A review of AC Choppers

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Abstract

AC choppers are a family of ac-to-ac power converters that can be derived from the traditional dc-to-dc converters. Research activity in this kind of converter has recently increased in applications for power conditioning—such as voltage control in the distribution system and power flow control in the transmission system—as an alternative for the dc-link approach compensators based on voltage source converters. The control is simpler and the power rating of the devices is smaller for compensators with the same power rating; the main drawback is they cannot control the output-voltage frequency as the matrix converter.

This paper presents a state-of-the-art review on the development of ac-choppers. The principle of operation is explained by using the six switches three-phase buck converter as an example. The main applications used in power conditioning and power flow control are introduced along with emerging topologies.

1. Introduction

AC choppers are a family of power converters derived from traditional dc-to-dc converter topologies such as the buck, boost, buck-boost and so forth [1]. Their main application is power conditioning in the distribution system and power flow control in the ac transmission power systems [2-20]. They differ from a matrix converter, which is more complex in terms of control and number of devices and is mainly used as a motor speed controller.

There are two main differences between ac choppers and a matrix converter. One difference is that the number of devices for a three-phase configuration is usually 18 in the matrix converter and 6 in traditional ac choppers.

Fig. 1. Ac-choppers (a) buck, (b) boost, (c) buck-boost, (d) Cúk.
The other difference is that ac-choppers are not designed to change frequency, only the amplitude of the voltage, and the control system is based in pulse width modulation (PWM) with a constant duty cycle (not sinusoidal) in the same way as dc-dc converters.

Figure 1 shows buck, boost, buck-boost and Cuk dc-dc converters with their respective three-phase ac-chopper derivation. Srinivasan and Venkataramanan state [1] that ac-choppers follow the same equations as dc-dc converters, and the PWM also has a constant duty cycle.

The principle operation of ac choppers, also called ac-link converters, can be explained with the circuit shown in Fig. 2, where the dc-dc and three-phase ac-ac buck converter are shown. The six transistors are divided in two three-phase switches, \( S_1 \) and \( S_2 \), and they switch complementarily as in the dc-dc converters. The transistor and the diode switch are complementary when they operate in continuous conduction mode (CCM). The ac voltage is chopped and then filtered to obtain a voltage waveform with different amplitude but the same shape and frequency.

![Fig. 2. Buck type AC chopper and voltage waveforms.](image)

According to the switching state of \( S_1 \) and \( S_2 \) in the buck type converter, see Fig. 2, two different equivalent circuits can be obtained, and when the three-phase switch, \( S_1 \), is closed while \( S_2 \) is open, the converter can be modeled as an equivalent circuit, as shown in Fig. 3(a).

![Fig. 3. Equivalent circuits of the ac-ac buck converter.](image)

It is important to notice than even if the diodes in \( S_2 \) are able to drain the current at any time, if all three transistors in \( S_2 \) are open, there is no path for the current to flow and the transistor will block the line-line voltage.

During this switching state, the voltage in the inductors can be expressed as:

\[
\begin{bmatrix}
    v_{L1} \\
    v_{L2} \\
    v_{L3}
\end{bmatrix} = \begin{bmatrix}
    v_{d1t} \\
    v_{d2t} \\
    v_{d3t}
\end{bmatrix} + \begin{bmatrix}
    v_{a1n2} \\
    v_{a2n2} \\
    v_{a3n2}
\end{bmatrix}
\]

(1)

Both switches cannot be closed at the same time, because a short circuit would occur. The inductors’ current should not go into an open circuit, and one switch should be closed at any time, but only one. Then the switching period \( T \) can be divided only two times, the time \( t_{S1} \), when the switch \( S_1 \) is closed while \( S_2 \) is open. The time \( t_{S2} \) occurs when switch \( S_2 \) is closed while \( S_1 \) is open, and—to avoid a short circuit or an open connection of inductors—the next equation should hold steady for all of the time.

\[
T = t_{S1} + t_{S2}
\]

(2)

