A Rapid DC Component Elimination Strategy for Alternative Current in Frequency Converter

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\textbf{Abstract:} The principle achievement of this contribution is to develop and to describe a rapid DC component elimination strategy for AC currents in the frequency converter, simply by selecting transient period. To avoid DC component on the line current, it’s known that the transition of active and/or reactive power should not be rapid. If the transition time is relatively long compared to the fundamental period, the current may be considered as symmetrical and the DC component can be neglected. In comparison to the usually slow transient that characterizes a DC component free current transient; in this paper much faster transient also without DC component is achieved, simply by choosing a well-defined transition period. The present method is verified for a simple linear circuit. It can also be used, for example, with a three or more level inverter including, but not limited to, a Neutral Point Clamped. Simulation and verification results for different operating points and transitions between them highlight the capabilities of the proposed control strategy. These include the ability to operate with unity power factor and better current quality without continuous component.

\textbf{Keywords:} DC-component, Grid connected inverter, Transient-period, Active-Power, reactive-power, frequency-converter, angle-shift.

\section{1. Introduction}
Power converters connected to the grid usually involve DC-AC conversion in order to exchange AC power with the grid. Because AC power of these converters comes from a DC source, the line current can contain some DC component, it is important to guarantee that there is no direct current injected into the grid. Excessive amount of DC injection can cause a decline in power quality and affect the normal operation of the equipment. This may be particularly problematic for power systems in a vehicle such as an aircraft or aerospace vehicle. Therefore, it is necessary to strictly limit the DC component on the inverter output current. To avoid DC component on the line current, it’s known that the transition of active and/or reactive power should not be rapid. If the transition time is relatively long compared to the fundamental period, the current may be considered as symmetrical and the DC component can be neglected.

In comparison to the usually slow transient that characterizes a DC component free current transient; in this paper much faster transient also without DC-component is achieved, simply by choosing a well-defined transition period. The present method is verified for a simple linear circuit. It can also be used, for example, with a three or more level inverter including, but not limited to, a Neutral Point Clamped.

This paper is organized as follows; Section 2 cites some related works, Section 3 describes a new method to eliminate DC component using a simple linear circuit. Section 4 proposes an application of the method using a non-linear system. Section 5 shows simulation and practical verification results. Finally Section 6 concludes the paper.

\section{2. Related works}
Many authors emphasize and focus their researches on low total harmonic distortion or high efficiency. However there are only few concerning the DC component elimination.
Descriptions of various systems for reducing the DC component are presented; the system in [1] proposes to use a DC component remover circuit to take out a DC component from the first output instruction signal to derive a second output instruction signal, inverting operation of the DC/AC inverter circuit is controlled based upon the second output instruction signal to prevent DC magnetization of transformer. [2] proposes a control system for a PWM inverter, it consists to produce a DC offsetting voltage with an opposite polarity from the DC component, the opposite polarity DC offsetting voltage may effectively cancel the DC component of the inverter. Another algorithm to eliminate a DC component has been suggested in [3], its contribution is to control the switching angle of the circuit breaker during closing time; the algorithm used extracts and filters out the DC offset current from the input signals and eliminates it totally. Further method used to eliminate the DC component of grid-connected inverter is given by [4]. Most of these references note that the DC component depends to the transient time and it is reduced when the transition period is long.

As an important contribution, this paper proposes a new fast-ramping DC component elimination strategy for AC currents. This method which is patented in [5] is verified with a simple linear circuit and applied with three level Neutral Point Clamped inverter. In this application the converter can reach any operating point through an angular shift and adaptation of the continuous voltage. It can be used typically as an interface between a fast running synchronous generator and the grid [6] [7], where the ratio between input and output voltage is kept constant by using a SWM at both the generator and the line side (see Figure 1). The main advantage of this mode is the quasi absence of switching losses and then high efficiency. The produced active and reactive power can be controlled by voltage magnitude adaptation which can be achieved through the generator’s excitation, together with the angle shift between the grid and output inverter voltages [8].

