

Control of a star connected alternate arm converter

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Abstract

This paper details a novel energy management technique that is applied to the Alternate Arm Converter (AAC), to ensure converter stability. The control strategy is modeled in Matlab/Simulink and tested on a HVDC active and reactive power operating envelope. To realize the commercial benefits of the AAC, stability in all normal operating conditions is verified. Simulations run over the PQ envelope are shown and the commercial benefits of the new energy management technique assessed.

Introduction:

The use of High Voltage DC (HVDC) technology for power transmission can provide a number of benefits compared to classic HVAC [1]. As delocalized, remote renewable energy sources become more common, the high efficiency and lower costs of HVDC over long distances makes this technology more attractive [2], as pictured in figure 1, where the break-even distance for Over Head line connection is around 600 km and for Submarine Cables is around 80 km.

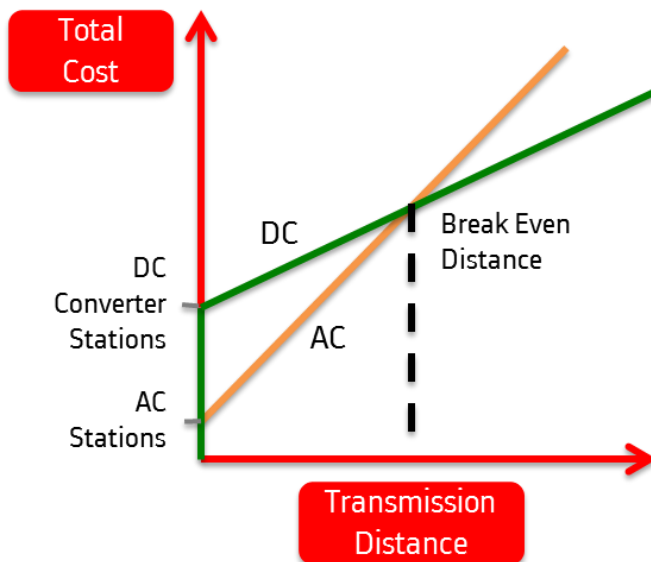


Figure 1: Cost vs. Transmission Distance of HVAC and HVDC.

Also, HVDC links are asynchronous and faults do not propagate across such systems, so even in a Back-to-Back configuration, this technology provides benefits such as interconnection between different frequency networks and a controlled, "Firewall" protection between systems [3]. Finally, use of HVDC instead of HVAC allows increasing the transmission capacity of a fixed corridor, as it can deliver up to 3 times more power per tower [4].

The uptake of projects using Voltage Source Converters (VSC) for HVDC power transmission is increasing as the new technology offers: faster build times, lower costs, reduced footprint and improved reactive power support. VSC provide several advantages over traditional thyristor based LCC converters [5]; in particular they operate with a high fidelity sinusoidal terminal converter voltage, so there is no need for the large harmonic filters associated with LCC. In addition VSC can be used to both source and sink reactive power in a controlled manner and also offer improved dynamic performance. Further, unlike LCC, the DC output voltage of a VSC converter remains unipolar for both forward and reverse power flows, which results in reduced cable costs and DC multi-terminal capability. However, although VSC offers significant benefits over thyristor based LCC converters, their use of IGBT devices makes them unable to compete with the voltage and current ratings of thyristor based LCC.

Currently, two variants of VSC technology coexist in the market. First, ABB's HVDC Light® is based on classical two level VSC converters used for low power applications, and makes use of strings of series-connected IGBT's and high frequency PWM modulation. Hence, additional filtering is required to remove the high frequency switching noise present as both conducted and radiated RFI. Another drawback of this topology is the vulnerability to faults in the DC terminals, since due to the anti-parallel diodes present in the circuit, an uncontrollable current will circulate through the diodes during the fault.

Second, Siemens' HVDC PLUS® and Alstom's HVDC MaxSine® use Modular Multi-level Converter (MMC) topology. This technology was first revealed in 1998 for STATCOM type applications [6], was extended in 2003 for HVDC Power Transmission [7] and further work was done in [8]–[10]. The idea is to replace the series IGBTs in the classic 2-level converter with a large number of Half-Bridge cells (see figure 2 a). These cells consist of a capacitor charged with a low voltage and a set of IGBTs. The operation of the cells will result in a high voltage waveform with numerous steps. This results in a high fidelity AC current that no longer requires any filtering and in a converter that does not have to rely on high frequency PWM to synthesize the waveforms.

