FACTS: Powerful Means for Dynamic Load Balancing and Voltage Support of AC Traction Feeders

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Abstract—With increasing focus on economical as well as environmentally friendly means for mass transit, rail transport is getting renewed momentum in many countries. This means investing in novel rail infrastructure as well as upgrading and electrifying of existing facilities. The feeding of heavy rolling stock from AC grids will in many cases cause unacceptable voltage drops as well as unsymmetry between phases of the feeding grid. FACTS devices offer means of remedy, restoring grid symmetry as well as voltage stability. The paper treats dynamic load balancing of grids supplying power to rail transport, as well as dynamic voltage support, by means of Thyristor-controlled Var Compensation (SVC) as well as Voltage Source Converters (VSC).

Index Terms—Active filtering, Auto transformer scheme, Booster transformer scheme, IGBT, Load balancing, Power factor, Power quality, Pulse Width Modulation, Voltage flicker, Voltage Source Converter, Voltage support, Static Var Compensator, SVC Light.

I. INTRODUCTION

With growing importance of traction as load on electrical supply grids, aspects concerned with the efficiency of feeders (voltage stability) as well as power quality in surrounding grids need to be addressed in a new and serious way. Locomotives taking their supply from overhead or rail feeders must be sure to encounter voltages which are stable and do not sag, lest power be lost when most needed in the operating cycle of the loco. Voltage and current unbalances between phases of AC supply systems must likewise be confined in magnitude and prevented from spreading through the grid into other parts of the system, lest they become a nuisance to others.

II. FEEDING SYSTEM

There are a number of different ways to feed traction systems with electric power. One modern system used in many recent electrification projects is to directly supply it by the 50 Hz mains power. The transmission/subtransmission voltages are then directly transformed by a power transformer to the traction voltage. There are two competing systems on the traction side, the booster transformer scheme and the auto transformer scheme. In the booster transformer scheme (Fig. 1), the mains voltage is transformed into one single-phase voltage of 25 kV. One of the power transformer traction winding ends is earthed and the other end connected to the catenary wire. In the auto transformer scheme (Fig. 2), the traction winding is connected to earth on its midpoint. The other two ends of the winding are connected to the catenary wire and the feeder wire respectively. The earthed points are connected to the rail in both schemes.

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. In this case the power transformers are connected between different phases. The traction load is relatively large, today it is common with power ratings in the range of 50-100 MW per feeding transformer. These loads connected between two phases on the mains will create unbalances in the supply system voltage. By the role of thumb the unbalance is equal to

$$U_{unbalance} = \frac{P_{load}}{S_{nuc}}$$

A common requirement is that the negative phase sequence voltage resulting from unbalanced load should not exceed 1%. Assuming loads as above, the feeding system must have a short circuit level of at least 5000 to 10000 MVA to stay within the unbalance requirements. In many cases the traction system is relatively far apart from strong high voltage transmission lines, while weaker sub-transmission lines normally run somewhere in the vicinity of the rail. These lines can be utilised for the rail supply in case the unbalance caused by the traction load can be eliminated/mitigated. There are means available today by controllable high voltage power electronic equipment for unbalance compensation / suppression. Conventional Static Var Compensators (SVC) or the most recently developed Voltage Source Converters (SVC Light) can serve as “load balancers” by use of special control algorithms.
III. THEORY BEHIND LOAD BALANCING

The detailed mathematical description of unbalance compensators is found in APPENDIX. A conclusion is that load balancing is all about transferring active and reactive power between different phases. It is shown that the transfer of power can be performed by either conventional SVCs or SVC Lights.

IV. ASPECTS ON CONNECTION TOPOLOGY

There are two different ways to connect the traction load and the unbalance compensators to the power grid. The first one is to connect the traction power transformer directly to the grid and the load balancer with its power transformer to the same point of connection. The second alternative is to make use of an intermediate voltage level. In this case an ordinary three phase power transformer is connected to the grid. On the intermediate level the traction transformer and the load balancer (without power transformer) are connected.

