Assessment of Sequence Extraction Methods Applied to MMC-SDBC STATCOM Under Distorted Grid Conditions

Ahmed Meligy, Taoufik Qoria, and Ilknur Colak, Senior Member, IEEE

Abstract—Under grid distortions, Modular Multilevel Converters (MMC) must adopt proper control strategies to fulfill the power system requirements and ensure a stable operation. An inappropriate control under such conditions may lead to energy unbalances between the MMC legs, inaccurate current injection, and failure in the synchronization process. In this context, sequence extraction methods play a critical role in enhancing the performance of the control, firstly, by aiding the Phase-Locked Loop (PLL) to maintain the synchronization with the AC grid by following the positive sequence fundamental component of the voltage, secondly, by allowing accurate active and reactive currents injection via the decoupled Voltage Oriented Control (dVOC), thirdly, by properly managing the internal energy of the MMC through the circulating current control. In prior researches, some sequence extraction methods have been used for MMC STATCOM. However, the sequence extraction was not the core of the performed studies and their impact on the system behavior has not been highlighted or tested in several grid conditions. This work fills this gap by first assessing the performance of a Single Delta Bridge Cell MMC (SDBC-MMC) STATCOM with four well-known sequence extraction methods (i.e., Decoupled Double Synchronous Reference Frame (DDSRF), Dual Second Order Generalized Integrator (DSOGI), Improved DSOGI, and Fortescue matrix-based (FMB) filter under normal and abnormal grid conditions, then, finding the most suitable one in terms of stability, dynamics, and functionalities.

Index Terms—DC voltage offset, harmonics, SBDC-MMC, sequence extraction methods, unbalanced grid voltage.

I. INTRODUCTION

Due to the increase of non-linear and unbalanced loads, in the modern medium voltage (MV) grids, concerns about power quality are on the rise [1]. To mitigate these issues, STATCOM units are used to maintain appropriate performances under distorted grid conditions while respecting the grid code requirements [2]. Different MMC-based STATCOM topologies have been discussed in the literature for MV applications [3]: Single Star Bridge Cell (SSBC), Single Delta Bridge Cell (SDBC), Double Star Chopper Cell (DSCC), and Double Star Bridge Cell (DSBC). Referring to [4], the SDBC MMC, also named Delta Configured Cascaded H-Bridge converter (CHB) [5] is the most suitable MMC topology for STATCOM applications. Besides its high scalability, modularity, and efficiency, the SDBC has the advantage over the SSBC for its capability to regulate both positive and negative sequences of the reactive power and to ensure capacitor voltage balancing thanks to the circulating current flowing through its legs [3]. Additionally, from an economic point of view, the SDBC is more convenient as it requires less full-bridge cells compared to the double star topology [3].

For STATCOM applications, it is crucial to have a reliable operation and to ensure system stability during grid distortions caused by several factors e.g., DC offsets [6], [7], harmonics [8], voltage unbalances [9], and faults. DC components in the AC grid are mainly due to voltage or current measurements deviation, switching devices being non-linear, and A/D conversion error. These oscillations affect the grid voltage and current, and consequently lead to an inaccurate estimation of the grid angle and frequency, a fluctuation of the injected reactive power, and an unbalance of the energy between the MMC legs [5]. To mitigate these undesirable distortions, appropriate control strategies should be utilized, where the sequence extraction method plays an important role [15], [16]. It provides each symmetrical component separately and thereby enables the STATCOM to independently control the positive and negative sequence of the current and the voltage. In other words: 1) it allows the PLL to track the positive component of the AC voltage, and thus estimate properly the grid frequency and angle, 2) it decouples the grid current controller into positive and negative sequence current loops, and therefore gives more degrees of freedom to the control, 3) it allows the calculation of the required amount of the active power that serves to balance the clusters’ voltages. Many research have been devoted to investigate the control of the SDBC-MMC STATCOM under unbalanced conditions, and which incorporates a sequence
II. SYSTEM CONFIGURATION AND CONTROL

A. System Configuration

The studied system is illustrated in Fig. 1. It consists of an SDBC MMC connected to a 20 kV distribution power system through Maschinenfabrik Reinhausen platform, which comprises different connection transformers. In this work, the distribution system is represented by an equivalent three-phase voltage source \( v_{ea,b,c} \) in series with its equivalent impedance \( L_g, R_g \). The SDBC MMC presents between each two phases of the grid voltage \( u_j \) (\( j = 12, 23, 31 \)) a leg consisting of a reactance \( L_\Delta \), and \( N \) H-bridge cells.

A three-phase current source \( i_{\mu_{a,b,c}} \) is connected in parallel with the MMC to emulate the nonlinear load and generate the current harmonics.

The variables \( i_2(x = ab, bc, ca) \), \( \Delta_{u,ab,c} \), \( v_{lm} \), \( v_{en} \), and \( i_{\mu_{a,b,c}} \) depicted in Fig. 1 refer to the internal currents, the compensating currents, the cluster voltages, the capacitors voltages, and the grid currents, respectively.