Although the MMC solves some of the issues associated with the 2-level VSC applied to HVDC transmission, it is still vulnerable to DC faults. The choice of Half-Bridge cells minimizes the number of semiconductors in the current path and so reduces the conduction power loss; however the inability of the Half-Bridge cells to produce a negative voltage means that a collapse of the DC voltage will also result in an uncontrollable current circulating through the anti-parallel diodes. Choosing Half-Bridge cells is justified by the high cost related to the power losses, but implies that the converter will have to rely on an AC breaker to be able to clear a DC fault.

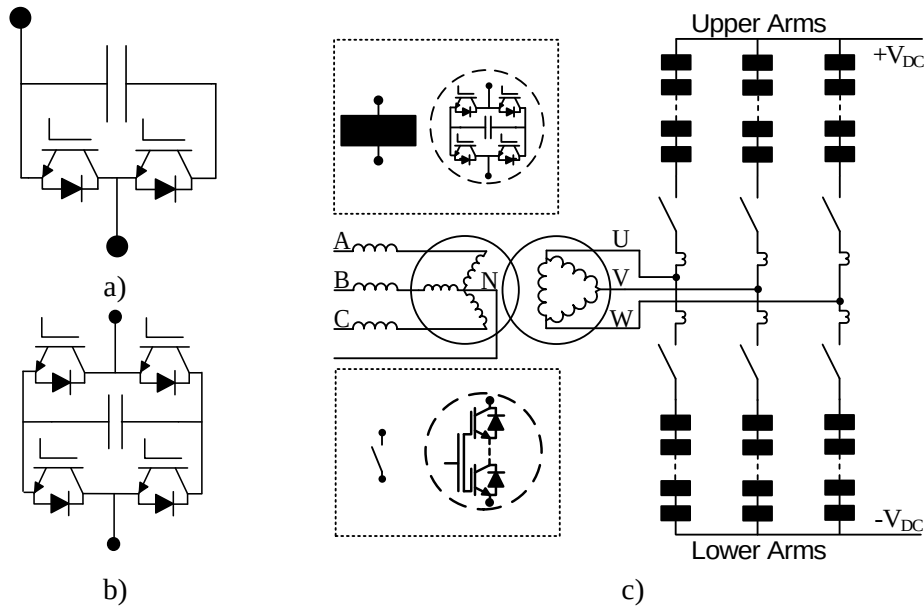


Figure 2: Half-Bridge cell (a), Full-Bridge (b) cell, electrical scheme of AAC topology (c)

Relying on a slow, mechanical AC breaker to clear DC faults means that the semiconductors will have to withstand the fault current until the fault is cleared. This will affect the value of the inductors to

limit the rising slope of the fault current, and the design of the cells to be able to cope with the high peak current. Also, it prevents the converter from being able to work as a STATCOM during the fault and inject reactive power in the grid.

The Alternate Arm Converter (AAC) topology pictured in figure 2 c) and first presented in [11], and further analyzed in [12]–[14], uses a combination of Full-Bridge cells pictured in figure 2 b) and Director Switches. Due to the ability of the Full-Bridge cells to generate a negative voltage, the AAC has an inherent capability of blocking DC Faults without the need of additional switchgear, and maintains the conduction losses low. Another benefit of this design is the reduced footprint, as the voltage that has to be synthesized by the cells is significantly reduced.

The operation of the Director Switches means that the available current paths within the circuit are continuously changing, making the implementation of the control algorithm difficult and the rebalancing of the energy that gets stored in, or lost from the cell capacitors particularly challenging. This is where variations of the AAC topology such as the one presented in this paper become important.

Operation of the AAC

In the AAC, the AC voltage is synthesized in a step-wise manner alternatively by the upper and lower Arms. During the positive stage, the Director Switch in the upper Arm (DS+) will be closed, that in the lower arm (DS-) opened and the AC voltage will be constructed by switching the cells in the upper Arm. Subsequently, during the negative stage, DS- will be closed, DS+ opened and the AC voltage will be constructed by switching the cells in the lower Arm. This process is illustrated in figure 3 a). The maximum voltage that each stack of cells has to produce is approximately half the DC link voltage.

