Power Control of AC-Supplied Rail Vehicles

This note provides a basic introduction to the concept of using a 4-quadrant converter for controlling the power flow to (or, in the case of regenerative braking, from) a locomotive or another railway vehicle that is supplied from an AC electrified overhead line, while at the same time controlling the line voltage to be within the normal limits.

1 Fundamentals

1.1 Introduction: A DC System

Consider first the very simple electric circuit in figure 1. This circuit consists of two DC sources, one of which is variable, that are interconnected via a resistor. Both sources are ideal such that they accept currents in either direction.

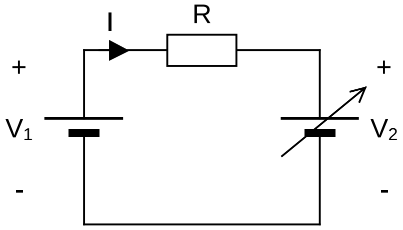


Figure 1. Circuit model for DC power flow analysis.

There are three possible cases:

$V_2 < V_1$: The current I is positive, i.e., it flows in the direction indicated by the arrow. The right-hand-side source receives the power $P_2 = V_2 \cdot I$

$V_2 = V_1$: The current is zero, and no power is transferred

$V_2 > V_1$: The current I is negative, i.e., it flows in the opposite direction as indicated by the arrow. The right-hand-side source delivers the power $P_2 = V_2 \cdot I$

In other words, the power flow is controlled by controlling the amplitude of the variable DC source. The magnitude of the current is simply governed by Ohm's law:

$$I = \frac{V_1 - V_2}{R}$$

This of course is very basic, but things immediately get more complicated with the voltage sources being AC rather than DC.

1.2 The AC Circuit Model

The premises for the AC analysis are that:

- The left-hand-side voltage source V_1 has constant amplitude and constant frequency
- The right-hand-source V_2 operates (at steady-state) with the same frequency as V_1, but the amplitude and the phase angle of its voltage can be controlled independently.
- The two sources are interconnected not simply by a resistor but a complex impedance. Practically, this impedance is resistive-inductive, i.e., $\underline{Z} = R + jX$

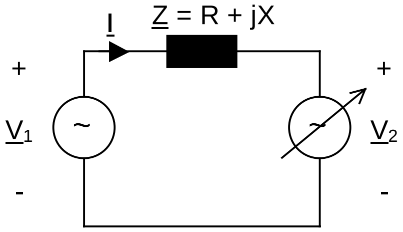


Figure 2. Circuit model for AC power flow analysis.

The current flow is still governed by Ohm's law, but now in its complex form:

$$\underline{I} = \frac{\underline{V}_1 - \underline{V}_2}{\underline{Z}}$$

Figure 3 shows an example of the phasor diagram of this circuit

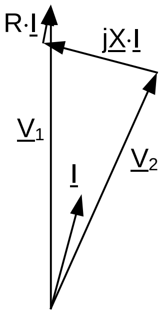


Figure 3. Phasor diagram

In this example, $\underline{V}_2$ has lower amplitude and a lagging phase angle compared to $\underline{V}_1$. This means that V_1 supplies active power to R and to V_2, and most of the reactive power to X. V_2 supplies the remaining reactive power to X – the current $\underline{I}$ leads $\underline{V}_2$.

1.3 AC Power Flow Cases

The fact that the amplitude and the phase angle of V_2 can be controlled independently means that the number of cases for the power flow becomes much higher, compared to the DC case. Figure 4 below summarises some typical cases. The comments about the AC-supplied locomotive are further developed and illustrated in section 3.

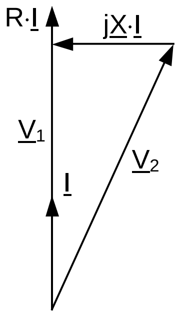
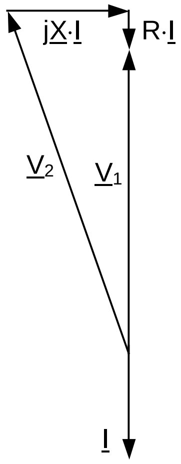
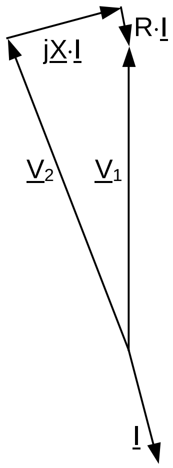
Case	Characteristics	Phasor diagram
1	$\underline{V}_2$ is controlled such that $\underline{V}_1$ and $\underline{I}$ are in phase, i.e., V_1 supplies only active power to R and to V_2, while all of the reactive power for X is supplied by V_2. This is the normal situation of an AC-supplied locomotive in driving, with V_1 being the line voltage at the pantograph, and V_2 the voltage of the 'inner' voltage source of the locomotive (i.e., the 4-quadrant converter).	
2	The amplitude of $\underline{V}_2$ is increased, and its phase angle advanced in front of $\underline{V}_1$ such that $\underline{V}_1$ and $\underline{I}$ are in counter-phase. V_2 supplies all active and reactive power. This is the normally the situation of an AC-supplied locomotive in regenerative braking.	
3	In case the amplitude of $\underline{V}_2$ cannot be increased as high as shown in case 2, $\underline{V}_1$ and $\underline{I}$ will not be in perfect counter-phase. This means that V_1 will supply part of the reactive power. This is a normal situation if an AC-supplied locomotive brakes regenerative on long and/or weak supply lines.	

