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.
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 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 formers are then connected between different phases.

Nowadays, the traction load, \( P_{\text{load}} \), 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 \( S_{\text{ssc}} \), the imbalance, \( U_{\text{imbalance}} \), is equal to

\[
U_{\text{imbalance}} = \frac{P_{\text{load}}}{S_{\text{ssc}}}
\]

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 subtransmission 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.

Footnote

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

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.

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 asymmetrically controlled SVC, was installed → 8.
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 \(\rightarrow 9\). The per-phase reactive powers can be related to a set of phase-to-phase reactive powers as follows:

\[
Q_{RS} = Q_A + Q_S - Q_T \\
Q_{ST} = Q_S + Q_T - Q_A \\
Q_{TR} = Q_T + Q_R - Q_S
\]

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 \(\rightarrow 10\) 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.

**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 stand-alone 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.
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. 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. 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.

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

**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 and insulated gate bipolar transistor (IGBT) technologies have been brought together to create a highly dynamic and robust system 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 \( \sqrt{3} \) times larger. The delta-type connection is less efficient 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

<table>
<thead>
<tr>
<th>Rated voltage, kV</th>
<th>Dynamic range, Mvar</th>
<th>TCR rating, Mvar</th>
<th>Quantity of SVCs</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>-27/+33</td>
<td>60</td>
<td>2</td>
</tr>
<tr>
<td>22</td>
<td>-37/+23</td>
<td>60</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>-16.5/+16.5</td>
<td>33</td>
<td>1</td>
</tr>
</tbody>
</table>
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 single-phase active load of up to 16 MW.

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 $S_{ssc} \geq 600$ MVA under normal network conditions and no greater than 1.5 percent for $300$ MVA $\leq S_{ssc} \leq 600$ 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 increased, which in turn would require the erection of new overhead lines and the upgrading of many substations.

**References**