B. MMC-SDBC STATCOM Control Strategy Under Distorted Grid Conditions

The control strategy adopted for the MMC SDBC STATCOM is described in Fig. 2. It is divided into five main parts: Synchronization, decoupled Voltage Oriented Control (dVOC), Cluster Voltage Balancing Control, Harmonics Compensation/Rejection, and Voltage Reference Generation. Each control function is highlighted in Fig. 2 and discussed in the following subsections.

1) Synchronization: A common method to achieve grid synchronization is using the Synchronous Reference Frame Phase-Locked Loop (SRF-PLL) [11], [21]. The SRF-PLL is used as part of the control system that aims to acquire the grid phase angle and the grid frequency [11], [12]. It aligns the rotating reference frame with the direct (d) positive sequence component of the voltage and sets the quadrature (q) positive sequence component to zero through a PI controller. Thus, \( v_q^+ \) takes the value of the voltage magnitude, whereas \( v_q^+ \) is used to detect the grid frequency and the positive phase angle [22], [23]. Since the negative sequence is rotating conversely to the positive sequence [24], the negative angle is determined by integrating \(-\dot{\omega}_g\).

2) Decoupled Voltage Oriented Control: The dVOC simultaneously manages the active current (\( d \)—component) and the reactive current (\( q \)—component) for both positive and negative sequences [11], [23], [25]. The \( d-q \) currents are controlled via four-parallel PI controllers. \( L_T\dot{\omega}_g i_q^+ + \Delta_{d,q} \) terms and the grid-voltage feed-forwards are considered in the control feedback to decouple the \( d-q \) components and to reject the grid disturbances, respectively. Note that \( L_T \) is equal to the sum of \( L_\Delta/3 \) and the equivalent inductance \( L_{eq} \) of the transformer (340 V/4.3 kV). \( I_{\mu_{a,b,c}}^\Delta \) and \( I_{\mu_{a,b,c}}^\Delta \) have the same functionality as \( I_{\Delta_d} \) and \( I_{\Delta_q} \) for the conventional current controller in balanced conditions, whereas \( I_{\mu_{a,b,c}}^\Delta \) and \( I_{\mu_{a,b,c}}^\Delta \) are regulated separately to compensate the current during unbalanced grid conditions.
MELIGY et al.: ASSESSMENT OF SEQUENCE EXTRACTION METHODS APPLIED TO MMC-SDBC STATCOM

Fig. 1. Model of MMC SDBC STATCOM Connected to 20 kV distribution power system through Maschinenfabrik Reinhausen platform.

Fig. 2. MMC-SBDC STATCOM control strategy under distorted grid conditions.

The references are provided by an outer DC voltage control and the power control [11], [25] given in (1).

The DC voltage in the DC control loop is defined as the average value of the total capacitor voltages $v_{c_{totx}}$. It contains fluctuations around $\omega$ and $2\omega$, which may affect the current controller operation. Therefore, a notch-filter or a moving average filter (MAF) are used in the DC voltage measurements to avoid the stated issue.

$$
\begin{bmatrix}
I_{g_d}^+ \\
I_{g_q}^+ \\
I_{g_d}^- \\
I_{g_q}^-
\end{bmatrix} =
\begin{bmatrix}
V_d^+ & V_q^+ & V_d^- & V_q^- \\
V_d^- & V_q^- & V_d^+ & V_q^+ \\
V_q^- & -V_d^- & V_q^+ & -V_d^+ \\
V_q^+ & -V_d^+ & V_q^- & -V_d^-
\end{bmatrix}^{-1}
\begin{bmatrix}
P^+ \\
P_q^+ \\
P_d^- \\
P_q^-
\end{bmatrix}
$$

When no grid faults occur, $I_{g_d}^-$ and $I_{g_q}^-$ are equal to zero. Contrariwise, during grid disturbances, two operation modes can be achieved by the STATCOM using the dual current controller. The negative sequence references $I_{g_d}^-$ and $I_{g_q}^-$ could be set to zero in order to eliminate the negative sequence and hence guarantee a symmetrical current, or, they can be used to suppress the second harmonic power oscillations by injecting an appropriate negative sequence current thanks to the power controller.

Note that either active or reactive power oscillations could be suppressed at a time. Therefore, either $P_{c2}$ and $P_{s2}$ are set to zero while $Q_{c2}$ and $Q_{s2}$ are omitted from the matrix or vice versa.

