A GENERALIZED CONTROL SCHEME FOR ACTIVE FRONT-END MULTILEVEL CONVERTERS

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ABSTRACT: A generalized control scheme that allows the operation as an active filter and/or frequency changer in active front-end multilevel converters is proposed and analyzed in this paper. The basics characteristics of the proposed control scheme is that permits the operation of the converter in four quadrants, giving full control on the active and reactive power and current harmonics absorbed by the converter. The control scheme is designed for the application in multilevel converters. The control scheme is described in terms of principles of operations, and the operation in the four quadrant regions. Simulated results are proved in a laboratory prototype of 10 kVA.

I.- INTRODUCTION

Multilevel active front-end converters have proved to be a viable solution for medium voltage static power conversion [1] – [3]. The series connection of multiples dc voltage sources in the dc bus allows the operation in medium voltage systems, with lower voltage stresses across each semiconductor switch [4], in both cases as a rectifier or as multilevel inverter. Moreover, the multi-step composition of the output voltage (for the inverter), or the input current (for the rectifier) presents lower THD factors as compared with the two levels converter, due to the presence of multiple steps in the respective waveforms. The main application of this converter topology has been found in ac drives and also in reactive power compensators.

A lot of research has been carried out during the last decade trying to optimized the converter topology making possible the implementation of a larger number of levels, and the development and implementation of new PWM techniques to improve the overall converter performance [5] – [6]. Most of this research has been oriented for the specific operation as active front-end rectifiers or as multilevel inverters. Special attention has been paid to the control and balance of the dc bus voltage [7], since the presence of two or more electrolytic capacitors connected in the converter dc bus, requires a special treatment so they can share the same voltage under steady-state and transient operating condition. The operation with unbalanced voltage in the dc bus affects the converter performance due to the generation of uncharacteristics harmonics, and the presence of overvoltages across the semiconductor switches.

The power circuit topology of the three-level active front-end converter employed in this paper is shown in Fig. 1. 

![Fig. 1. The power circuit topology of the tree-level active front-end converter.](image)

The generalized control scheme proposed in this paper allows the operation of the active front-end converter in the four quadrant of the P-Q plane. The principal advantage of this characteristic is that allows the converter to operate as a rectifier or as an active power filter, or both at the same time. In the rectification mode the converter can operate as a frequency changer supplying active power from the dc bus to an output inverter, while keeping the input current sinusoidal and with unity power factor. As an active power filter, the active front-end rectifier...
operates as a controllable current source injecting the current harmonics required by non-linear loads. In this type of application, the voltage across each electrolytic capacitor remains constant and balanced even under severe dynamic operating conditions. However, the most important characteristic of the proposed control scheme, is that allows the operation as a frequency changer (or active front-end rectifier), while it compensates for current harmonics and reactive power required by the distribution system. Moreover, the converter control scheme only senses the system current and voltage waveforms to generate the required reference signals, thus reducing the number of components and the simplicity of the control topology.

In this paper, the proposed control scheme is discussed in terms of principles of operations for steady-state and transient operating conditions, as a frequency changer and active power filter respectively. Finally, simulated results are proved on a 10 kVA laboratory prototype.

II.- PRINCIPLES OF OPERATION

Control requirements of multilevel converters depends on their applications. Basically, the control scheme is responsible of the input current and output voltage waveforms, and also on the amount of active and reactive power interchanged with the power distribution system. In case of active power filter application, the control scheme must be able to keep the dc voltage constant and equal in each electrolytic capacitor. This function is important and not easy to achieve since it depends on the capacitor value, and on the dynamic response of the control scheme. As an active front-end rectifier, the control scheme must supply the adequate active power to the dc bus, keeping the dc voltage constant and the input current waveform sinusoidal and with unity power factor.

The proposed control scheme must perform two important duties. The first one is to keep the dc bus voltage constant, balanced and equal to a defined reference value, and the second one is to force the power distribution system current to be sinusoidal and in phase with the respective phase-to-neutral voltage, independently of the load value connected to the dc bus. For these reasons, the active front-end converter can operate as a rectifier (in case it has a load connected to the dc bus), or as an active filter (in case no load is connected to the dc bus). Moreover, when the active front-end converter operates as a rectifier, it forces the system line current to be sinusoidal and in phase with the respective phase to neutral voltage, which means that is also operating as an active power filter. The block diagram of the proposed control scheme is shown in Fig. 2. The advantage of this control scheme is that does not require to decouple active and reactive power neither to obtain the load current harmonic components that need to be eliminated.