The latter alternative has two major advantages: it is easier to control the harmonics both from the rail and the load balancer itself (conventional SVCs), and secondly it is more efficient in keeping the traction voltage at a constant level irrespectively of the traction load. Both features have the same origin, a relatively large inductance separates the intermediate level from the power grid. The impedance up to the grid makes it simple to trap harmonic currents in passive filters, as the filter circuit efficiently becomes a low impedance path compared with the power transformer and the network. In case the load balancer is connected directly to the grid, it is very difficult to trap the traction harmonic with a conventional SVC. The SVC Light, having active filters is equally efficient also in both positions. The intermediate voltage alternative makes it possible to choose a main transformer impedance sufficiently large to limit the short circuit currents to acceptable levels for the traction system and to have a traction transformer with a minimum of impedance. A stiff (low impedance) connection between the load balancer and the traction system makes it efficient also in maintaining a constant traction voltage. There are new power transformer schemes using insulated cables in their windings making it possible to keep the impedance to virtually zero.

V. LOAD BALANCING BY CONVENTIONAL SVC

An SVC is a device having a variable impedance. This is achieved by combining elements having fixed impedances such as capacitors and transformers with controlled reactors. The reactors themselves also have fixed impedances but the fundamental frequency component of the current through them is controlled by thyristor valves, giving an apparent variable impedance.

The branch current is controlled by phase angle control of the firing pulses to the thyristors, that is the voltage across the reactors is the full system voltage at 90 degrees firing angle and zero at 180 degrees. The current through the reactors is the integral of the voltage (Fig. 5), thus it is fully controllable with the thyristor valves between the natural value given by the reactor impedance and zero.

In the conventional SVC the load balancing effect is obtained by transmitting active power between the phases by control of reactive elements. In its simplest form the load balancer consists of a controllable reactor connected between two phases and a fixed capacitor bank in parallel with a controlled reactor 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 addition of filters. These can be either wye connected or connected directly in parallel with the reactors.

The control of the load balancer may be based on the simple fact that three line to line voltages having the same magnitude cannot contain 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.

VI. LOAD BALANCING BY SVC LIGHT

A system such as SVC Light, having the ability to generate voltages with any amplitude and phase angle, can realize the requirement necessary for a load balancer. Using a macroscopic approach of the Voltage Source Converter connected to a grid, it can be treated as a synchronous machine with controllable voltage. The voltage can be controlled both in amplitude, in phase and in frequency, with full independence between the three
attributes. In addition, the VSC modulated with high frequency Pulse Width Modulation (PWM), is capable of synthesizing also a negative sequence voltage. Fig. 6 shows a schematic picture of this approach. The VSC is here connected to the grid via a reactor $X$.

![Fig. 6. Schematic picture of the Voltage Source Converter (VSC) connected to a grid.](image)

The overall objective is to control the SVC Light current. This is accomplished by applying a controlled voltage across the reactor. If the reactance contains only inductance, $L$, the following relation between its voltage $u$ and current $i$ is valid:

$$i = \frac{1}{L} \int u dt$$

That is, the current is given by the voltage-time area applied across the reactor. In the figure below, the inner instantaneous control of a VSC is outlined.

![Fig. 7. Inner control loop of VSC.](image)

The current reference (from the outer control loop) is differentiated to form the output voltage reference, which in its turn is added to the bus voltage. The resulting voltage reference ($U_{VSC}$) is the waveform forming the input to the modulator (PWM or other). The modulated output voltage from the VSC will contain a replica of the fundamental component of $U_{VSC}$, and the desired current ($I_{VSC}$) consequently will represent the current reference. By feedback of the bus voltage the control loop is closed. The voltage-time area applied across the reactor gives the current. Thus this voltage-time area should be controlled such that the overall performance of the SVC Light is optimized. Several control objectives are of interest and can to a high degree be fulfilled simultaneously. The identified objectives are:

