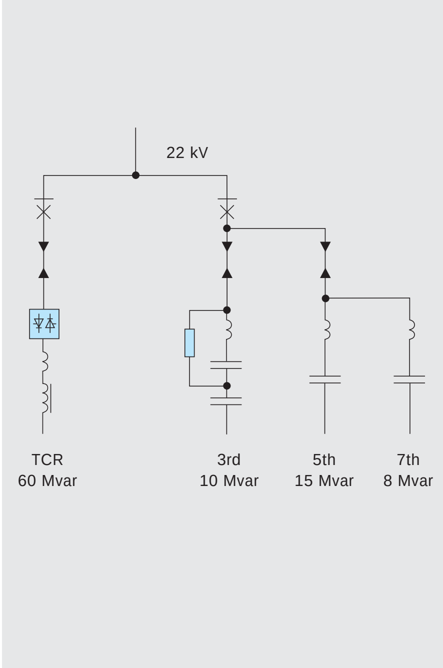
Load balancing

The traction load, with a power rating of up to 120 MW, is connected between two phases. Without compensation, this load would give a negative phase sequence voltage of about 2 percent. To counteract this imbalance, the load balancer, an asymetrically controlled SVC, was installed → 8.

10 A High-Speed 1 (HS 1) load balancer main scheme



11 A single-line diagram of a typical SVC used by the London underground



A load connected between two phases of a three-phase system can be made to appear symmetrical and have unity power factor – as seen from the three-phase feeding system – by applying reactive elements between the phases, as shown in → 9. The per-phase reactive powers can be related to a set of phase-to-phase reactive powers as follows:

$$Q_{RS} = Q_R + Q_S - Q_T$$

$$Q_{ST} = Q_S + Q_T - Q_R$$

$$Q_{TR} = Q_T + Q_R - Q_S$$

If a single-phase load consumes an active power P and a reactive power Q, the reactive values needed between the phases for total three-phase symmetry as well as unity power factor are given by:

$$Q_{C1} = Q$$

$$Q_{C2} = P/\sqrt{3}$$

$$Q_L = P/\sqrt{3}$$

In the case of comprehensive traction loads, the aggregate values of P and Q change substantially with time. By means of SVC, the effective phase-to-phase susceptances also become variable, thereby satisfying the above equations in all instances.

The load balancer schematic in → 10 is optimized to handle a load connected between the "a" and "c" phases. In accordance with load-balancing theory, to balance a purely active load, a reactor needs to be connected between the "a" and "b" phases and a capacitor between the "b" and "c" phases. The traction load has a reactive part which also needs to be balanced. Not only is the asymmetry compensated for, but the addition of a capacitor between the "c" and "a" phases also regulates the power factor to unity.

The load balancer is controlled to compensate for the negative phase sequence component present in the current drawn from the supergrid. Furthermore, the power factor is regulated to unity. The positive phase sequence voltage can also be controlled if the capacity is available. This depends, however, on the load balancer working point.

VSC and IGBT technologies have been brought together to create a highly dynamic and robust system with a high bandwidth known as SVC Light.

Connecting the London underground

In order to take power from the public grid, the London underground needed to close its old gas/oil-fired power plant at Lots Road. Because the underground load consists mainly of diode converters that feed DC current to the trains, special measures had to be taken to limit or even prevent disturbances, such as voltage fluctuations and harmonics, from reaching the public grid.[2]

In 2009, an SVC was commissioned for the 11 kV feeding grid to work together with several other SVCs in operation since mid 2000. This brings to six, the number of SVCs (as well as some standalone harmonic filters) that now operate at critical points of the London underground 22 kV and 11 kV grid. Space issues and their proximity to underground stations – and thus large groups of people – meant the SVC installations had to

Footnote

2 Extensive system studies were undertaken to map sources of distortion and identify the measures needed in order not to exceed the permitted disturbance limits at the points of common coupling.