Figure 2 shows that the control scheme has basically two blocks. The first one keeps the dc bus voltage constant and balanced, while the second one is in charged of forcing the power distribution line current to be sinusoidal and with unity power factor.

It is important to note that the dc voltage control system must perform two functions simultaneously: the first one is to keep the dc bus voltage constant and equal to a given reference value, and the second one is to maintain the voltage across each electrolytic capacitor constant and balanced. The voltage across each capacitor is equal to the total dc bus voltage divided by the number of capacitors.

Figure 2 shows that the dc bus voltage is controlled by adjusting the amount of active power absorbed by the active front-end converter, while the balance across each capacitor is achieved by changing the amplitude of each triangular carrier waveforms. Finally, the gating signals of the active front-end converter are obtained by comparing the error current signal with two carrier triangular waveforms, with fixed frequency and variable amplitude, as shown in Fig. 3.

![Fig. 3. Generation of gating signals by comparing the current error signals with two triangular carrier waveforms with fixed frequency and variable amplitude.](image-url)
The modification of the triangular carrier waveform amplitudes allows to control the voltage across each electrolytic capacitor, keeping them constant, balanced and equal to a given reference value. In order to achieve that goal the difference between the voltages across each capacitor \((V_{C1} - V_{C2})\) is compared with the difference voltage reference (which must be equal to zero), and the generated error signal is used to modify the triangular carrier waveforms amplitudes. The procedure used to change the triangular waveforms amplitudes is shown in Fig. 4.

![Fig. 4. The algorithm used to generate the triangular carrier waveforms.](image)

The two triangular carrier waveforms are in phase and their amplitudes are complementary modified following the magnitude of the differential dc voltage controller \((M_{Vc-R})\). In that way, when a voltage across one capacitor must be increased, the amplitude of the respective carrier waveform increases, while the complementary one is reduced in the same proportion. On the other hand, if the voltage across one capacitor must be reduced, the respective carrier waveform is decreased, and the complementary one increased in the same proportion. Since the total dc voltage is kept constant by another control loop, the changes in the voltage across each capacitor is such that the total dc voltage is always constant.

The six different possible gating states for one leg of the active frond-end converter are shown in Fig. 5.

![Fig. 5. Different gating combinations of the converter active front-end converter one leg.](image)

The effect of changing the amplitude of the triangular carrier waveforms is reflected in the number of intersection of this signal with the respective current error waveform. The larger the amplitude of the carrier waveform the more number of intersection with the current error will exist, and therefore the voltage across this capacitor will increase. The opposite effect occurs if the amplitude of the triangular carrier waveform is decreased.

### III.- SIMULATED RESULTS

In order to validate the analysis presented in the previous section, the control scheme was tested by simulation obtained with the PSIM software. The control scheme is proved for the operation as a pure active power filter, as an active front-end rectifier, and both at the same time. In this last case an unbalanced resistive load is connected in parallel to the dc bus voltage.

In all the simulated conditions, the active front-end converter was tested with the following parameters:

- Synchronous link reactor: 2 mH
- Dc capacitor: 3000 uF
Van: 268.7 V
R1 = 50 Ω
R2 = 35 Ω

3.1 - Operation as an Active Power Filter

Simulated waveforms shown in Fig. 6 illustrate the operation of the proposed control scheme while the active converter operates as an active power filter. The voltage across each capacitor is forced to be equal to 400 V. At the beginning of the operation, the control that keeps the voltage across each capacitor balanced is not operating, at t = 0.1 s this module is activated. At t = 0.2 s the phase angle of the nonlinear load is changed from $\alpha = 45^\circ$ to $0^\circ$, and finally, at t = 0.3 s the firing angle of the nonlinear load is changed from $\alpha = 0^\circ$ to $45^\circ$.

![Waveforms](image)

Fig. 6. Simulated results for the operation as an active power filter. (a) Phase-to-neutral source voltage ($V_{an}$) and respective system line current ($I_a$). (b) Voltage across the upper capacitor ($V_{C1}$). (c) Voltage across the lower capacitor ($V_{C2}$). (d) Load current ($I_{a1}$). (e) Current generated by the active front-end converter.