The duty cycle of the converter can be defined as:

\[
d = \frac{t_{S1}}{T}
\]

(3)

The complementary of the duty cycle is:

\[
(1-d) = \frac{t_{S2}}{T}
\]

(4)

During the time \( t_{S2} \) the circuit will be equivalent to the circuit shown in Fig. 3(b), with the input voltage disconnected and switch \( S_2 \) providing a freewheeling path for the inductors’ current. During this time the inductors’ current can be expressed as:

\[
\begin{bmatrix}
    v_{L1} \\
    v_{L2} \\
    v_{L3}
\end{bmatrix} = \begin{bmatrix}
    v_{d1t} \\
    v_{d2t} \\
    v_{d3t}
\end{bmatrix} - \begin{bmatrix}
    v_{a1n2} \\
    v_{a2n2} \\
    v_{a3n2}
\end{bmatrix}
\]

(5)

Considering that the switching period is very small compared with the ac-cycle, in steady state, the average voltage during one switching cycle should be equal to zero for all inductors, and this can be expressed as:

\[
\begin{bmatrix}
    v_{L1} \\
    v_{L2} \\
    v_{L3}
\end{bmatrix} = d \begin{bmatrix}
    v_{d1t} \\
    v_{d2t} \\
    v_{d3t}
\end{bmatrix} - \begin{bmatrix}
    v_{a1n2} \\
    v_{a2n2} \\
    v_{a3n2}
\end{bmatrix} + (1-d) \begin{bmatrix}
    v_{a1n2} \\
    v_{a2n2} \\
    v_{a3n2}
\end{bmatrix} = 0
\]

(6)

From (6) it is possible to obtain (7).
\[
\begin{bmatrix}
    v_{d1l} \\
    v_{d1l} \\
    v_{c1l}
\end{bmatrix} - d \begin{bmatrix}
    v_{d3n2} \\
    v_{d3n2} \\
    v_{c3n2}
\end{bmatrix} - (1-d) \begin{bmatrix}
    v_{d3n2} \\
    v_{d3n2} \\
    v_{c3n2}
\end{bmatrix} = 0
\] (7)

And finally, the output voltage can be expressed in terms of the input voltage and the duty cycle of the buck converter.

\[
\begin{bmatrix}
    v_{d3n2} \\
    v_{d3n2} \\
    v_{c3n2}
\end{bmatrix} = d \begin{bmatrix}
    v_{d1l} \\
    v_{d1l} \\
    v_{c1l}
\end{bmatrix}
\] (8)

From (8), the circuit shown in Fig. 2 behaves in ac exactly as the traditional buck converter behaves in the dc-dc conversion and from each dc-dc converter topology; the three-phase ac-ac converter can be derived holding the principle of operation [1]. It is important to notice than all topologies in Fig. 1 need snubber circuits in order to operate, a design procedure found in Ref. [1].

2. Applications

2.1 Voltage Control

As the traditional dc-dc converters, one of the main applications is to control three-phase voltage amplitude and by doing so reject variations in the input voltage [2-3]. The traditional six switches buck ac chopper (see Fig. 2) is used [2] to avoid the flicker effect. A topology that uses four switches is proposed in Ref. [3], see Fig. 4, to control the voltage in a sensitive load by reducing the number of devices and then simplifying the control circuit. In this topology snubber circuits across switches are not mandatory, the resistors and capacitors connected on the input side drain the load current during the dead time, along with the anti-parallel diodes of switches [3].

\[\text{Fig. 4. Buck type converter proposed in [3].}\]

In the case of the buck converters, the output voltage cannot be higher than the input voltage; it can only reject step-up variations (swells). This is an important limitation because most voltage perturbations are step-down variations (sags). A transformer is needed to increase the voltage and reject sags or else another topology can be used such as the boost, buck-boost, Ćuk, and so on.

In the mentioned applications, when an ac chopper is directly used to control the voltage, the converter should be rated to the load’s power; an additional way to control the voltage with a smaller converter is combining an ac chopper with a transformer.