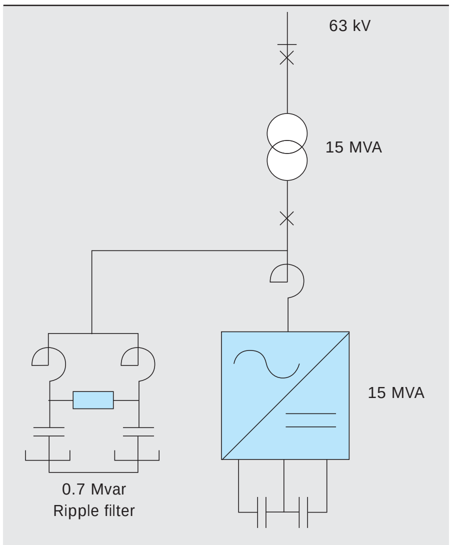
12 Categorizing the SVCs used in the London underground

Rated voltage, kV	Dynamic range, Mvar	TCR rating, Mvar	Quantity of SVCs
22	-27/+33	60	2
22	-37/+23	60	3
11	-16.5/+16.5	33	1

13 The TCR iron-core reactor arriving on site in London

14 An SVC showing the thyristor valve (left) and valve cooling system (right)

15 SVC Light single-line diagram



16 The IGBT valve hall at one of the French sites

The converter valve is suspended from the ceiling, and the DC capacitors and bus are shown in the foreground.

be compact and completed in such a way as to confine noise and magnetic fields. In fact the magnetic field must not exceed 1.6 mT at the boundary of any of the SVCs.[3] For these reasons, the SVCs use iron-core TCR reactors instead of the more common air-core reactors.

Typically, each SVC consists of one TCR and a set of harmonic filters that are individually tuned and rated ➔ 11. By means of phase angle control of the TCR, a continuous variable output, from maximum Mvar capacitive to maximum Mvar inductive reactive power, can be obtained from steady state. Harmonic filter arrangements vary from site to site, depending on the fault level of the feeding grid at each site and the harmonic requirements. The main parameters of the six SVCs can be sub-divided into different categories ➔ 12.

An iron core reactor arriving on site in London is shown in ➔ 13 and an on-site picture of an SVC is shown in ➔ 14.

With its ability to generate voltages of any amplitude and phase angle, SVC Light has what it takes to fulfil the role of a load balancer.

SVC Light

With the advent of controllable semiconductor devices capable of high power handling, voltage source converters (VSCs) with ratings beyond 100 MVA are now feasible. Now VSC [4] and insulated gate bipolar transistor (IGBT) technologies have been brought together to create a highly dynamic and robust system with a high bandwidth known as SVC Light, for a variety of power conditioning tasks in grids and beyond. Using pulse width modulation (PWM), an AC voltage almost sinusoidal in shape can be produced without the need for harmonic filtering.

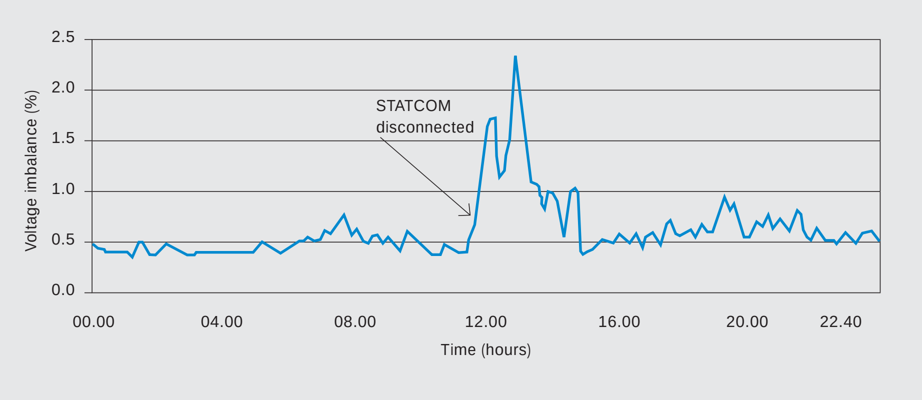
Balancing rail traction loads

With its ability to generate voltages of any amplitude and phase angle, SVC Light has what it takes to fulfil the role of a load balancer. By connecting the VSC to the grid, SVC Light can be treated as a synchronous machine in which the amplitude, phase and frequency of the voltage can be independently controlled. In addition, with high frequency PWM switching, the VSC is also capable of synthesizing a negative sequence voltage.