![Figure 1. Schematic of the electrical power generation system using frequency converter.](image)

3. DC Elimination method for AC Current using a linear system

This section describes a new method to eliminate DC component using a linear circuit. As an example a simple circuit which input and output voltages are presented by a sinusoidal signals and connected together through an inductance $L_n$ (see Figure 2).

![Figure 2. Simple circuit.](image)

The input voltage is: $V_{inv}(t) = \sin(\omega t + \theta(t))$

The output voltage is: $V_n(t) = \sin\omega t$
$\theta(t)$ is the angle shift between $V_n$ and $V_{inv}$, it is given by (1) and it is shown in Figure 3.

![Figure 3. Transition time limiter](image)

\[
\theta(t) = \begin{cases} 
\frac{\theta_{nc}}{T_{tr}} t & \text{if } t < T_{tr} \\
\theta_{nc} & \text{if } t \geq T_{tr} 
\end{cases}
\]

(1)

The current generated in the circuit is given by (2):

\[
I_n(t) = \frac{1}{L_n} \int_0^t (V_{inv}(t) - V_n(t)) \, dt
\]

(2)

(1) can then be inserted into (2) to yield:

\[
I_n(t) = \frac{1}{L_n \omega} \left( \frac{\theta_{nc}}{\omega T_{tr} + \theta_{nc}} \right) \left( \cos(\omega T_{tr} + \theta_{nc}) - 1 \right) + \frac{1}{L_n \omega} \left( \cos(\omega t) - \cos(\omega t + \theta_{nc}) \right)
\]

(3)

On the other hand, the mean value of the current is given by (4):

\[
I_{mean} = \frac{1}{L_n \omega} \left( \frac{\theta_{nc}}{\omega T_{tr} + \theta_{nc}} \right) \left( \cos(\omega T_{tr} + \theta_{nc}) - 1 \right)
\]

(4)

The current’s mean value $I_{mean}$ or DC component is composed by two terms and it depends on the transition time $T_{tr}$. DC component will be equal zero when one of these term is null:

\[
\frac{1}{L_n \omega} \left( \frac{\theta_{nc}}{\omega T_{tr} + \theta_{nc}} \right) = 0
\]

(5)

Equation (5) will be verified if $T_{tr}$ is relatively long in comparison to $\theta_{nc}$.

\[
(\cos(\omega T_{tr} + \theta_{nc}) - 1) = 0
\]

(6)

Equation (6) will be verified when $T_{tr}$ is equal to an integer multiple of the fundamental period. $T_{tr}$ in fact is given by (7):

\[
T_{tr} = k T_f - \frac{\theta_{nc}}{\omega}
\]

(7)

with $T_f = \frac{2\pi}{\omega}$ and $k = 1,2,3\ldots$(an integer value)

The method presented in this section proves that for particular value of transition period $T_{tr}$, the DC component can be equal zero. However it is important to notice that analytical
calculation is done for fixed input voltage and for the linear ramp, and the system depicted in Figure 1 is not linear. Section 4 proposes an application of the method using a non-linear system.

4. DC Elimination method for AC current using a non-linear system

Figure 4 shows a principle circuit diagram of a three level NPC inverter. Using the NPC topology [9] [10] [11], three level converters allow to spread the output voltage on three levels as shown in Figure 5. In this figure, \( \delta_n \) represents a selected switching angle, which depends on the harmonics component. By selecting \( \delta_n \) the harmonic distortion of the output voltage can be reduced [12]. Figure 4 illustrates also the inverter control block. This control is based on angular shift between the network and the output inverter voltages (block (3)), together with voltage magnitude adaptation in the input of the inverter (block (4)). They are given by (8):

\[
\theta_n = \arctan \left( \frac{P(t)}{3 \frac{V_x^2}{X_x} - Q(t)} \right)
\]

\[
U_{dc} = \frac{\pi}{2 \cos \delta} \left[ \left( V_n - \frac{2}{3} \frac{X_x}{V_x} Q(t) \right)^2 + \left( \frac{2}{3} \frac{X_x}{V_x} P(t) \right)^2 \right]
\]

Figure 4. Schematic diagram of the dedicated control strategy for 3L3P NPC inverter.