The transformer can inject the voltage in series with the load controlling the voltage with a converter with a power rating much smaller than the load’s power rating [4-8], see Fig. 5.

\[\text{Fig. 5. Voltage regulator with a transformer and ac-chopper.}\]

The voltage regulator shown in Fig. 5 can be considered an ac-chopper–based dynamic voltage restorer (DVR), which is a voltage source converter (VSC) based power conditioner designed to control the voltage in a sensitive load.

2.2 Power flow control

Another attractive application for ac choppers is the implementation of Flexible Alternating Current Transmission Systems, or FACTS, in the same way as the voltage regulator (shown in Fig. 5) does the analog behavior of the DVR. A pure capacitive reactance can be implemented with (i) an ac chopper, (ii) a series injection transformer and (iii) compensating capacitors. When connected in series with a transmission line, this kind of compensator can operate in ways such as the static synchronous series compensator (SSSC). Figure 6(a) shows the series compensator proposed by Lopes and Joos [9], which is based on the buck type four switches ac-chopper topology proposed by Vincenzi, Jin, and Ziogas [3] and also shown in Fig. 4.

Figure 6(b) shows the series compensator based in the six switches topology also shown in Fig. 1(a) [10]. A comparative evaluation of series compensators has shown that the ac-chopper compensator—also called Ξ controller “ξ controller”—has advantages over the dc-link approach, such as a smaller power rating for the power stage and less stored energy for the same function and power rating [11] against the SSSC. Similarly to the voltage regulator shown in Fig. 5, a static phase shifter can be implemented with a parallel transformer feeding an ac-chopper and injected in series with the transmission line.
The six switches topology [see Fig. 1(a)] was used by Johnson and Venkataramanan [12] to implement a phase shifter in a hybrid structure where most of the power was handled by a conventional tap changing transformer and a small amount of power was handled by the ac-chopper, which was used to provide a continuous range of compensation against the steps range given by the conventional tap changing phase shifter. Other static phase shifters based on the six switches topology were proposed and studied by Kaniewski and Fedyczak [13].

The four switches topology was used for implementing a phase shifter and a multi-module topology was proposed [14]. Other structures were studied by Kim and Kwon [15].

In this case, the phase of the injected voltage is given by the transformer arrangement; the ac-chopper cannot change the phase or the frequency by itself.

This kind of static phase shifter, based on the ac chopper, can be combined with the traditional power flow controllers making hybrid structures such as [16] and providing a continuous range of compensation. Furthermore, other transformer based compensators such as the family of Sen transformers [17-18] and static phase shifters [19-20] can be combined with ac choppers to get a fast response.

This development along with the emerging semiconductors technology based on silicon carbide and recently proposed topologies make ac-chopper attractive for practical implementations.

3. Emerging Topologies

A family of two switches three-phase ac choppers was proposed by Peng, Cheng, and Zhang [21], see Fig. 7, analog to Fig. 1 where the six switches ac chopper family was shown.
The main drawback of the two switches topologies family is that some connections in the three-phase input voltage or load need to be open, for example in the buck converter, see Fig. 7(a) where the input voltage is located in an open connection (neither Y nor \(\Delta\)). The same thing occurs with the output voltage in the boost converter and the input and output in the buck-boost converter. The Cuk converter is the only one in the family that doesn’t need an open connection, which makes the two switches three-phase Cuk converter attractive for voltage regulation in sensitive loads. Another advantage of reducing the number of switches is that it reduces the number of snubber circuits.

Other new converter topologies such as the Z-source converter [22] can be also used in dc-dc conversion [23] and adapted to become a three-phase ac-chopper [24] in the six switches topology, see Fig. 8(a), or in the two switches topology [24], see Fig. 8(b).

The disadvantage of the open connection is not a problem in the power flow control where compensators are coupled to the transmission lines with transformers and the transformer’s secondary connection can be open. Ac-chopper-based flexible ac transmission systems can be implemented in this way, as proposed by Rosas-Caro, Ramirez, and Peng [25].