Figure 4. Some AC power flow cases.

2 The 4-Quadrant Converter, a Variable Voltage Source

A suitable device that can perform independent control of the amplitude and the phase angle of a single-phase AC voltage, and which at the same time can handle power flow in either direction, is found in the 4-quadrant converter, or 4QC for short.

The 4QC consists of two bridge-coupled phase legs equipped with IGBTs or another type of switchable semiconductors. The phase legs are supplied from a constant DC voltage. By turning on one or the other of the IGBTs in a phase leg, its mid point is effectively connected to either the positive or the negative DC supply pole.

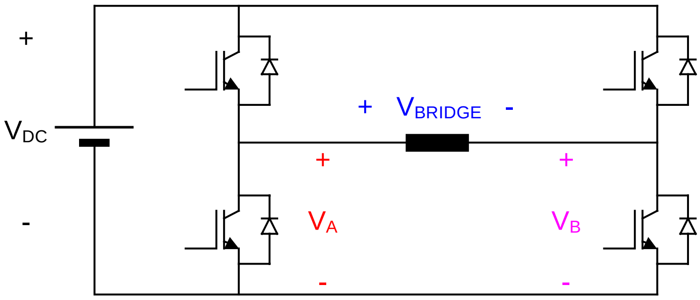


Figure 5. 4-quadrant converter.

Figure 6 below shows the principles of voltage generation by means of the 4QC, a process known as sinusoidal Pulse Width Modulation or PWM.

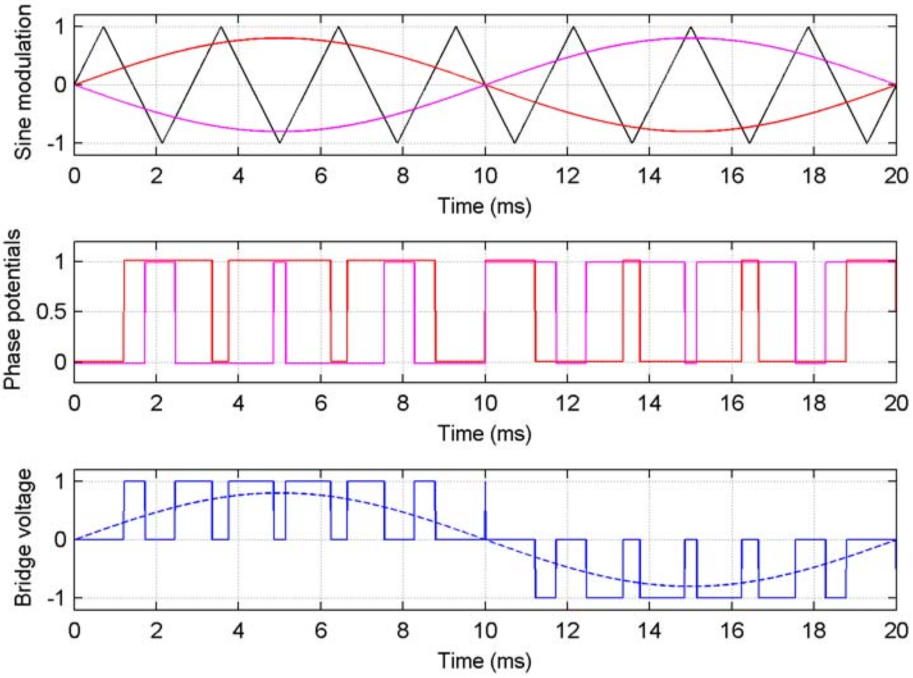


Figure 6. 4QC voltage generation. Upper plot: Reference voltages, phase A (red) and phase B (pink), and triangular modulation carrier. Middle plot: Phase voltage potentials V_A (red) and V_B (pink). Lower plot: Bridge voltage, with 1st harmonic.

A sinusoidal reference signal that corresponds to the desired output voltage, as well as its inverted signal (red and pink curves in the upper plot of figure 6, respectively), is compared to a triangular carrier signal. The intersections determines the switching points of the IGBTs, such that the upper IGBT in a phase leg is turned on when the corresponding reference exceeds the carrier, and vice-versa. This produces the phase leg voltages seen in the middle plot.