3) Cluster Voltage Balancing Control: The control of capacitors voltage balancing across each leg depends on the total power flow between the STATCOM and the grid. Note that under unbalanced conditions, the negative sequence components of both voltage and current contribute to the total power exchange between the converter and the AC grid. This may cause unbalanced power sharing among legs if no adequate control is adopted. Referring to [4], the circulating current could be employed as a degree of freedom to ensure capacitors voltage...
balancing under balanced and distorted grid conditions. As illustrated in Fig. 2, the cluster voltage balancing control calculates the reference value of the circulating current, which can be written as:

\[ i_0 = I_0 \cos (\hat{\theta}_g + \phi_0) \]  

(2)

The square values of the cluster voltages are controlled via two PI-controllers. The power disturbances in the clusters are denoted by \((P_{ab}, P_{bc}, P_{ca})\). According to [4], the magnitude and the phase of the circulating current reference are given by:

\[ I_0 = \frac{P_{ab} - X_{11}}{X_1 \cos \phi_0 + X_2 \sin \phi_0} \]  

(3)

\[ \phi_0 = \arctan \left( \frac{P_{ab} - X_{11}}{(P_{ab} - X_{11})X_4 - (P_{bc} - X_{22})X_2} \right) \]  

(4)

with,

\[ X_{11} = \frac{V^+ + V^-}{2} \cos \left( \delta^+ - \phi^- + \frac{\pi}{3} \right) \]

\[ + \frac{V^+ - V^-}{2} \cos \left( \delta^- - \phi^+ - \frac{\pi}{3} \right) \]

\[ X_{22} = \frac{V^+ + V^-}{2} \cos \left( \delta^+ - \phi^- + \pi \right) \]

\[ + \frac{V^+ - V^-}{2} \cos \left( \delta^- - \phi^+ - \pi \right) \]

\[ X_1 = \frac{\sqrt{3}}{2} V^+ \cos \left( \delta^+ + \frac{\pi}{6} \right) + \frac{\sqrt{3}}{2} V^- \cos \left( \delta^- - \frac{\pi}{6} \right) \]

\[ X_2 = \frac{\sqrt{3}}{2} V^+ \sin \left( \delta^+ + \frac{\pi}{6} \right) + \frac{\sqrt{3}}{2} V^- \sin \left( \delta^- - \frac{\pi}{6} \right) \]

\[ X_3 = \frac{\sqrt{3}}{2} V^+ \cos \left( \delta^+ - \frac{\pi}{2} \right) + \frac{\sqrt{3}}{2} V^- \cos \left( \delta^- + \frac{\pi}{2} \right) \]

\[ X_4 = \frac{\sqrt{3}}{2} V^+ \sin \left( \delta^+ - \frac{\pi}{2} \right) + \frac{\sqrt{3}}{2} V^- \sin \left( \delta^- + \frac{\pi}{2} \right) \]

In this paper, the generated circulating current reference is compared to the measured one and controlled through a Proportional Multi-Resonant controller (PMR) given in (5), instead of the proportional controller conventionally used in the literature. The aim is to perfectly track the reference signal, which improves the quality of generated output voltage \(v_m^*\).

\[ H_{PR} = k_p + \sum T_s \frac{1 - z^{-1} \cos (\omega_0 T_s)}{1 - 2z^{-1} \cos (\omega_0 T_s) + z^{-2}} \]  

(5)

The PR is discretized using the Impulse Variant Method (IVM) because of its stability with high range of harmonics.

4) Harmonics Compensation/Rejection: The harmonics control concept is illustrated in Fig. 2 and given with more details in [8]. Usually, the odd harmonics are targeted as they are more dominant in the grid. The measured current at the PCC \(i_g\) undergoes sequence extraction at different phase angles/harmonic frequencies (i.e. 3rd, 5th, . . .), thus transforming each harmonic component to its DC equivalent represented in the \(d-q\) frame. The transformed DC signals are compared with the corresponding reference signal. If the reference is set to zero, then harmonic compensation takes place and the STATCOM takes all the harmonics from the grid. Otherwise, the harmonics remain on the grid side and the STATCOM output is unaffected. Similar to the dVOC, each harmonic component is regulated via dual-PI controllers.

5) Voltage Reference Generation: The aim of this control is to generate a voltage reference for each leg that will be used thereafter to generate the modulation index \(m\) in the case of an average model, or the pulses \(q_i\) in the case of a detailed switching model [26], [27]. In this paper, only the average model is used since the paper focuses on the system level.

The reference voltage of each leg is determined based on the reference voltages \(v_{m,1-3}^*\) generated by the current controllers and \(v_0\) generated by the circulating current controller, such that:

\[
\begin{bmatrix}
 v_{m,ab}^* \\
 v_{m,bc}^* \\
 v_{m,ca}^*
\end{bmatrix} = \begin{bmatrix}
 v_{v1}^* - v_{v2}^* + v_0^* \\
 v_{v2}^* - v_{v3}^* + v_0^* \\
 v_{v3}^* - v_{v1}^* + v_0^*
\end{bmatrix}
\]  

(6)

III. SEQUENCE EXTRACTION

Under non-ideal grid conditions, the MMC may fail to accurately synchronize with the AC grid and/or inject the desired current due to the interaction between the positive and negative sequences [22]. By implementing two Park’s transformations using two frames rotating in opposite directions (+\(\theta\), –\(\theta\)), the resultant is two signals formed by the coupling of both positive and negative sequences [22]. These coupled signals are given by (7) and (8), respectively. \(x\) in the equations represents any electrical variable and the bar on top (e.g. \(\bar{x}\)) represents a DC component of this variable.