Figure 9(a) shows the two switches ac chopper based series compensator two switches xi controller [25], which has the same operation of Fig. 6. The main drawbacks of the two switches topologies are (i) the conduction losses increase because there are more devices draining the current and (ii) the number of switching devices decreases but the total installed power in switching semiconductors holds the same because each device in a two switches topology drain three times the current of each device in a six switches topology, the switch is three times bigger.

On the other hand, as only two gate drives and two snubber circuits are needed, the switching process becomes a one quadrant switching.

4. The Vector Switching Converter

The three-phase vector switching converter (VeSC) was proposed and deeply analyzed by Venkataramanan [26]. Figure 10 shows a two-throw single-pole three-phase VeSC, where two three-phase voltage sources feed one three-phase current source switching among both three-phase voltage sources.

![Fig. 8. Z-source ac chopper (a) six switches based (b) two switches based.](image_url)

![Fig. 9. Two switches based xi controller.](image_url)

![Fig. 10. Three-phase vector switching converter.](image_url)
If the switches are controlled by PWM in Fig. 10, it is possible to define duty cycles for each switch if $t_{1\text{closed}}$ is the time when $S_1$ is closed, and $t_{2\text{closed}}$ is the time when $S_2$ is closed, then duty cycles for each switch can be defined as:

$$d_1 = \frac{t_{1\text{closed}}}{T}; \quad d_2 = \frac{t_{2\text{closed}}}{T};$$

(9)

Both switches cannot be closed at the same time because the input voltage sources would be in short circuit, and both switches cannot be open at the same time because the load would get in an open connection (the load is considered inductive and modeled as a current source during the switching process); one of them should be closed while the other is open and so on. That can be expressed as:

$$\frac{t_{1\text{closed}} + t_{2\text{closed}}}{T} = d_1 + d_2 = 1$$

(10)

According to the state of the switches, the circuit can get two equivalent circuits, see Fig. 10, one with the load connected to $v_1$ and the other one with the load connected to $v_2$. The average voltage (in a switching cycle) in the load terminals can be expressed in terms of the duty cycles for the switches and the input voltages as:

$$\begin{bmatrix} v_{1a}(t) \\ v_{1b}(t) \\ v_{1c}(t) \\ v_{2a}(t) \\ v_{2b}(t) \\ v_{2c}(t) \end{bmatrix} = \begin{bmatrix} v_{ia}(t) & v_{ia}(t) & v_{2a}(t) \\ v_{ib}(t) & v_{ib}(t) & v_{2b}(t) \\ v_{ic}(t) & v_{ic}(t) & v_{2c}(t) \end{bmatrix} \begin{bmatrix} d_1(t) \\ d_2(t) \end{bmatrix}$$

(11)

The average current (in a switching cycle) for each input voltage source can be expressed in terms of duty cycles and the load current as:

$$\begin{bmatrix} i_{1a}(t) \\ i_{1b}(t) \\ i_{1c}(t) \\ i_{2a}(t) \\ i_{2b}(t) \\ i_{2c}(t) \end{bmatrix} = \begin{bmatrix} i_{1a}(t) \\ i_{1b}(t) \\ i_{1c}(t) \end{bmatrix} = d \begin{bmatrix} i_{1a}(t) \\ i_{1b}(t) \\ i_{1c}(t) \end{bmatrix}; \quad \text{for } i = 1, 2.$$  

(12)

It can be seen from (11) that the output voltage is the sum of the products of duty cycles, and the input voltages. If the input voltages have different phases, a phasor analysis can be used to get the output voltage phase [26-27].

The topology can be extended to any number of phases and input voltage sources, and (11) and (12) can be also extended to represent the voltage and current in complex interconnections. Actually, the VeSC was proposed to control the power flow in complex interconnections—a node can be fed by several lines through a VeSC in order to control the power that each line provides to this node [26], enabling a high flexibility for the control of a very complex interconnected system, and, therefore, most of the ac-choppers and chopper compensators can be represented as a specific case of the VeSC approach.

