Reactive Power Compensation of Modular Multilevel Cascaded Converter STATCOM using Average Power Inter-Cluster Control Method under Unbalanced Voltage Conditions

Oghenewvogaga Oghorada* a) Non Member, Huang Han** Non Member, Ayodele Esan* Non Member

(Manuscript received May 27, 2020, revised Sept. 07, 2020)

Abstract: This presents a reactive power control strategy for the single delta bridge cell modular multilevel cascaded converter (SDBC-MMCC) for static synchronous compensator (STATCOM) under asymmetric voltage conditions. An average power balancing method is proposed to support continuous injection of reactive power under grid voltage fault conditions, considering sub-module capacitor voltage balancing and STATCOM maximum phase current protection. Analytical solutions of the STATCOM phase currents are presented. A maximum current limit control scheme is proposed to ensure continuous reactive power injection and STATCOM operation under unbalanced voltage condition. The fault-ride through capability of the SDBC STATCOM under asymmetrical condition is analyzed using the proposed method. A comparative analysis shows that the current requirement of the proposed strategy is superior to the zero-sequence current balancing technique.

Keywords: Static Synchronous Compensator; asymmetrical fault; modular multilevel cascaded converter; average active power balancing control; inter-cluster balancing; reactive power

1. Introduction

Static synchronous compensators (STATCOMs) have now established itself as a better tool in providing voltage control, reactive power control and current harmonic cancellation in power system networks [1-3]. In contrast to thyristor controlled reactors, static VAR compensators and capacitor banks, the STATCOM provide superior benefits of a smaller footprint, a low harmonic current supply to the grid, flexible and excellent dynamic response [4]. With the growth in electrical energy demand resulting from population growth rate, technological advancement; more unbalanced and non-linear loads are connected to the grid system. With the urgent need to reduce the emission of greenhouse gases, integration of renewable energy sources (RES) (i.e. solar and wind power plants) to the grid are increasing by the day. These integrations of renewable energy sources and the use of non-linear loads introduce power quality challenges to the power system network [5]. In handling these power system problems, reactive power support is very crucial since it provides grid voltage regulation, power factor improvement and fault ride-through capability especially for RES connected to the grid during asymmetric voltage conditions [4].

Modular multilevel cascaded converter (MMCC) based STATCOMs are more effective for high voltage and power applications compared to the two-level and multilevel converters because of their benefits of scalability, modular nature, reduced switching losses and reduced filtering requirement [6-10]. Even with the above-mentioned benefits of the MMCC-STATCOM, when applied under asymmetric voltage or unbalanced load conditions, power imbalance is experienced across each phase of the MMCC. This power imbalance is because the MMCC has no common dc bus across its three phases resulting from the sub-modules having separate dc-link capacitors [11-16] unlike in the case of two-level H-bridge converter. MMCC-STATCOMs are configured either as a single star or delta MMC [17]. Both configurations can provide positive and negative sequence reactive power and voltage regulation support. For this investigation, our attention is on the delta connected MMCC.

Several works of literature have investigated the delta-connected STATCOM [18-20] for grid applications. The power imbalance is the major challenge associated with MMCC-STATCOM. The major approach in addressing this problem is by categorizing the control power balancing strategies into three namely; overall capacitor voltage balancing, inter-cluster balancing and sub-module balancing control [21]. Among all the control balancing strategies, the inter-cluster power balancing technique is the most crucial because the unbalanced average active power across any phase results in sub-module voltage imbalance.