The lower plot shows the resulting voltage between the two phase legs, i.e., the output voltage of the 4QC bridge. The fundamental of this voltage is equal to the reference voltage, i.e., the 4QC can in principle generate any desired voltage.

When used in a locomotive, the 4QC is connected to the secondary side of the main transformer. The DC supply is made up by the intermediate DC link of the converter system.

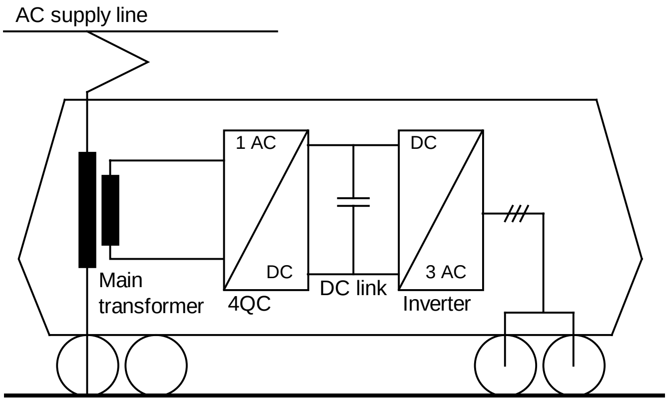


Figure 7. Locomotive converter system.

Practically, it is common to use a number of 4QCs in parallel, by means of a main transformer with multiple secondary windings and a 4QC connected to each winding.

3 Power Control and System Performance Considerations

This section develops the analysis of section 1.3, looking at the power control strategies that can be adopted in a railway environment. In particular, the performance at long and/or weak supply lines is discussed.

Figure 8 shows the components of a generic AC electrified railway system, including the substation, the impedance of the overhead supply line, and the locomotive.

The locomotive is characterised by the (mainly inductive) leakage impedance of the main transformer, and by the 4QCs.

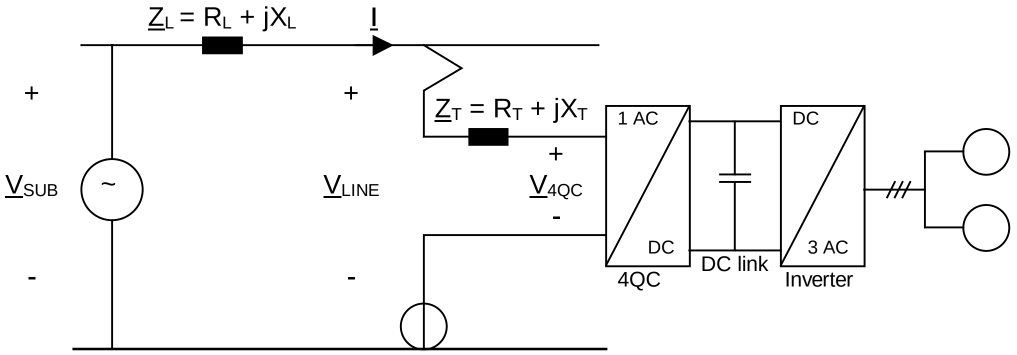


Figure 8. Generic AC-AC railway system.

3.1 Operation at Unity Power Factor

It is common to operate the 4QC in such a way that the power factor locally at the locomotive is as close as possible to one, i.e., such that the locomotive acts as a pure resistive load at the fundamental in driving (or motoring), and as an ideal generator in regenerative braking.

The phasor diagrams corresponding to these situations are shown in figure 9 below, for driving (left) and regenerative braking (right). The amplitudes of the substation voltage and of the current are equal in the two figures.

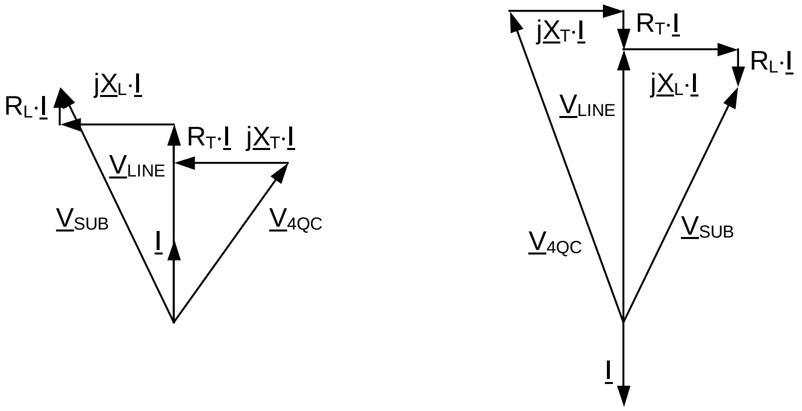


Figure 9. Phasor diagram driving (left) and regenerative braking (right), unity power factor at the locomotive.