Compared to the classical SVC based on delta-connected TCRs for the same rated power, an SVC Light with phase-wise connected valves and a common DC link can compensate a train load that is √3 times larger. The delta-type connection is less efficent for balancing unsymmetrical active power than it is for symmetrical reactive power compensation. This difference does not exist if a phase-wise connection is used.

Two SVC Light installations are in operation in the French railway system. Both are fed from the national power grid, one at 90 kV and the other at 63 kV subtransmission levels. At both sites, SVC

17 Measurement of voltage imbalance (values taken every 10 minutes)



Light is used to dynamically balance the asymmetry between phases caused by the mode of traction feeding. In these cases, the thyristor locomotives are fed power from two phases of a three-phase grid. The locomotives generate harmonics which are then actively filtered by SVC Light. [5]

In → 15, the load balancer is rated at 63 kV, 15 MVA and can accommodate a

To meet the requirements of imbalance if SVC Light were not available, the supply network in-feed would have to be increased, which in turn would require the erection of new overhead lines and the upgrading of many substations.

single-phase active load of up to 16 MW. Its task is to confine grid unbalance at 63 kV to no more than 1 percent under normal network conditions and no greater than 1.8 percent for abnormal (N-1) network conditions. One double-tuned filter, tuned to the 40th and 51.5th harmonics, has been installed on the AC side. No passive harmonic filters are used on the 63 kV side. This gives a robust solution which can be applied to varying network configurations.

The second SVC Light installation is rated at 90 kV, 16 MVA to accommodate a single-phase active load size of up to 17 MW → 16. Its task is to confine the grid unbalance at 90 kV to no more than 1 percent for S_{ssc}≥600 MVA under normal network conditions and no greater than 1.5 percent for 300 MVA≤S_{ssc}≤600 MVA for abnormal (N-1) network conditions. Measurements taken since SVC Light was installed show a distinct improvement in voltage imbalance [1]. To be more specific, the voltage imbalance does not exceed 1 percent → 17.

SVC Light cost benefits

SVC Light offers not only a technically but also an economically advantageous solution [2]. To illustrate this point, suppose SVC Light is not available. Therefore, to meet the requirements of imbalance, the supply network in-feed would have to be transferred from 63 kV to 225 kV or 400 kV. This in turn would require the erection of new overhead lines as well as the upgrading of a number of substations currently supplied with 63 kV or 90 kV.

Rolf Grünbaum
Per Halvarsson
Björn Thorvaldsson
ABB Power Systems, Grid Systems/FACTS
Västerås, Sweden
rolf.grunbaum@se.abb.com
per.halvarsson@se.abb.com
bjorn.thorvaldsson@se.abb.com

Footnotes
3 Measurements have confirmed that this requirement has been fulfilled.
4 In the SVC Light, the VSC uses switching frequencies in the kHz range.
5 Active filtering is possible because of the high bandwidth inherent in the SVC Light concept. Active filtering occurs as long as there is the capacity to do so, for example, when the load is lower than the compensator rating.

References

[1] Courtois, C., Perret, J.P., Javerzac, J.L., Paszkier, B., Zouiti, M. (2006). VSC based imbalance compensator for railway substations. Cigré B4-103, 2006.
[2] Grünbaum, R., Hasler, J-P., Larsson, T., Meslay, M. (2009). STATCOM to enhance power quality and security of rail traction supply. ELECTROMOTION 2009, Lille, France.