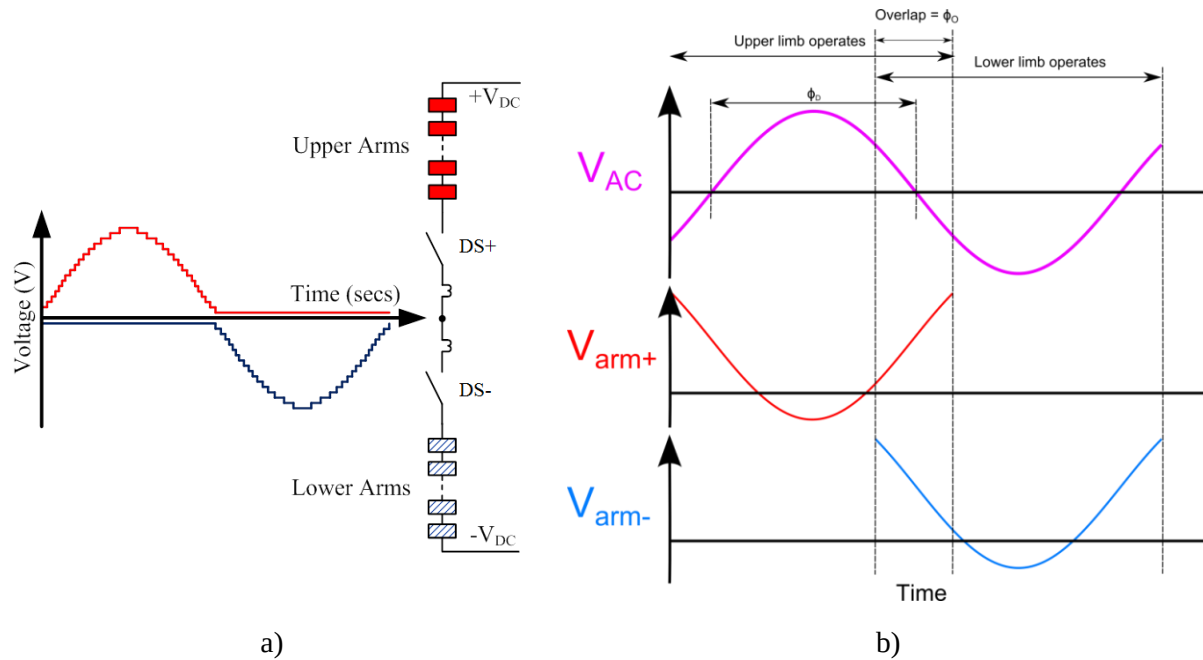


Figure 3: Synthesis of AC voltage with AAC a) and detail of AAC operation with overlap b).

In practice, the voltages that each stack of cells will have to generate will be higher than half the DC voltage. This is due to the need of an overlap period around the zero crossing point where the director switches in the upper and lower Arms are both closed. This overlap period, pictured in figure 3 b), is needed for controllability purposes; to be able to perform the handover of the current from one arm to the other, but a compromise between the length of the overlap and the losses has to be reached. The longer the overlap period, the higher the voltage the stack of cells has to produce. Thus the number of cells and hence the number of semiconductors will increase and the efficiency will be subsequently reduced.

Considering the converter to be operating as a rectifier, the AC current will be injected into the DC line. To be able to operate in a stable manner, the converter will have to work at an operating point

where the energy that comes to or from the AC will be equal to the energy that comes to or from the DC. Figure 4 illustrates such a condition where the AC energy, E_{AC} , is equal to the energy stored in the cells, E_{CAP} , plus the energy passed to the DC. The aforementioned operation point, referred as “sweet spot”, is chosen to allow E_{CAP} to be reset to zero during the power cycle, was previously defined in [14] and [15] and is represented in equation (1).