3.2 Operation at Non-Unity Power Factor

The right-hand-side diagram in figure 9 illustrates the problem of regenerative braking, namely the increased line voltage locally at the locomotive, and in particular the very high voltage that must be generated by the 4QC. However, one can easily overcome this problem by controlling the 4QC in such a way that the locomotive consumes a small amount of reactive power while regenerating active power.

The phasor diagram corresponding to this situation is shown as III in figure 10 below. In this way, the line voltage at the locomotive can be kept at the same level as the substation voltage, even at full regeneration.

This way of operating the 4QC is commonly used on the comparably weak 16 2/3 Hz railway lines in Scandinavia.

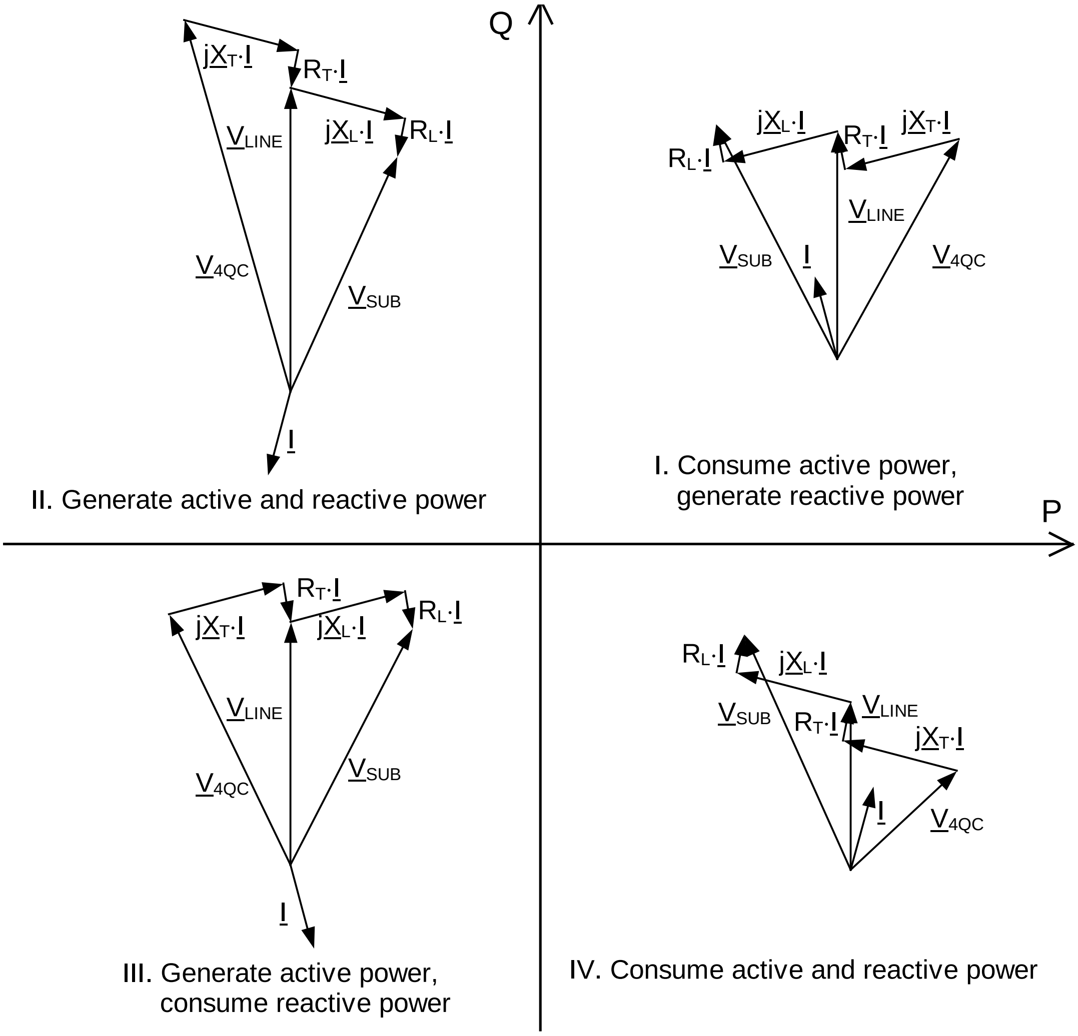


Figure 10. Phasor diagrams at non-unity power factors.

Diagram I in figure 10 shows the interesting option of phase compensating the mainly inductive supply line by means of the locomotive. Operating the 4QC in this way will dramatically increase the power that can be transferred to the locomotive; however, certain types of line protection relays are not compatible with this operation. In addition, the components of the locomotive must be designed for the increase of reactive power that is supplied by the DC link filter.

The diagrams II and IV are clearly not recommendable ways of operating the 4QC.