Several investigations have been carried out on this inter-cluster balancing of delta connected MMCC-STATCOM. [1], [12], [19] and [20] provided reactive power and unbalanced load compensation using sinusoidal zero-sequence current circulating in the three-phase clusters of the delta connected MMCC to maintain cluster active power balance. This zero-sequence current component is generated through three proportional+integral controllers across the three clusters of the delta connected STATCOM. In [18] a third harmonic component of the sinusoidal zero sequence current is added to its fundamental component to extend its operating range. Authors in
[13] use this sinusoidal zero sequence current in achieving inter-cluster balancing of STATCOM while rebalancing unbalance grid voltages. The limitation of using this zero-sequence current for unbalance condition was not discussed. [22] discussed in detail the influence of the degree of unbalance voltage in evaluating zero-sequence current. This research revealed that applying zero-sequence current for inter-cluster balancing control under unbalanced voltage condition, a large amount of current is required as the degree of voltage unbalance \( k_v \) increases. [23] investigated the use of STATCOM in providing reactive power support in suppressing voltage fluctuation created by unregulated large wind power plants connected to a weak power network. Authors in [24] discussed using zero-sequence current inter-cluster balancing technique under three current reference calculation strategies of active power oscillation elimination (APOE), reactive power oscillation elimination (RPOE) and balanced positive sequence current (BPSC). This paper revealed how these current references influence this inter-cluster balancing method when providing reactive power support to the grid under asymmetric voltage condition.

This paper presents an average power balancing technique for the delta connected MMCC-STATCOM. This proposed scheme provides continuous reactive power support and inter-cluster power balancing control of the sub-module dc capacitor voltages under asymmetric fault conditions. This proposed technique provides superior current requirements than the zero-sequence current technique. To ensure continuous safe reactive power support to the grid via the delta configured MMCC-STATCOM under asymmetric voltage condition, a maximum current limit control scheme is proposed and discussed. The paper is organized as follows: system configuration is presented in section 2; the average power inter-cluster balancing control method is presented in section 3; in section 4, the STATCOM control scheme of the maximum current limit control is presented; Section 5 analyses the influence of the proposed technique on the current rating requirement of the delta connected STATCOM under the asymmetric condition; the simulation results are validated and presented in section 6.

2. System Configuration

The single delta bridge converter (SDBC) MMCC STATCOM is shown in Fig. 1(a). Each phase comprises of three-level H-bridge (3L-HB) cascaded sub-modules as depicted in Fig. 1(b). The converter is connected to the grid through the converter filters. The transmission line is represented by the grid line impedance and \( v_m, v_a, v_c \) is the point of common connection (PCC) voltages.

Under unbalance voltage conditions, the phase voltages at the point of common coupling \( v_a, v_b, v_c \) and currents \( i_a, i_b, i_c \) are expressed as:

\[
\begin{align*}
    v_m &= V_F \sin (\omega t + \phi_{VP} - k \frac{2\pi}{3}) + V_N \sin (-\omega t + \phi_{VN} - k \frac{2\pi}{3}) \\
    i_m &= I_P \sin (\omega t + \phi_{IP} - k \frac{2\pi}{3}) + I_N \sin (-\omega t + \phi_{IN} - k \frac{2\pi}{3})
\end{align*}
\]  

Equations (3a) and (3b) are simplified by substituting both (2) and (4) respectively. This simplification is shown in equation (5), which shows how the voltage and current quantities relate to the average phase active powers and the average reactive power. Equation (5) depicts the average power flow equation of the single delta connected MMCC STATCOM. The phase average active powers \( P_{avg_a}, P_{avg_b} \) can also be determined by the overall and inter-cluster dc capacitor voltage controls.

\[
\begin{align*}
    v_{ab} &= \begin{bmatrix} 1 & -1 & 0 \end{bmatrix} v_a \\
    v_{bc} &= \begin{bmatrix} 0 & 1 & -1 \end{bmatrix} v_b \\
    v_{ca} &= \begin{bmatrix} -1 & 0 & 1 \end{bmatrix} v_c \\
    i_{ab} &= \begin{bmatrix} 1 & -1 & 0 \end{bmatrix} i_a \\
    i_{bc} &= \begin{bmatrix} 0 & 1 & -1 \end{bmatrix} i_b \\
    i_{ca} &= \begin{bmatrix} -1 & 0 & 1 \end{bmatrix} i_c
\end{align*}
\]

Where \( V_F, V_N, I_P \) and \( I_N \) are the magnitude of the positive and negative sequence voltage and current and \( k = 0, 1, 2 \) for phases \( m = a, b, c \). The phase angles of the positive and negative sequence voltages and currents are \( \phi_{VP}, \phi_{VN}, \phi_{IP} \) and \( \phi_{IN} \) respectively.