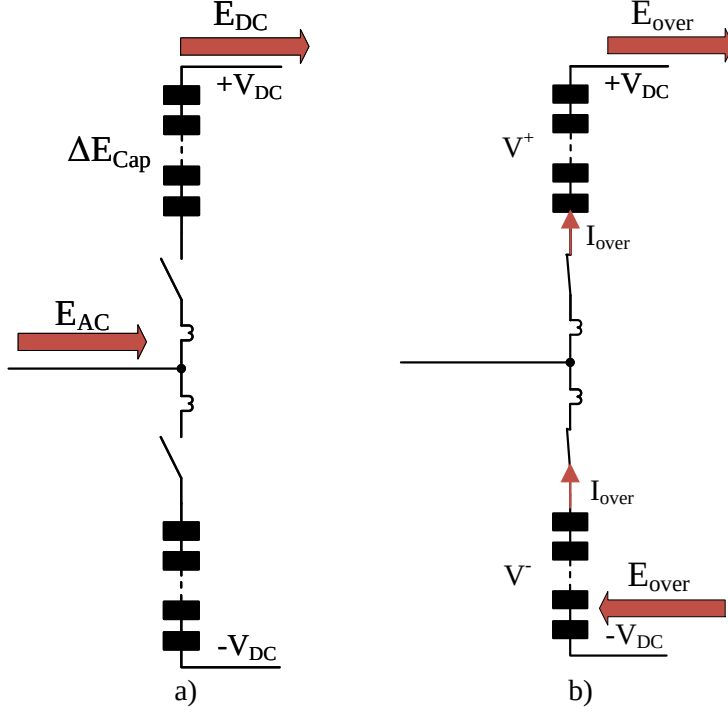


Figure 4: Energy flows in the AAC a) and energy exchange during the overlap b).

$$V_{DC_{opt}} = \frac{\pi}{2} \hat{V}_{AC} = \frac{\pi}{\sqrt{6}} V_{Line-to-line} \quad (1)$$

Keeping this relationship between the DC and the AC voltages will allow all the energy stored in the capacitors to be reset at the end of each power cycle. However, this method is not able to correct an existing energy unbalance in the system, and because the system is inherently unstable, any energy unbalance will tend to increase and lead to the converter operation collapsing. Thus, a reliable system to control and correct such an energy unbalance is needed.

Energy balance control:

An option to control the energy stored in the cells is to maintain a circulating current in the Arms during the overlap period. This current will transfer energy between the Arms and the DC grid as pictured in figure 4 b), thus making it possible to rebalance small deviations on the energy due to unforeseen factors that will upset the sweet-spot operation. The technique mimics the MMC energy balancing where a DC current is continuously present, even though in the case of the AAC the current can only be run for a short time during the overlap.

The energy that will be exchanged during this period is calculated in equations (2) and (3):

$$\begin{aligned} E_{over}^+ &= \frac{1}{\omega} \int_{\phi_s - \frac{\phi_o}{2}}^{\phi_s + \frac{\phi_o}{2}} V^+(t) (-I_{over}) d\theta + \frac{1}{\omega} \int_{\phi_s - \frac{\phi_o}{2}}^{\phi_s + \phi_D + \frac{\phi_o}{2}} V^+(t) (-I_{over}) d\theta \\ &= -2V_{DC}^+ I_{over} \frac{\phi_o}{\omega} + 4 \frac{\hat{V}_{AC} I_{over}}{\omega} \sin\left(\frac{\phi_o}{2}\right) \cos\left(\frac{\phi_D}{2}\right) \sin\left(\phi_s + \frac{\phi_D}{2}\right) \end{aligned} \quad (2)$$

$$\begin{aligned}
E_{over}^- &= \frac{1}{\omega} \int_{\phi_s - \frac{\phi_o}{2}}^{\phi_s + \frac{\phi_o}{2}} V^-(t)(-I_{over})d\theta + \frac{1}{\omega} \int_{\phi_s - \frac{\phi_o}{2}}^{\phi_s + \phi_D + \frac{\phi_o}{2}} V^-(t)(-I_{over})d\theta \\
&= -2V_{DC}^- I_{over} \frac{\phi_o}{\omega} - 4 \frac{\hat{V}_{AC} I_{over}}{\omega} \sin\left(\frac{\phi_o}{2}\right) \cos\left(\frac{\phi_D}{2}\right) \sin\left(\phi_s + \frac{\phi_D}{2}\right)
\end{aligned} \tag{3}$$

Where:

ϕ_o : Width of the overlap angle.

ϕ_s : Phase shift between voltage and current.

ϕ_D : Width of the duty cycle angle.

V^+ : Voltage generated by the upper arm cells.

V^- : Voltage generated by the lower arm cells.

I_{over} : Magnitude of the overlap current.