\[
\begin{bmatrix}
 x_d^+ \\
 x_q^+
\end{bmatrix} = \begin{bmatrix}
 \cos(2\theta) & \sin(2\theta) \\
 -\sin(2\theta) & \cos(2\theta)
\end{bmatrix} \begin{bmatrix}
 x_d \\
 x_q
\end{bmatrix} + \begin{bmatrix}
 \cos(2\theta) & \sin(2\theta) \\
 -\sin(2\theta) & \cos(2\theta)
\end{bmatrix} \begin{bmatrix}
 \bar{x}_d \\
 \bar{x}_q
\end{bmatrix}
\]  

(7)

\[
\begin{bmatrix}
 x_d^- \\
 x_q^-
\end{bmatrix} = \begin{bmatrix}
 \cos(-2\theta) & \sin(-2\theta) \\
 -\sin(-2\theta) & \cos(-2\theta)
\end{bmatrix} \begin{bmatrix}
 x_d \\
 x_q
\end{bmatrix} + \begin{bmatrix}
 \cos(-2\theta) & \sin(-2\theta) \\
 -\sin(-2\theta) & \cos(-2\theta)
\end{bmatrix} \begin{bmatrix}
 \bar{x}_d \\
 \bar{x}_q
\end{bmatrix}
\]  

(8)

To remove this coupling effect, a proper method of sequence extraction must be utilized. Four sequence extraction methods are investigated in this section.

A. Decoupled Double Synchronous Reference Frame (DDSRF)

DDSRF was presented in [13] as a solution for accurately detecting the positive sequence components under distorted or unbalanced voltage conditions. This method utilizes two rotating synchronous reference frames and decouples the sequence interaction by subtracting the interference of each sequence on the other. (9) and (10) provide a clear demonstration of the working principle of the DDSRF, which are obtained by rearranging (7) and (8). The implementation of (9) and (10) can be seen in Fig. 3. Following [13], the extracted components from the DDSRF go through a low-pass filter (LPF) that is
Fig. 3. Sequence extraction using DDSRF.

Fig. 4. SOGI filter.

tuned to a cut-off frequency of $\tilde{\omega}_g \sqrt{2}$.

$$\begin{bmatrix} \bar{x}_d \\ \bar{x}_q \end{bmatrix} = \begin{bmatrix} \bar{x}_d \\ \bar{x}_q \end{bmatrix} - \begin{bmatrix} \cos(2\theta) & \sin(2\theta) \\ -\sin(2\theta) & \cos(2\theta) \end{bmatrix} \begin{bmatrix} \bar{x}_d \\ \bar{x}_q \end{bmatrix}$$

$$\begin{bmatrix} \bar{x}_d \\ \bar{x}_q \end{bmatrix} = \begin{bmatrix} x_d \\ x_q \end{bmatrix} - \begin{bmatrix} \cos(-2\theta) & \sin(-2\theta) \\ -\sin(-2\theta) & \cos(-2\theta) \end{bmatrix} \begin{bmatrix} x_d \\ x_q \end{bmatrix}$$

B. Dual Second Order Generalized Integrator (DSOGI)

SOGI is the most popular method used for grid synchronization [28], [29] and is made up of a frequency adaptive band-pass filter. One of the main features of the SOGI is its dual outputs: the (band-pass) filtered signal $x_f$ and a $90^\circ$ shifted orthogonal (low-pass) filtered signal $x_q^f$. The SOGI filter is described by the block diagram in Fig. 4, where, $k$ is the constant responsible for changing the bandwidth of the filter.

Following [30], and using the Fortescue matrix, the positive and negative sequences can be calculated using (11) and (12) respectively. DSOGI is a combination of two SOGIs implemented for $\alpha$ and $\beta$ components. The implementation of the sequence extraction using DSOGI is represented in Fig. 5.

$$\begin{bmatrix} x_+^\alpha \\ x_+^\beta \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & -e^{-j(\pi/2)} \\ e^{-j(\pi/2)} & 1 \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix}$$

$$\begin{bmatrix} x_-^\alpha \\ x_-^\beta \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & e^{-j(\pi/2)} \\ -e^{-j(\pi/2)} & 1 \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix}$$

C. Improved Dual Second Order Generalized Integrator (IDSOGI)

Since the $x_f$ and $x_q^f$ signals of the SOGI are only filtered input signals, the SOGI has no ability to suppress DC offsets [28]. On the other hand, controlling the gain $k$ to attenuate low-order harmonics will come at the expense of the system dynamics [28]. Therefore, authors in [6] have proposed an improved SOGI (ISOGI) with the aim of tackling the limitations of the conventional one i.e., compensating DC offsets and increasing the control accuracy without compromising the system dynamics. Its block diagram is presented in Fig. 6.

This method increases the filtering capabilities of the SOGI by transforming it to a third order transfer function as shown in Fig. 6. The additional integrator is used to generate a state variable that is equal to the DC offset, which is subtracted from the input signal. The parameter $k_0$ is a gain used in the DC offset estimation channel, and it is tuned based on the roots of the system closed-loop transfer function [6]. Similar to the DSOGI method, the sequences are extracted by substituting the conventional SOGI filter from Fig. 5 by ISOGI and therefore forming the IDSOGI.