The main difference between a VeSC and a classical matrix converter is the realization of the power switching structure that in a classical matrix converter for three-phase power flow control requires switches with bi-directional current control and voltage blocking capability usually implemented with 18 transistors. On the other hand, due to the ganging together of appropriate throws, all three phases of a pole are switched simultaneously. As a result, due to inherent symmetry in three-phase voltage and current waveforms, when all the three-phase ac ports are three wire systems, the throws may be realized using the bi-directional current conducting, but unidirectional voltage blocking capability as illustrated in Fig. 10. As already mentioned, when all switches are open even if diodes can drain current at any time transistors will block the voltage. Furthermore, as the duty ratio arises directly from the average value of the switching function, the modulation strategy can be performed by comparing the duty ratio with a saw-tooth (or triangular) high frequency carrier, as it is done with dc/dc converters. It doesn’t need to be synchronized with the grid.

The fundamental component averaged vector (or single-phase) equivalent circuit of the converter system may be represented as shown in Fig. 11, representing the converter by means of dependent sources.

![Fig. 11. (a) VeSC single phase equivalent circuit (b) Throw realizations and obtainable pole voltage.](#)

The realizable output voltage depends on the amplitude and phase of the input voltages and duty ratios. Figure 7(b-d) shows the realizable voltage values (represented by the gray shaded region in the phasor plane) for different cases of input voltage sources and their phases.

It may be observed that the region of the realizable pole voltages is given by the largest polygon whose vertices are
the locations of the corresponding throw voltages and the phasor origin. More information of the phasor representation can be found in Refs. [27, 31].

New FACTS devices have been recently proposed based on the VeSC [27-28] and the inclusion of those new FACTS controllers in the power system has been investigated [29]. Following the trend in ac chopper development, a simplification of the VeSC was proposed by Rosas-Caro, Ramirez, and Peng [25] by using few switches for each FACTS device.

Future power systems will involve complex distribution systems with advanced solid state transformers and power compensators. Silicon carbide (SiC) devices can break the limits of using power converters in the power system because of the superior properties of the material [30]. The ac choppers are a suitable technology for controlling the voltage in the distribution system [2-8] and the power flow control in the transmission system [9-20, 25-30].

A topological comparison between the dc-link and the ac-link approach for power flow control and power quality enhancement was presented in Ref. [31].

The most attractive features of the vector switching converter approach for power conditioning and power flow control in contrast to the dc-link approach based on the voltage source converter are (i) the elimination of the dc-link that is the less reliable part of the VSC and (ii) a reduced number of active switches in relationship to the matrix converter, as the matrix converter can be employed to the proposed applications but 18 switches are needed for a three-phase configuration.

Additionally, the PWM strategy in ac choppers and vector switching converters follows the same principle as in dc/dc converters, which is well understood and easy to implement [31], they can work PLL-less and asynchronous from the grid frequency as the frequency and phase of the signals are given by the grid frequency and the transformers arrangement, that makes the control system insensitive to frequency and phase variations in the grid.

The detailed comparative evaluation performed for series compensation between ac and dc link converters suggests further evidences of the advantages of ac link converters [11], including smaller capacitors, and a potential lower cost. In summary, ac link VeSC-base devices present a viable alternative to the state-of-the-art technology, namely dc link VSI devices, and they are worth further consideration.

5. Conclusions

This paper presents a state-of-the-art discussion of ac-choppers, the traditional six switches family was introduced, and the principle of operation was presented with the buck ac-chopper. The main applications in voltage control of the distribution system and power flow control in the transmission system were explained. Emerging topologies of ac choppers with few switches were discussed.

The vector switching converter shows a global approach to representing ac choppers and new FACTS controller based in this approach have been recently proposed, With these applications and the advent of SiC devices, the ac chopper and VeSC promises to become a hot topic in power electronics research, especially in power conditioning and power flow control where VeSC promises the development of power compensators with smaller capacitors and a potential lower cost.

6. References


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