In turn, simplifying the equations with $\phi_D = \pi$ and $\phi_s = 0$, equations (4) and (5) are obtained:

$$E_{over}^+ = -V_{DC}^+ I_{over} \frac{\phi_o}{\omega} = -V_{DC} I_{over} \frac{\phi_o}{\omega} \tag{4}$$

$$E_{over}^- = -V_{DC}^- I_{over} \frac{\phi_o}{\omega} = -V_{DC} I_{over} \frac{\phi_o}{\omega} \tag{5}$$

This technique presents an effective method to balance the energies of the cell capacitors, but still some limitations have to be taken into account. The maximum energy that will be possible to exchange will be limited by the length of the overlap angle and the magnitude of the overlap current. Because of the compromise between the overlap length and the converter losses, and also the maximum current limits inherent to the IGBT semiconductors used in the scheme, it will be impossible for the converter to work far from the sweet-spot operation point. Also, the short DC current bursts at each overlap period will largely contribute to the distortion of the DC current waveform. Therefore, a new technique that overcomes these limitations is needed.

New proposed scheme

This technique, first mentioned in [11], [12], and analyzed and demonstrated in this paper, relies on driving third harmonic currents in a current path created between the middle point of the DC and the neutral point of a star transformer in the converter side, as pictured in figure 5.

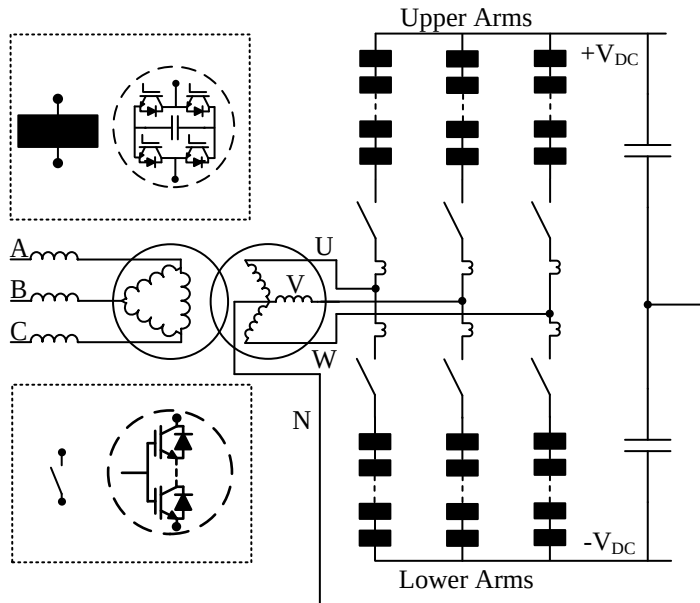


Figure 5: Electrical scheme of star connected AAC.

Due to the nature of the transformer arrangement, the zero sequence third harmonic will not be reflected in the primary of the transformer, thus it will not leak to the AC grid. Moreover, this additional AC current will also be rectified by the director switches along the main fundamental AC current, hence a small additional DC current will be present in the DC grid. As mentioned, this current does not exchange energy in the AC side, consequently it provides a new way of exchanging energy between the cell capacitors in the Arms and the DC grid. In the following equations (6)-(8) the energy exchanged with the upper and lower arms and the total energy are calculated (simplifying with $\phi_D = \pi$ and $\phi_S = 0$ also in this case), and example waveforms illustrating the technique are pictured in figure 6 below.

$$E_3^+ = \frac{1}{\omega} \int_{\phi_S}^{\phi_S + \phi_D} V^+(t) (-I_3(t)) d\theta = \frac{1}{\omega} \int_0^\pi V^+(t) (-I_3(t)) d\theta = 2 \frac{V_{DC}^+ \hat{I}_3}{3\omega} \sin\left(\phi_3 + \frac{3\pi}{2}\right) \quad (6)$$

$$E_3^- = \frac{1}{\omega} \int_{\phi_S}^{\phi_S + \phi_D} V^-(t) I_3(t) d\theta = \frac{1}{\omega} \int_0^\pi V^-(t) I_3(t) d\theta = 2 \frac{V_{DC}^+ \hat{I}_3}{3\omega} \sin\left(\phi_3 + \frac{3\pi}{2}\right) \quad (7)$$

$$E_3 = E_3^+ + E_3^- = 2 \frac{V_{DC} \hat{I}_3}{3\omega} \sin\left(\phi_3 + \frac{3\pi}{2}\right) \quad (8)$$

Where:

E_3 : Total energy exchanged by the triplen harmonic current.