D. Fortescue Matrix-Based Filter in $\alpha\beta$ Frame (FMB Filter)

This technique decouples the sequences in the $\alpha\beta$ frame following (11) and (12). It uses an LPF to remove second order harmonics and a High Pass Filter (HPF) to shift the signal by $90^\circ$. Both are set with a cut-off frequency of 100 Hz. The block diagram of this method is shown in Fig. 7.

IV. VERIFICATION AND COMPARISON OF THE SEQUENCE EXTRACTION METHODS

To verify the proficiency of the proposed control based on the aforementioned sequence extraction methods, time-domain simulations were performed in Matlab/Simulink and conducted...
with the system and control parameters listed in Table I. The simulation time step is $T_{sim} = 1$ ms. The system is running with $T_{sys} = T_{sim}$ and the control is running with $T_{c} = 50$ ms.

Five test cases are performed in the following subsections to assess the system behavior based on each sequence extraction method: 1) Reactive power change, 2) Single-phase voltage sag, 3) Three-phase voltage sag, 4) Harmonics injection, 5) Single-phase grid voltage measurement DC offset.

Note that the tuning of the control loops is unchanged when switching from one method to the other and from one test case to the other. This is important to find out the most suitable method that can deal with different distorted conditions without a need for additional control adaptations.

A. Case A: Reactive Power Change

A step change of $Q = 0.9$ p.u. is applied to the system at $t = 0.5$ s. The grid current and the reactive power responses based on each extraction method are presented in Fig. 8. The results show a stable system operation with the four techniques. However, their transient behavior is different, i.e., the FMB filter presents the lowest overshoot of 46% compared to the DDSRF, DSOGI, and IDSOGI which exhibited an overshoot of 156%, 178.5%, and 178%, respectively. Moreover, with the FMB filter, the system recovers stably its equilibrium point within less than 15 ms. With DDSRF, DSOGI, and IDSOGI, the system took approximately 50 ms to recover. This difference is explained by the fact that DDSRF, DSOGI, and IDSOGI introduce $\tau \geq 4.5$ ms time-delay in the current and voltage measurements and thereby a delay in the control, whereas, the FMB filter introduces a smaller time-delay of $\tau = 1.6$ ms, which results in faster regulation. Based on the obtained results, the FMB filter presented the best dynamic performances in case of an operating point change under balanced grid conditions.

B. Case B: A Single-Phase Voltage Sag

The voltage sag along with the grid currents for each method is given in Fig. 9. For this test case, the system is initially operating with $Q = 1$ p.u., then a 100% single phase voltage sag occurs at $t = 0.5 s$. The results globally show the proficiency of the dVOC adopted to compensate the negative sequence of the currents caused by the voltage unbalance. Compared to test case A, the voltage sag leads to the same overcurrent transient peaks for each method. However, regarding the recovery time duration, the system based on the FMB filter stabilized within less than 20 ms, whereas, the DDSRF, DSOGI, and IDSOGI recover stably their operating points with noticeable distortions within 50 ms, 55 ms, and more than 100 ms, respectively. In this case, and for the same reasons as for Case A, the FMB filter presented the best dynamic performances under unbalanced faulty conditions, followed by the DDSRF, DSOGI, and finally the IDSOGI.
C. Case C: Three-Phase Voltage Sag

For this test case, the system is initially operating with $Q^* = 0.5$ p.u. Then, a 250 ms three-phase voltage sag is applied at $t = 0.5$. The grid voltages and currents signals are presented in Fig. 9. A similar trend to test case B is illustrated by the obtained results i.e., the FMB-filter showed the lowest current overshoot of 148% and 194% at both the beginning and end of the fault event, respectively, followed by DDSRF with 379% and 355%, then DSOGI with 417% and 388%, and finally the IDSOGI with 419% and 554%. As seen in Fig. 10, the IDSOGI exhibited an additional transient response after the fault. This transient behavior exists with all sequence extraction methods, however it is more dominant with the control strategy utilizing IDSOGI due to the high abrupt grid current which leads to a larger deviation of the cluster voltages from their reference compared to the other methods. In the case of the IDSOGI, the cluster voltages attenuate and stabilize within 130 ms. In terms of system current dynamics, all the extraction methods showed the same settling time as in test case B, with FMB filter once more having the fastest system recovery. In accordance with the previous two test cases, the FMB-filter is the most suitable sequence extraction method for balanced grid conditions as well as both unsymmetrical and symmetrical fault conditions.