Figure 5. Output-voltage waveform of three-level converter operated in SWM.
\[
P(t) = \frac{|P_{nc} - P_n|}{T_{tr}} t
\]

\[
Q(t) = \frac{|Q_{nc} - Q_n|}{T_{tr}} t
\]

\[P(t)\text{ and } Q(t)\text{ are given by (9):}\]

\[\theta_n\text{ and } U_{dc}\text{ are not linear. They are presented in Figure 6.}\]

Starting from the active and reactive power references, the system runs initially in no load operation, with active and reactive power equal to zero (Figure 6). Both inverter and network voltages have the same phase with amplitude equal to nominal. Therefore the current is equal to zero.

In the first transition at \(t = 0.04s\), network active and reactive power are ramped to \(P_{nc} = S_n \times \cos \phi\) and to \(Q_{nc} = S_n \times \cos \phi\) respectively. Consequently the angle shift and the continuous voltage change from \((\theta_{nh}, U_{h})\) to \((\theta_{nc}, U_{dc})\) (Figure 6). Their values depend on the active and reactive power references.

In the second transition at \(t = 0.1s\), the reactive power ramps down to zero as illustrated in Figure 6. Consequently the angle shift and the continuous voltage must change from \((\theta_{nc}, U_{dc})\) to \((\theta'_{nc}, U'_{dc})\), Then the reactive power can be compensated and the system can be operated using a unity power factor.

![Active and reactive powers references](image)

Figure 6. Active and reactive powers references

However the line current can contain some DC component due to the transients. To overcome this problem, the transition of active and reactive power references should not be rapid. If the transition time \(T_{tr}\) is relatively long compared to the fundamental period \((T_r = 20\text{ms})\), the current may be considered as symmetrical, and the DC component can be neglected [13]. The question now is as follows: How fast is the slew rate of the current transient be allowed to be in Square Wave Modulation?

Simulation and verification results using a non-linear system can answer this question and also prove that for particular value of transition period \(T_{tr}\), the DC component can be equal zero.

5. Simulation and Practical Verification

The system shown in Figure 4 has been simulated in PLECS [14] using the following characteristics: \(V_n = 1\text{pu}\) is the network voltage, \(X_n = 0.2\text{pu}\): inductance between the inverter and the network. \(S_n = 1.5\text{pu}\) is the apparent power. The same model has been built and tested using a low-voltage laboratory prototype; it is depicted in figure 7. Simulation and experimental results are presented in figures 8 to 23.
A. Simulation Results

In order to validate the theoretical results discussed in section 4, a non-linear system has been simulated under the same conditions, using the same characteristics and for different values of k. The transition period $T_n$ depends to k according to this equation: $T_n = kT_f - \frac{\theta_{nc}}{\omega}$

with $T_f$ is the fundamental period $(2\pi/\omega)$ and $\theta_{nc}$ is the angle shift between inverter and network voltages.

Figure 8. First transition: $k=0.2$ (not integer) $i_{\text{mean}} \neq 0$

Figure 9. Second transition: $k=0.2$ (not integer) $i_{\text{mean}} \neq 0$
Figures 8, 10, 12, 14 and 16 present power references, the alternative line current and its DC component measured by simulation for the first transition at $t = 0.04s$, when $\theta(t)$ changes from $\theta_{n0}$ to $\theta_{nc}$ according to Figure 6. The network active and reactive powers are ramped from no load to $P_{nc} = S_n \times \cos \phi$ and to $Q_{nc} = S_n \times \sin \phi$ respectively. The system operates with $\cos \phi \neq 1$. These curves are measured and presented in Figures 9, 11, 13, 15 and 17 also in the second transition at $t=0.1s$, when $\theta(t)$ changes from $\theta_{nc}$ to $\theta_{nc}'$. The system operates with $\cos \phi = 1$.

![Figure 10. First transition: $k=1$ (an integer) $i_{\text{mean}} = 0$.](image1)

![Figure 11. Second transition: $k=1$ (an integer) $i_{\text{mean}} = 0$.](image2)

![Figure 12. First transition: $k=1.3$ (not integer) $i_{\text{mean}} \neq 0$.](image3)
Figure 13. Second transition: $k=1.3$ (not integer) $i_{\text{mean}} \neq 0$.