E_3^+ : Energy exchanged by the triplen harmonic current with the upper arm cells.

E_3^- : Energy exchanged by the triplen harmonic current with the lower arm cells.

ϕ_3 : Angle of the triplen harmonic current.

I_3 : Magnitude of the triplen harmonic current.

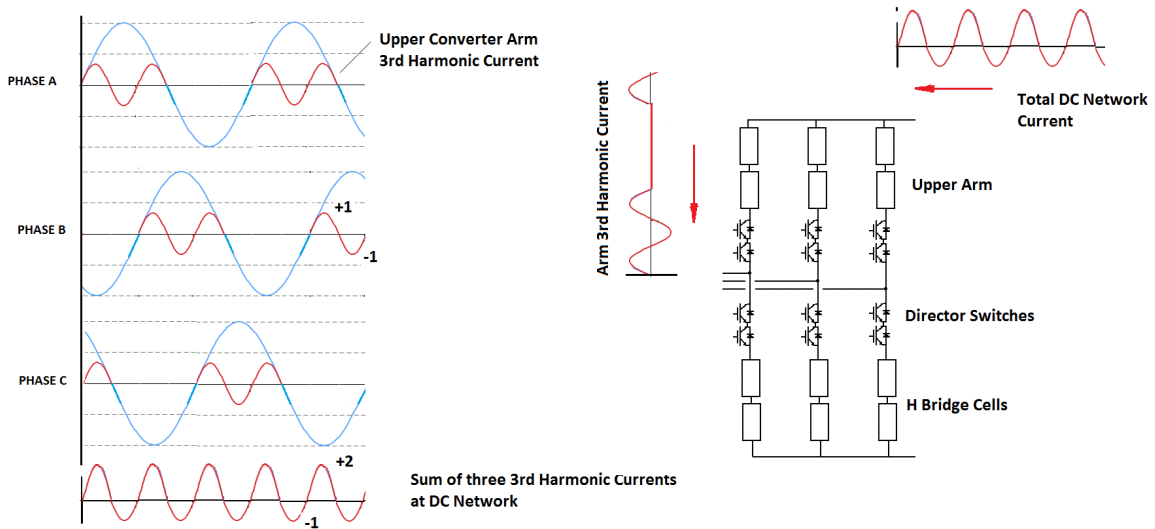


Figure 6: Waveforms for third harmonic energy balancing strategy.

To maximize the effectiveness of the third harmonic technique the duty-cycle angle has to be set to π and the third harmonic has to be in phase with the rectification process of the director switches, i.e. $\phi_3 = -3\phi_S = 0$. The simplified energy balancing equations (9)-(11) will be as follows:

$$E_3^+ = -2 \frac{V_{DC}^+ \hat{I}_3}{3\omega} \quad (9)$$

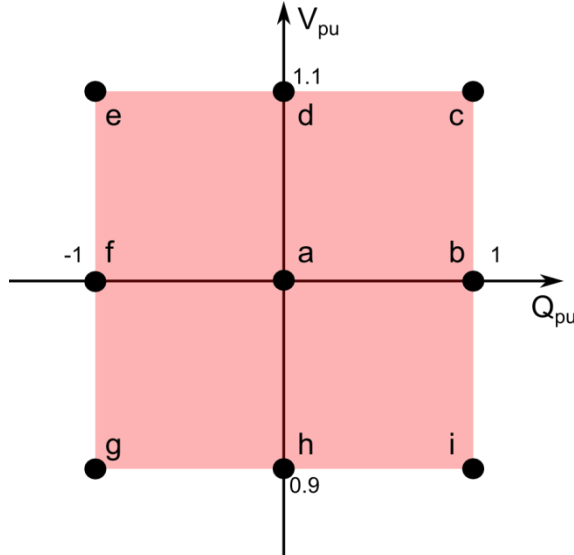
$$E_3^- = -2 \frac{V_{DC}^- \hat{I}_3}{3\omega} \quad (10)$$

$$E_3 = -2 \frac{V_{DC} \hat{I}_3}{3\omega} \quad (11)$$

Dividing the energy from the overlap technique and the results obtained in equation (11) to compare the effectiveness of both techniques, for the same current magnitude the triplen harmonic injection technique will be able to deliver significantly more energy. Also, this method does not depend on the value of the overlap angle, and thus does not adversely affect the efficiency of the converter, making the triplen harmonic energy balancing technique a practical alternative.