The waveforms shown in Fig. 6 demonstrate the effectiveness of the proposed control scheme, for the operation as an active power filter. The transient response can be checked by observing the dc voltage behavior during the changes of the nonlinear load. It is clear that the power distribution line current is sinusoidal and in phase with the respective phase to neutral voltage (Fig. 6-a), even during transient changes in the load currents. Also, it is possible to see how the voltage across each capacitor remains constant after the perturbation is applied. Moreover, after the voltages stabilize, the final value in each capacitor is equal to 400 V. It is clear that the control scheme is operating as it was expected.

3.2 - Operation as an active front-end converter

In this case an unbalanced resistive load is connected at the dc bus terminals. The two resistances are not equal, just to enhance the capability of the control scheme to force the voltage to remain equal to 400 V. The resistor values are equal to 50 Ω ($R_1$) and 35 Ω ($R_2$). The simulated waveforms for this operating conditions are shown in Fig. 7.

![Waveforms](image)

Fig. 7. Simulated results for the operation as an active front-end converter and active power filter simultaneously. (a) Phase-to-neutral source voltage ($V_{an}$) and respective system line current ($I_a$). (b) Voltage across the upper capacitor ($V_{C1}$). (c) Voltage across the lower capacitor ($V_{C2}$). (d) Load current ($I_{a1}$). (e) Current generated by the active front-end converter.

The operating conditions for this case are similar to the one presented previously. At the beginning the converter operates without the voltage differential control scheme, which is activated at t = 0.1 s. Once this control starts working the dc voltages stabilizes in less than 40 ms. At t = 0.3 and 0.4 s the nonlinear load changes the amount of active power required. It can be observed that the power distribution line current remains sinusoidal with unity power factor all the time.

It is important to note that in this case the active front-end converter also supplies real power to the two resistors of 50 and 35 Ω connected to the dc bus. This is one of the most important feature of this control scheme, since the figures prove that it is possible to compensate current harmonics and the reactive power required by the nonlinear load, and to supply the active power to the dc bus. This gives the possibility to operate in the four quadrants, taking full advantage of the power converter capabilities.

IV.- EXPERIMENTAL RESULTS

In order to prove the viability of the proposed control scheme, a 10 kVA laboratory prototype was
implemented and tested for different operating conditions. Steady-state and transient current and voltage waveforms are shown in the following figures.

![Waveform Image](image1)

Fig. 8. Experimental results for nonlinear load compensation. (a) Nonlinear load current and respective phase-to-neutral voltage. (b) Source current and respective phase to neutral voltage.

Figure 8 shows experimental waveforms obtained when the active front-end converter is operating only as active power filter. Figure 9 (b) illustrates the effectiveness of the control scheme, since the source line current is almost sinusoidal.

The operation as an active front-end rectifier and active power filter simultaneously is proved by connecting two resistances to the dc bus of 75 and 150 Ω respectively, while compensating at the same time the current harmonic components generated by a 6 pulse controlled rectifier. The current and voltage waveforms are shown in Figs. 9 and 10.

In Fig. 9 (b) the effectiveness of the dc voltage control loop is demonstrated. At the beginning the differential voltage control scheme was not operating, and the voltages across each capacitor was different. At t = 235 ms, the differential voltage control scheme was activated, and after 80 ms the two voltages reach equilibrium and the voltage difference across them becomes zero.

![Waveform Image](image2)

Fig. 9. Experimental results for nonlinear load compensation and operation as active front-end rectifier. (a) Source current and respective phase to neutral voltage. (b) Voltage across each dc capacitor.

![Waveform Image](image3)

Fig. 10. Experimental current waveforms for the operation as an active power filter and front-end rectifier simultaneously. (a) Nonlinear load current. (b) Active front-end converter input current. (c) Source line current.

Finally, Fig. 10 proves that the control scheme is able to allow the operation of the multilevel converter as an active power filter and rectifier simultaneously. The harmonics current components required by the nonlinear load are generated by the converter, while it also able to supply active power to its dc bus.
V.- CONCLUSION

A generalized control scheme that allows the operation as an active filter and/or frequency changer in active front-end multilevel converters was proposed and analyzed in this paper. The basics characteristics of the proposed control scheme is that permits the operation of the multilevel converters in four quadrants, giving full control on the active, reactive power and current harmonics absorbed simultaneously by the active front-end converter. Simulated results were proved on a laboratory prototype of 10 kVA.

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