Applying inverse dq-transformation, the phase voltages and currents are expressed as:

\[
\begin{align*}
    [v_a] &= \sqrt[3]{2/3} \begin{bmatrix} 2/3 & -1/2 & -\sqrt[3]{3}/2 \end{bmatrix} \begin{bmatrix} \sin(\omega t + \phi_{VP}) & -\cos(\omega t + \phi_{VP}) & \sin(\omega t + \phi_{VP}) \\ -\cos(\omega t + \phi_{VP}) & \sin(\omega t + \phi_{VP}) & \cos(\omega t + \phi_{VP}) \\ \sin(\omega t + \phi_{VP}) & \cos(\omega t + \phi_{VP}) & \sin(\omega t + \phi_{VP}) \end{bmatrix} \begin{bmatrix} V_F^p \\ \cos(\omega t) \sin(\omega t) \\ \sin(\omega t) \cos(\omega t) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix} \begin{bmatrix} V_N^p \\ \cos(\omega t) \sin(\omega t) \\ \sin(\omega t) \cos(\omega t) \end{bmatrix} \\
    [i_a] &= \sqrt[3]{2/3} \begin{bmatrix} 2/3 & -1/2 & -\sqrt[3]{3}/2 \end{bmatrix} \begin{bmatrix} \sin(\omega t + \phi_{VP}) & -\cos(\omega t + \phi_{VP}) & \sin(\omega t + \phi_{VP}) \\ -\cos(\omega t + \phi_{VP}) & \sin(\omega t + \phi_{VP}) & \cos(\omega t + \phi_{VP}) \\ \sin(\omega t + \phi_{VP}) & \cos(\omega t + \phi_{VP}) & \sin(\omega t + \phi_{VP}) \end{bmatrix} \begin{bmatrix} I_P^p \\ \cos(\omega t) \sin(\omega t) \\ \sin(\omega t) \cos(\omega t) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix} \begin{bmatrix} I_N^p \\ \cos(\omega t) \sin(\omega t) \\ \sin(\omega t) \cos(\omega t) \end{bmatrix} \\
    \end{align*}
\]

Where superscript \( p \) and \( n \) denote positive and negative sequence, and subscript \( d \) and \( q \) represent the direct and quadrature axis.

3. Average Power Inter-cluster Balancing Control

This method achieves reactive power and inter-cluster dc capacitor voltage control under unbalance voltage condition. Both actions are achieved by regulating the average reactive power and average active cluster powers of the MMCC. These are determined by evaluating the average phase active powers \( P_{avg} \) and average reactive power \( Q_{avg} \) of the delta connected MMCC as:

\[
\begin{align*}
    P_{avg} &= \frac{1}{T} \int_0^T v_{av} i_{av} dt \\
    Q_{avg} &= \frac{1}{T} \int_0^T (v_{av} i_{qv} - v_{pv} i_{pq}) dt
\end{align*}
\]

Where the delta connected MMCC phases are represented as \( w = ab, bc, ca \) and subscript \( \alpha \) and \( \beta \) represent alpha-beta components of current and voltage. \( T \) is the line fundamental period.

The single delta configured MMCC voltages and currents are given as:

\[
\begin{align*}
    v_{ab} &= \begin{bmatrix} 1 & -1 & 0 \end{bmatrix} v_a \\
    v_{bc} &= \begin{bmatrix} 0 & 1 & -1 \end{bmatrix} v_b \\
    v_{ca} &= \begin{bmatrix} -1 & 0 & 1 \end{bmatrix} v_c \\
    i_{ab} &= \begin{bmatrix} 1 & -1 & 0 \end{bmatrix} i_a \\
    i_{bc} &= \begin{bmatrix} 0 & 1 & -1 \end{bmatrix} i_b \\
    i_{ca} &= \begin{bmatrix} -1 & 0 & 1 \end{bmatrix} i_c
\end{align*}
\]