Simulations

A 20kV DC, 1kA converter model with 9 Full-Bridge cells per arm is used to simulate the performance of the new energy balancing technique. The nominal voltage of the cell capacitors is of 1.5kV, and simulations have been run in the following operation envelope:



- a) $P = P_{nom}$; $Q = 0$; $V_{ac} = 1 \text{ pu}$.
- b) $P = P_{nom}$; $Q = Q_{ind \text{ max}}$; $V_{ac} = 1 \text{ pu}$.
- c) $P = P_{nom}$; $Q = Q_{ind \text{ max}}$; $V_{ac} = 1.1 \text{ pu}$.
- d) $P = P_{nom}$; $Q = 0$; $V_{ac} = 1.1 \text{ pu}$.
- e) $P = P_{nom}$; $Q = Q_{cap \text{ max}}$; $V_{ac} = 1.1 \text{ pu}$.
- f) $P = P_{nom}$; $Q = Q_{cap \text{ max}}$; $V_{ac} = 1 \text{ pu}$.
- g) $P = P_{nom}$; $Q = Q_{cap \text{ max}}$; $V_{ac} = 0.9 \text{ pu}$.
- h) $P = P_{nom}$; $Q = 0$; $V_{ac} = 0.9 \text{ pu}$.
- i) $P = P_{nom}$; $Q = Q_{ind \text{ max}}$; $V_{ac} = 0.9 \text{ pu}$.

Figure 7: Simulated operation points.

In figure 8 and figure 9 the simulation results at points g, h, c, e, d and i are pictured. In these operating conditions, the average capacitor cell voltages in the arms stabilize to 1.5 kV in approximately 0.35 seconds after the ramp.

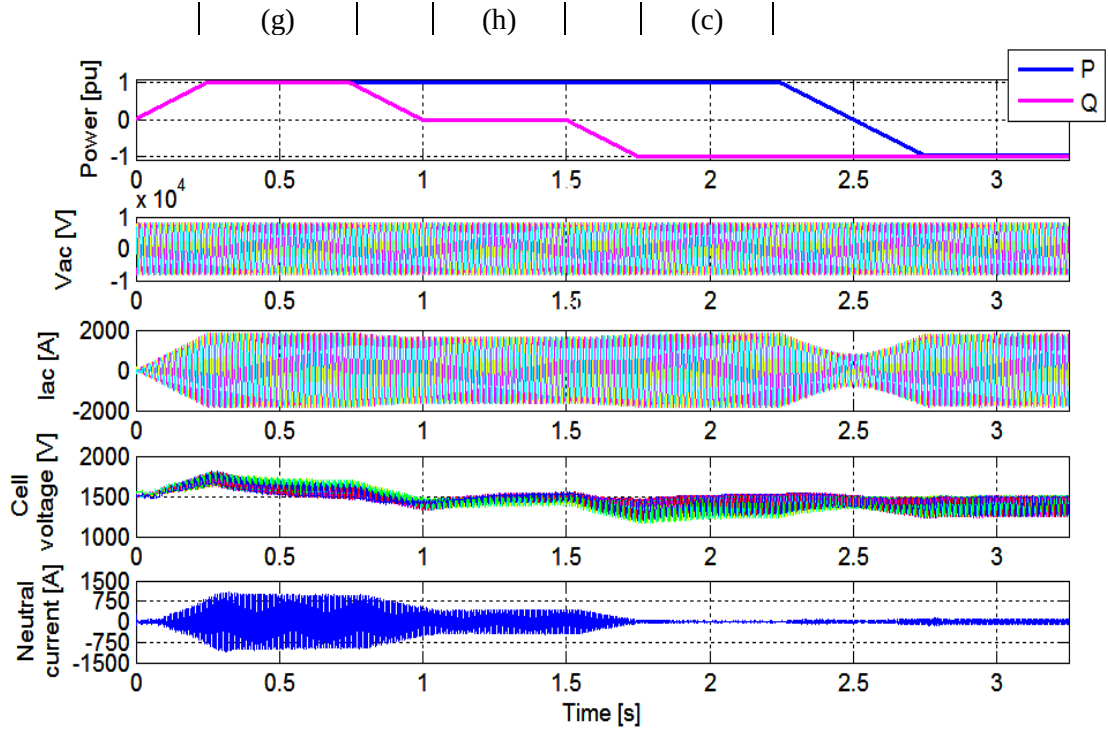


Figure 8: Simulation results with 0.9 Vpu.