- compensation of unbalanced loads
- power factor correction
- compensation of voltage flicker
- active filtering of harmonics

In order to illustrate how the voltage source behaves we refer to the basic bridge connection that forms the converter. Refer to Fig. 8:

![Fig. 8. Basic Voltage Source Circuit (three-level NPC).](image)

The idea then is to create sinusoidal-like voltages at the three output terminals, from the assumed constant DC voltage across the capacitors, such that the current drawn by the converter circuit meets the identified objectives. The controllable elements in the circuit in Fig. 8 (the IGBTs) must alternately connect the phase output terminals to respective DC terminal, or to the midpoint between the capacitors. In doing so they will produce a square-wave type of waveform, as each IGBT constitutes a switch which can take two states, either conducting (as a short-circuit) or blocking (open circuit). It shall be noted that this voltage shall be generated independently of the phase relation of the current that will flow to the converter bridge. The diodes that are connected in anti-parallel to each IGBT will assure that there is always a path for the current to flow.

To show the function of the three-level converter, a simplified scheme is shown in Fig. 9. In the figure, all the valves have been changed into bi-directional switches that connect the phase outputs to one out of three potentials on the DC side. For this converter, the phase connections a, b and c can have the same potential as either the positive or the negative terminal of the DC side or its midpoint i.e. three possible values. Hence the name: three-level converter.

![Fig. 9. Simplified model of the three-level converter.](image)

The resulting waveforms for a three-level bridge are shown in Fig. 10 below. One of the fundamental properties of the VSC is its ability to control current by applying a voltage across a reactor. The VSC obtains the voltage from the DC side capacitor. An important aspect is, however, that the capacitor does not primarily work as energy storage. Instead, under balanced conditions, all switchings of semiconductors lead to currents being circulated within the three phases. Under unbalanced conditions, the DC side capacitor will be loaded with some 2nd harmonic currents.
From the above we should conclude that the VSC can synthesize a voltage including a positive sequence component and a negative sequence component. Equally important is the fact that we can use a principle of superposition and state that the two voltages can be treated separately. We can state that the positive sequence voltage is used to determine reactive power on the AC side. The voltage unbalances on the AC grids bus will be controlled by the negative sequence voltage.

The load current can be expressed by phase vectors. In case the load is connected between two phases (B & C) only, two phase vectors can express the traction current, one representing the positive-sequence and the second one representing the negative-sequence (see Fig. 11). The summation of the two vectors is the resulting current (current of phase A is zero and currents in phase B and C are of equal magnitude but phase opposed). Note that the vector amplitudes are not truly representative.

To compensate the negative-sequence and thus balance the current to be generated by the generator, the SVC Light generates a negative-sequence current as shown in Fig. 12. The SVC Light current \( I_{VSC} \) is a pure negative-sequence current.

The primary feedback to the controls is taken from the load. Out of the load current measurement, the current vectors representing the symmetrical reactive power and the negative sequence currents are calculated. Having extracted these vectors, we can rely on the “Internal Current Controller” to act such that we will generate current vectors from the VSC that are in phase opposition to the measured (reactive) load current vectors.

The apparent power drawn by the load is governed by the relation

\[
S = U_{+} x I_{+}^* + U_{-} x I_{-}^* + U_{0} x I_{0}^* \quad \text{(read vectorially)}
\]

Normally we can neglect the zero sequence term as the loads and the SVC Light all include zero sequence blocking transformers. If it is assumed that no active power can be handled by the SVC Light, its controls will assure that the output voltage is in phase with the industrial bus voltage. However, since the SVC Light generates significant negative sequence currents, also the term \( U_{-} x I_{-}^* \) will force a (small) active power to be drawn by the VSC. This active power will charge/discharge the DC capacitor, as no energy can be stored in the VSC converter itself. The SVC Light will automatically compensate for this such that a small positive sequence current (with a small phase shift versus the bus voltage) is generated in order to keep the DC voltage close to its nominal voltage. This DC voltage control loop has a very short response time.