D. Case D: Harmonics Injection

The capability of the sequence extraction methods to retrieve the symmetrical components oscillating at various frequencies is assessed in this section. Initially, the system is operating with $Q^* = 0.5$ p.u, then, three odd harmonics were injected to the grid, the $5^{th}$, $7^{th}$ and $19^{th}$ harmonics with the magnitudes 0.1 p.u, 0.1 p.u, and 0.2 p.u, respectively. Both compensation and rejection modes are evaluated. Simulation results are gathered in Fig. 11 and Fig. 12, where, the grid current $i_g$, the MMC compensated current $i_{\Delta}$, the Total Harmonic Distortion (THD), and the estimated grid frequency $\tilde{\omega}_g$ are displayed.

1) Control Mode I: Harmonic Compensation: One can notice from the obtained results in Fig. 11 that the STATCOM absorbed the harmonic content as excepted, while the grid current is kept free from any harmonics (THD = 0.35%). The harmonic content of the grid current is almost the same with the four studied methods. Therefore, the DDSRF, DSOGI, IDSOGI, and FMB filter could be interchangeable in such a condition.

2) Control Mode II: Harmonic Rejection: The results for this control mode can be seen in Fig. 12. Conversely to the harmonics compensation mode, the STATCOM output currents $i_{\Delta}$ show almost no harmonic content with the DDSRF, DSOGI, and IDSOGI since the harmonics are rejected from the STATCOM output and completely fed by the AC grid (THD = 48.9%). This is not completely the case with the FMB filter, actually, the grid current harmonics naturally affect the AC voltage $v_g$ used by the PLL for synchronization. Since the FMB has no harmonics filtering capability as the DDSRF, DSOGI, and IDSOGI, the estimated frequency through it is consequently affected in steady state, which results in an inaccurate harmonics rejection. In this control mode, the four extraction methods guarantee a stable operation, nevertheless, the DDSRF, DSOGI, and IDSOGI show higher performances against the FMB filter.

E. Case E: AC Voltage Measurement Single-Phase DC Offset

A 0.1 p.u DC offset is applied to the measured AC voltage $v_g$ phase A at $t = 0.5$. The effect of the DC offset on the grid voltage magnitude positive sequence $V_g^+$, the estimated grid
frequency $\omega_g$, and the cell’s capacitor voltages $v_c$ is analyzed. The results are shown in Fig. 13. The DC offset commonly introduces a fundamental frequency oscillation on the AC voltage. Out of the four sequence extraction methods, only the IDSOGI is able to reject the DC offset, and consequently ensure the system requirements by injecting a balanced AC current. From the other side, the DSOGI, the DDSRF, and the FMB filter are affected by the DC offset leading to the migration of the grid voltage oscillations to the estimated grid frequency. Despite that the three methods are impacted by this event, the consequences are significantly different i.e., with the DDSRF and the DSOGI, the grid currents and capacitor voltages are deteriorated and are out of control. Whereas, with the FMB, the capacitor voltages are almost non-affected and the grid currents are the image of the AC voltage containing the same DC offset degree of 10%, but still having a sinusoidal waveform.
V. CONCLUSION

In this paper, four sequence extraction methods based on a decoupled control algorithm for the SDBC-MMC STATCOM have been analyzed under different grid conditions and are compared in terms of stability, dynamic performances, and functionality. Regarding stability aspects, the four extraction methods resulted in stable operation of the studied system in various grid conditions. The main differences between the extraction methods are noted when comparing their effect on the dynamic performances and their functionalities. The difference in the transient response of the system is mainly attributed to the time delay introduced in the measurements by each method. On the basis of the simulation results, the FMB-filter is the most suitable technique to be used for the SDBC-MMC STATCOM to achieve higher transient dynamic performances under normal grid operation as well as single or multi-phase voltage sag conditions due to its short time-delay. In terms of functionality, the filtering capabilities of each method, especially in case of different harmonics and DC offsets, were assessed. The IDSOGI showed the most promising results as compared to its alternatives (DDSRF and DSOGI) as it has better filtering capabilities against harmonics and DC offsets. Since, the main goals in a power system are to support the AC grid, reject the grid disturbances, and guarantee the overall system stability, IDSOGI presented the best compromise between dynamic performances and functionalities for these targets. For future work, the authors suggest a combination of the FMB filter and the IDSOGI as a part of the control of the SDBC-MMC STATCOM. Such that, the FMB filter would be used to extract the symmetrical components of the current due to its fast response time and rejection of $2\omega$ oscillations, while the IDSOGI could be used in the voltage measurements to guarantee the grid harmonics and DC offsets rejection utilizing its superior filtering capabilities. Additionally, in this paper the grid weakness has not been considered, and in which the sequence extraction methods and the controllers tuning may have a significant impact on both small and large signal stability that deserves a special attention.

ACKNOWLEDGMENT

The authors would like to thank the contribution of Dr-ing Cem Özgür Gercek, MR EAP team and Amantys team.

REFERENCES

[1] T. Qoria et al., “WP3-Control and operation of a grid with 100% converter-based devices. Deliverable 3.2: Local control and simulation tools for large transmission systems,” MIGRATE Project, Tech. Rep., 2018, doi: 10.13140/RG.2.2.31256.34561.

[2] F. Shahnazian et al., “Control of MMC-based STATCOM as an effective interface between energy sources and the power grid,” Electron., vol. 8, no. 11, 2019, Art. no. 1264.