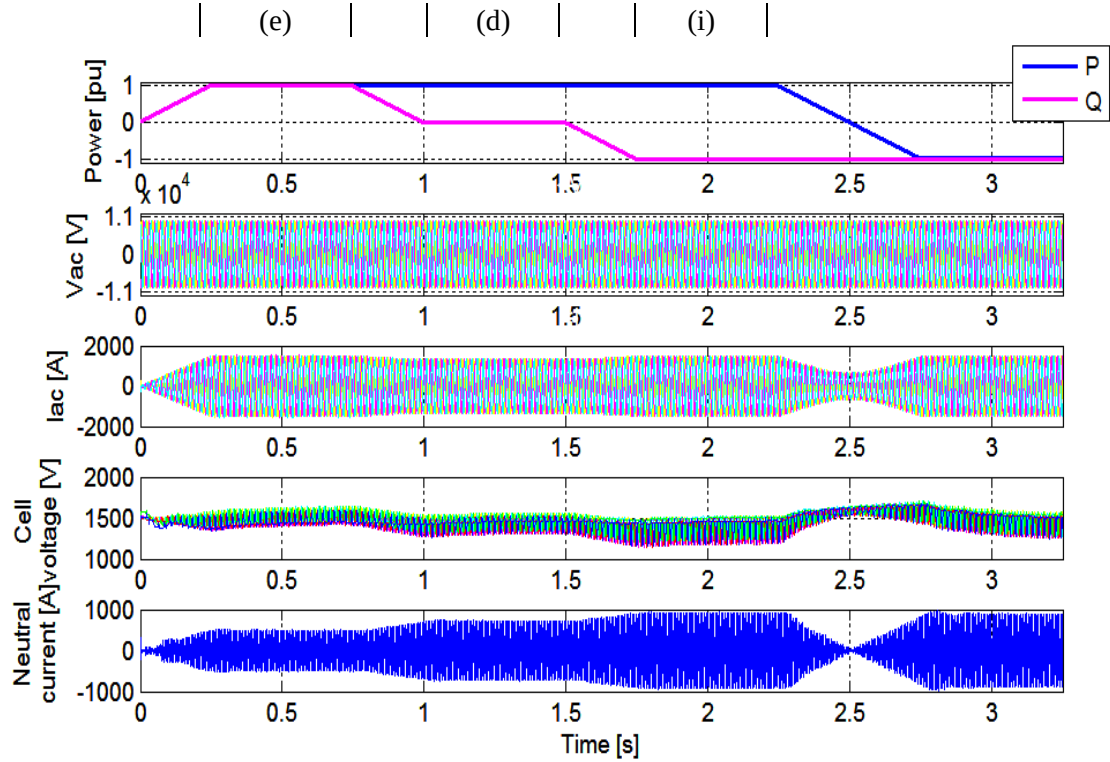


Figure 9: Simulation results with 1.1 Vpu.

Conclusion

The Alternate Arm Converter can be considered a hybrid between a Modular Multilevel Converter and a 2 level converter. The variant of the AAC analyzed in this paper uses Full-Bridge cells in series with Director Switches and a star transformer with the neutral connected to the middle point of the DC bus. The Director Switches are responsible for alternating the conduction of each Arm, leading to a significant reduction in the number of cells in the stacks compared to a MMC. However, due to the

operation of the Director Switches, the energy balancing of this type of converters becomes particularly challenging. A novel energy balancing technique using balanced zero phase sequence third harmonic current that overcomes these challenges is presented and mathematically analyzed in this paper. Unlike other energy balancing techniques, the energy that can be exchanged with the presented method is not limited by the width of the overlap angle, and thus is able to balance the energy stored in the cell capacitors more effectively. Also, the possibility using a small overlap angle reduces the size and improves the overall efficiency of the converter.

The model with the proposed energy balancing technique has shown good stability in all the operation points defined in figure 7, keeping the average cell capacitor voltages in the arms close to the reference value and stabilizing the converter in less than 0.6 seconds after the ramp in all the operation points.

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