VII. ACTIVE FILTERING

Beside the compensation of the negative sequence current generated by the load, the SVC Light is able to reduce the harmonic currents produced by the load and injected into the feeding network.

If the load produces harmonic currents, the SVC Light will inject currents such that the resulting current injected into the network contains exclusively current at the fundamental frequency.

To explain the principle of active filtering by the SVC Light, we will use a space vector representation. With this help, it is possible to represent a three-phase system in a single-phase equivalent form.

In Fig. 14, the voltages generated by the SVC Light, \( V_1 \ldots V_n \), the voltage at the Point of Common Coupling and the phase reactor determine the current of the SVC Light.
the case where the harmonic current of the SVC Light is equal to the harmonic currents of the load, then the current injected into the network is free of harmonics.

Fig. 14: Single-phase equivalent circuit.

To determine the voltages $V_1 \ldots V_n$, the load current is measured. The current components of interest in the load current, i.e. the negative sequence at fundamental frequency, the positive sequence and the negative sequence of the harmonics to be compensated are derived. The method consists of transforming the three-phase measured current to a rotating referential system, which rotates at a frequency equal to the frequency of the component to be extracted. In the rotating reference system, the DC component of the resulting signal contains the amplitude and phase of the harmonic to be extracted. This harmonic representation is transformed back to a non-rotating reference system.

A resulting current signal from the negative sequence of the fundamental component and of the harmonics are summed up to form the current reference. The current control computes the voltage reference from the current reference, the voltage measured at the Point of Common Coupling and the measured SVC Light current.

VIII. VOLTAGE SUPPORT

Besides load balancing, voltage support is of importance. The load balancers have the inherent capability to support the positive phase sequence voltage in addition to counteracting the negative one. The drawback is that the traction transformer between the compensated bus and the locomotives gives a voltage drop. In case voltage support is the primary objective, single phase SVCs can be connected directly to the traction system, i.e. between feeder and earth and between catenary and earth.

IX. DYNAMIC LOAD BALANCING: A CASE

A high-speed rail system is fed from the national grid. An SVC Light is utilized for dynamic balancing of unsymmetry between the phases caused by the mode of traction feeding, single-phase takeoff of power from a three-phase grid. The SVC Light also performs the task of active filtering of harmonics generated by thyristor and diode locomotives. Active filtering is enabled due to the high dynamic response inherent in the SVC Light concept.

To illustrate the SVC Light concept presented in this paper, a digital simulation of the power system shown in Fig. 15 is realized. The load is represented as a variable load, which includes harmonic current of orders 3, 5, 7 and 9. The initial load is 6 MW and a load step is simulated at $t = 50$ ms. The final load is 12 MW and it is assumed the amplitudes of the harmonics are proportional to the load. The system voltage is 90 kV. Fig. 15 shows the voltage at the Point of Common Coupling, the load currents, the SVC Light currents and the currents injected into the network.

Fig. 15 shows that the network currents are balanced and free of harmonics. For a load step, the load balancing is established within one half cycle of the fundamental.

Fig. 15. a) Voltages at PCC; b) Load currents; c) SVC Light currents; d) Network currents.

X. APPENDIX

The required power from the load balancer and the basis for its realisation are derived.

The voltages and currents in a three phase power system can be expressed in terms of zero, positive and negative phase sequence components,

$$I^0 = \frac{1}{3} [I_a + I_b + I_c]$$

$$I^+ = \frac{1}{3} [I_a + e^{\frac{2\pi}{3}} I_b + e^{-\frac{2\pi}{3}} I_c]$$

$$I^- = \frac{1}{3} [I_a + e^{-\frac{2\pi}{3}} I_b + e^{\frac{2\pi}{3}} I_c]$$

where the superscripts $+$ and $-$ stand for positive- and negative-phase sequence quantities respectively.