Figure 14. First transition: $k=2$ (an integer) $i_{\text{mean}} = 0$.

Figure 15. Second transition: $k=2$ (an integer) $i_{\text{mean}} = 0$. 
The simulation results confirm that the DC component is zero when $k$ is an integer (eg. $k = 1, 2, \ldots$), (See Figures 10, 11, 14, 15). Otherwise, it is different from zero (eg. $k = 0.2, 1.3$), (See Figures 8, 9, 12, 13). For large values of $k$, (eg. $k = 10.3$) the DC component can be neglected (See Figures 16, 17). The reactive power can be compensated rapidly and without DC component in the alternative line current (See Figures 11 and 15).

Figure 18 shows the simulated active and reactive powers for different operation modes, for the first transition at $t = 0.04s$, and for the second transition at $t = 0.1s$. The alternative line current is in phase with the network voltage when the reactive power is null.
B. Experimental Verification Results

Figure 19. Measured line current and DC component when $k$ is an integer $i_{mean} = 0$.

Figure 20. Measured line current and DC component when $k$ is not integer and large $i_{mean} \neq 0$.

Figures 19 to 23 show the practical measured results, the alternative line current is symmetrical and without DC component when $k$ is an integer or has a large value (See Figures 19 and 20). Otherwise, it is different from zero (See Figure 21).

Figure 21. Measured line current and DC component when $k$ is not integer $i_{mean} \neq 0$.

Figure 22. Measured results for $\cos \phi = 1$. 
Active and reactive powers are measured and presented in figures 22 and 23 together with the alternative line current, inverter and network voltages. When the reactive power is near zero, the alternative line current is in phase with the network voltage. The reactive power can be compensated rapidly and without DC component in the alternative line current.

6. Conclusion

In this paper a Rapid DC Component Elimination Strategy for AC Current is proposed. Indeed, in comparison to the usually slow transient that characterizes a DC component free current transient, it has been verified that much faster transient also without DC component is achieved, simply by choosing a well-defined transition period equal to an integer multiple of the fundamental period. The proposed method is verified for a simple circuit and applied with three level NPC inverter. This frequency converter can be used typically as an interface between a fast running synchronous generator and the grid. Verification results with different operating points and transitions between them highlight the capabilities of the proposed method. These include the ability to operate with unity power factor and better current quality without continuous component. The solution presented here solves the problem discussed and can be applied to other applications such as a static compensator for reactive power. The reactive power can be compensated rapidly and without DC component in the alternative line current.

7. References

Aziza Benaboud received a PhD from the Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland, in 2007, and a master degree in electrical engineering from the Ecole National Supérieure d'Electricité et Mécanique (ENSEM), Casablanca, Morocco, in 2002. Since 2009 she has been an assistant professor of electrical engineering and power electronics at Royal Navy School, Casablanca, Morocco. Her research focuses on power electronics and applications such as high efficiency frequency converters for high power generators and HVDC transmission system. She has authored one book and has published several papers and patent. She has also given several invited presentations in international conferences and universities.

Alfred Rufer (1951) received the M.S. degree from the Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland, in 1976. In 1978, he joined ABB where he was involved in the fields of power electronics and control, such as high-power variable-frequency converters for drives. In 1993, he became an Assistant Professor at EPFL. Since 1996, he has been a full Professor and Head of the Industrial Electronics Laboratory, EPFL. He has authored or coauthored several publications on power electronics and applications, and he holds several patents. In Alfred Rufer’s lab, the actual research activities focus on one hand on power converters, where several solutions and applications of multilevel converters have been studied, especially in the field of asymmetric or hybrid topologies. New activities dedicated to the Modular Multilevel Converter MMC topology are currently underway. Another important field initiated by Alfred Rufer is dedicated to supercapacitive energy storage, where many applications have been studied or are currently underway. Other new developments have recently been presented, as the example of a low aging, easy to recycle, hybrid energy storage device based on compressed air is proposed. In 2006, Alfred Rufer was elected to the IEEE Fellow grade.