[3] H. Akagi, “Classification, terminology, and application of the modular multilevel cascade converter (MMCC),” in Proc. Int. Power Electron. Conf. Asia, 2010, pp. 508–515.

[4] A. F. Cupertino, J. V. M. Farias, H. A. Pereira, S. I. Seleme, and R. Teodorescu, “Comparison of DSCC and SDBC modular multilevel converters for STATCOM application during negative sequence compensation,” IEEE Trans. Ind. Electron., vol. 66, no. 3, pp. 2302–2312, Mar. 2019.

[5] P. Wu, Y. Chen, and P. Cheng, “The delta-connected cascaded H-bridge converter application in distributed energy resources and fault ride through capability analysis,” IEEE Trans. Ind. Appl., vol. 53, no. 5, pp. 4665–4672, Sept./Oct. 2017, doi: 10.1109/TIA.2017.2702110.

[6] J. Li, J. Zhao, J. Wu, and P. Xu, “Improved dual second-order generalized integrator PLL for grid synchronization under non-ideal grid voltages including DC offset,” in Proc. IEEE Energy Convers. Congr. Expo., 2014, pp. 136–141, doi: 10.1109/ECCCE.2014.6953386.

[7] S. Lubura, S.-A. Lale, M. Elka, and M. Šoja, “Single-phase phase locked loop with DC offset and noise rejection for photovoltaic inverters,” IET Power Electron., vol. 7, no. 9, pp. 2288–2299, Sep. 2014.

[8] F. Blaabjerg, R. Teodorescu, M. Lisserre, and A. V. Timbus, “Overview of control and grid synchronization for distributed power generation systems,” IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1398–1409, Oct. 2006, doi: 10.1109/TIE.2006.881997.
[9] O. J. K. Oghoroda and L. Zhang, “Unbalanced and reactive load compensation using MMCC-Based SATCOMs with third-harmonic injection,” IEEE Trans. Ind. Electron., vol. 66, no. 4, pp. 2891–2902, Apr. 2019, doi: 10.1109/TIE.2018.2849962.

[10] G. Buticchi, E. Lorenzani, and G. Franceschini, “A DC offset current compensation strategy in transformerless grid-connected power converters,” IEEE Trans. Power Del., vol. 26, no. 4, pp. 2743–2751, Oct. 2011, doi: 10.1109/TPWD.2011.2167160.

[11] E. Ozsoy et al., “Control strategy for a grid-connected inverter under unbalanced network conditions—A disturbance observer-based decoupled current approach,” Energies, vol. 10, no. 7, 2017, Art. no. 1067, doi: 10.3390/en10071067.

[12] K. Sharifabadi, L. Harnefors, H.-P. Nee, R. Teodorescu, and S. Norrga, Design, Control and Application of Modular Multilevel Converters for HVDC Transmission Systems, 1st ed. Hoboken, NJ, USA: Wiley, 2018.

[13] P. Rodríguez, J. Pou, J. Bergas, J. I. Candela, R. P. Burgos, and D. Boroyevich, “Decoupled double synchronous reference frame PLL for power converters control,” IEEE Trans. Power Electron., vol. 22, no. 2, pp. 584–592, Mar. 2007, doi: 10.1109/TPEL.2006.890000.

[14] A. Meligy, T. Qoria, and I. Colak, “SDBC-MMC STATCOM control under unbalanced grid conditions based on different sequence extraction methods,” in Proc. 47th Annu. Conf. IEEE Ind. Electron. Soc., 2021, pp. 1–6.

[15] T. Hao, F. Gao, and T. Xu, “Fast extraction of symmetrical components from distorted three-phase signals based on asynchronous-rotational reference frame,” J. Power Electron., vol. 19, no. 4, pp. 1045–1053, Jul. 2019.

[16] H. Ahmed and M. Benbouzid, “Adaptive observer-based grid-synchronization and sequence extraction techniques for renewable energy systems: A comparative analysis,” Appl. Sci., vol. 11, no. 2, p. 653, 2021, doi: 10.3390/app11020653.

[17] D. Basic, M. Geske, and S. Schroeder, “Limitations of the H-bridge multilevel STATCOMs in compensation of current imbalance,” in Proc. 17th Eur. Conf. Power Electron. Appl. 2015, pp. 1–10, doi: 10.1109/EPE.2015.7311687.

[18] P. Wu, H. Chen, Y. Chang, and P. Cheng, “Delta-connected cascaded H-bridge converter application in unbalanced load compensation,” IEEE Energy Convers. Congr. Expo., vol. 53, no. 2, pp. 6043–6050, Mar./Apr. 2015, doi: 10.1109/ECCCE.2015.7310507.

[19] J. Jung, J. Lee, S. Sul, G. T. Son, and Y. Chung, “DC capacitor voltage balancing control for delta-connected cascaded H-bridge STATCOM considering unbalanced grid and load conditions,” IEEE Trans. Power Electron., vol. 33, no. 6, pp. 4726–4735, Jun. 2018, doi: 10.1109/TPEL.2017.2730244.