Let us consider a case with a traction load
Coupling. The power exchange with the three phase power positive sequence voltage at its Point of Common Assumption that the load balancer is connected to a pure sequence current in phase opposition to this system in order to create a balanced system. The load balancer has to create a pure negative phase sequence current. Therefore

\[ I^0 = 0 \]

\[ I^+ = \frac{1}{3} \left[ e^{j \frac{2\pi}{3}} - e^{-j \frac{2\pi}{3}} \right] I_b = \frac{1}{3\sqrt{3}} e^{j \frac{\pi}{6}} I_{load} e^{-j \frac{\pi}{2}} \]

\[ I^- = \frac{1}{3} \left[ e^{-j \frac{2\pi}{3}} - e^{j \frac{2\pi}{3}} \right] I_b = \frac{1}{3\sqrt{3}} e^{-j \frac{\pi}{6}} I_{load} e^{-j \frac{\pi}{2}} \]

The load balancer has to create a pure negative phase sequence current in phase opposition to this system in order to create a balanced system. Assume that the load balancer is connected to a pure positive sequence voltage at its Point of Common Coupling. The power exchange with the three phase power system then becomes

\[ S = V^+ I^+ + V^- I^- = V^0 + 0I^z = 0 \]

There is no active nor reactive power exchange with the power system on a three phase basis, i.e. active power does not have to be generated for load balancing. The positive sequence voltage is not affected as there is no reactive power exchange.

\[ S_a = V_a I_a^+ = V_{ia} e^{j(\pi - \phi)} I_{load} e^{-j(\pi - \phi)} = \frac{S_{load}}{3} e^{-j(\pi - \phi)} \]

\[ S_b = V_b I_b^+ = V_{ib} e^{-j\frac{\pi}{3}} I_{load} e^{j\frac{\pi}{3}} = \frac{S_{load}}{3} e^{-j\frac{\pi}{3}} \]

\[ S_c = V_c I_c^+ = V_{ic} e^{-j\frac{\pi}{3}} I_{load} e^{j\frac{\pi}{3}} = \frac{S_{load}}{3} e^{j\frac{\pi}{3}} \]

It can be noted that load balancing is to transfer active and reactive power between the phases. Note that the sum of the powers is equal to zero.

**Realisation**

SVC Light consists of three independent voltage sources behind reactances. The currents shown can easily be realised by adjusting the magnitudes and angles of these sources to appropriate values according to the above. The conventional SVC consists of purely reactive elements connected between phases. The line currents are

\[ I_a = [I_{ab} - I_{ca}] \]

\[ I_b = [I_{bc} - I_{ab}] \]

\[ I_c = [I_{ca} - I_{bc}] \]

Assuming a balanced system the line powers become

\[ S_a = V_a \left[ Q_{ab} e^{-j\frac{\pi}{2}} - Q_{ca} e^{j\frac{\pi}{2}} \right] \]

\[ = \frac{1}{3\sqrt{3}} \left[ -Q_{ab} - Q_{ca} \right] e^{-j\frac{\pi}{2}} \]

Similarly,

\[ S_b = \frac{1}{2\sqrt{3}} \left[ -Q_{bc} + Q_{ab} \right] e^{-j\frac{\pi}{2}} \]

\[ S_c = \frac{1}{2\sqrt{3}} \left[ -Q_{ca} + Q_{bc} \right] e^{j\frac{\pi}{2}} \]

It can be seen from the equations that a conventional SVC transfers active as well as reactive power and subsequently has the ability to work as a load balancer.

**XI. REFERENCES**


**XII. BIOGRAPHIES**

**Rolf Grünbaum** was born in Gothenburg, Sweden, on November 26, 1944. He received his M.Sc. degree in Electrical Engineering from Chalmers University of Technology, Gothenburg, Sweden in 1970. He is currently working for ABB Power Systems within its AC Systems Division at Vasteras, Sweden, where he is Area Manager of Marketing of FACTS and Reactive Power Compensation Systems.

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