[20] E. Behrouzian, M. Bongiorno, and H. Z. De LaPurra, “Investigation of negative sequence injection capability in H-bridge multilevel STATCOM,” in Proc. 16th Eur. Conf. Power Electron. Appl., 2014, pp. 1–10, doi: 10.1109/EPE.2014.6910883.

[21] H. Ahmed, M. Benbouzid, M. Ahsan, A. Albarbar, and M. Shahjalal, “Frequency adaptive parameter estimation of unbalanced and distorted power grid,” IEEE Access, vol. 8, pp. 8512–8519, 2020, doi: 10.1109/ACCESS.2020.2964058.

[22] F. Sevliyis and H. Karaca, “Performance analysis of SRF-PLL and DDSRF-PLL algorithms for grid interactive inverters,” Int. Adv. Researches Eng., vol. 3, no. 2, pp. 116–122, 2019, doi: 10.35860/arej.412250.

[23] D. Siemaszko and A. Rufery, “Double-frame current control with a multivariable PI controller and power compensation for weak unbalanced networks,” 2015, arXiv:160701630.

[24] T. Wijthoven, G. Deconinck, T. Neumann, and I. Erlich, “Control aspects of the dynamic negative sequence current injection of type 4 wind turbines,” in Proc. IEEE PES Gen. Meeting Conf. Expo., 2014, pp. 1–5, doi: 10.1109/PESGM.2014.6938931.

[25] H.-S. Song and K. Nam, “Dual current control scheme for PWM converter under unbalanced input voltage conditions,” IEEE Trans. Ind. Electron., vol. 46, no. 5, pp. 953–959, Oct. 1999, doi: 10.1109/41.793344.

[26] S. Kannan, C. Poongothai, I. Colak, and W. Ali, “Selective harmonic elimination for modular multilevel converter with averaging and circulating current control,” in Proc. 7th Int. Conf. Renewable Energy Res. Appl., 2018, pp. 221–226.

[27] A. Biessal, W. Ali, R. Leedham, and M. Snook, I. Elsaybrouty and I. Colak, “A hybrid pulse width modulation technique with temperature control for modular multilevel converters,” in Proc. 22nd Eur. Conf. Power Electron. Appl., 2020, pp. P1–P9.

[28] J. Xu, H. Qian, Y. Hu, S. Bian, and S. Xie, “Overview of SOGI-Based single-phase phase-locked loops for grid synchronization under complex grid conditions,” IEEE Access, vol. 9, pp. 39275–39291, 2021, doi: 10.1109/ACCESS.2021.3063774.

[29] H. Ahmed and M. Benbouzid, “Simplified second-order generalized integrator-frequency-locked loop,” Adv. Elect. Electron. Eng., vol. 17, no. 4, pp. 405–412, 2019.

[30] P. Rodríguez, A. Luna, R. S. Muñoz-Aguilar, I. Etxeberria-Otadui, R. Teodorescu, and F. Blaabjerg, “A stationary reference frame grid synchronization system for three-phase grid-connected power converters under adverse grid conditions,” IEEE Trans. Power Electron., vol. 27, no. 1, pp. 99–112, Jan. 2012, doi: 10.1109/TPEL.2011.2159242.

Ahmed Meligy received the B.Sc. degree in electrical engineering from the American University of Sharjah, Sharjah, United Arab Emirates, in 2018 and the M.Sc. degree in renewable energy engineering and management, Albert-Ludwigs-Universität Freiburg, Freiburg im Breisgau, Germany, in 2022. He has been a Research Assistant with Maschinenfabrik Reinhausen since 2021. His research interests include power electronics, control systems, battery energy storage systems, smart grids, and optimization.

Taoufik Qoria received the M.S. degree in electrical engineering for sustainable development from Lille 1 University of Science and Technology, Villeneuve d’Ascq, France, in 2016 and the Ph.D. degree in electrical engineering from the ENSAM ParisTech - Laboratory of Electrical Engineering and Power Electronics (L2EP), Lille, France, in 2020. From 2019 to 2020, he has been working as a Research and Development Engineer on the modeling and control of the power inverters dominated power system with Ecole Centrale de Lille L2EP-Lab. He is currently a Senior Research and Development Power Electronics Engineer with Maschinenfabrik Reinhausen, Germany. His research interests include the integration of power electronic devices in power systems. He was the recipient of the Ph.D. student of the year, by IEEE PES France, in 2021.

Ilknur Colak (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical engineering program from Istanbul Technical University, Istanbul, Turkey. In last 21 years she was with Industry and Research Centers such as ABB, Ansaldo Richerhe, TUBITAK, CERN and Maschinenfabrik Reinhausen. Since January 2022 Colak has been with Schneider Electric-Secure Power, France, as the Technical Director. Her research interests include multilevel converter topologies, modulation schemes, transformerless concepts, high power resonant converters, insulation- coordination, EMC and grounding, reliability and wave energy conversion systems.