The papers [13] use this sinusoidal zero sequence current in achieving inter-cluster balancing of STATCOM while rebalancing unbalance grid voltages. The limitation of using this zero-sequence current for unbalance condition was not discussed. [22] discussed in detail the influence of the degree of unbalance voltage in evaluating zero-sequence current. This research revealed that applying zero-sequence current for inter-cluster balancing control under unbalanced voltage condition, a large amount of current is required as the degree of voltage unbalance \( k_v \) increases. [23] investigated the use of STATCOM in providing reactive power support in suppressing voltage fluctuation created by unregulated large wind power plants connected to a weak power network. Authors in [24] discussed using zero-sequence current inter-cluster balancing technique under three current reference calculation strategies of active power oscillation elimination (APOE), reactive power oscillation elimination (RPOE) and balanced positive sequence current (BPSC). This paper revealed how these current references influence this inter-cluster balancing method when providing reactive power support to the grid under asymmetric voltage condition.
Overall active power reference for the overall dc capacitor voltage controller provides the active power required by the dc capacitors to compensate for power losses in the converter. This is achieved by using a PI regulator as shown in Fig. 2. The total active power reference for the overall dc capacitor voltage is:

$$P_T = V_{dc,avg} \left( (K_{P,dc} + \frac{K_{I,dc}}{S}) (V_{dc}^* - V_{dc,avg}) \right)$$  \hspace{1cm} (6)

Where $K_{P,dc}$ and $K_{I,dc}$ are the proportional and integral gain of the PI controller. $V_{dc}$ and $V_{dc,avg}$ are the desired value of all the sub-module capacitor voltages and the average value of all three-phase sub-module dc voltages respectively.

The inter-cluster dc capacitor voltage controller as shown in Fig. 3, is applied to maintain the average dc capacitor voltages of each phase. The inter-cluster dc capacitor voltage imbalance is regulated by generating the cluster active power command $P_{cw}$ as:

$$P_{cw} = V_{dc,avg} \left( (K_{P,apb} + \frac{K_{I,apb}}{S}) (V_{dc,avg} - V_{dcw}) \right)$$  \hspace{1cm} (7)

Where $w = ab, bc, ca$, $K_{P,apb}$ and $K_{I,apb}$ are the proportional and integral gain parameters for the inter-cluster control, $V_{dcw}$ are the average dc capacitor voltages across each phase. The average active power across each converter phase $P_{avgw}$ is determined as:

$$P_{avgw} = \frac{P_T}{3} + P_{cw}$$  \hspace{1cm} (8)

The average reactive power $Q_{avg}$ is determined by the reactive power capacity of the converter. To determine the converter reference currents required in providing reactive power support to the grid and sub-module capacitor voltage control, equation (5) is further simplified and expressed as equation (9).

Where level of unbalance voltage, $k_{uv} = \frac{V_b}{V_p}$, the positive sequence voltage is approximately equal to the negative sequence voltage, the current required in achieving reactive power control under unbalance voltage condition requires infinite current rating. This directly limits the operating range of the STATCOM device. Thus the maximum converters current rating influences the maximum reactive power flow of the converter.

4. STATCOM Control Scheme

Average active power control is applied to keep the sub-module capacitor voltages balanced for the SDBC configured STATCOM under asymmetrical conditions. Because of the asymmetric voltage condition, the current injected into the grid is also asymmetric and the magnitude of this current increases as the unbalance voltage condition increases. Knowing fully well that the maximum reactive power injected to the grid is dependent on the peak value of the injected current; to ensure safe operation of STATCOM and steady reactive power supply, a maximum current protection scheme is implemented for the delta connected STATCOM. The block diagram of the control scheme is shown in Fig. 4. The control strategy includes three sections namely; dc capacitor voltage balancing control, converter current reference determination and current controller. The dc capacitor voltage balancing control includes the overall dc capacitor voltage control, inter-cluster dc capacitor voltage control and individual dc capacitor voltage control. Both the overall and inter-cluster dc capacitor voltage controllers synthesize the total power $P_T$ and cluster active powers $P_{cw}$, respectively that contributes the average active powers, $P_{avgw}$ across each phase. The positive and negative sequence voltage extraction is based on decoupled double synchronous reference frame (DDSRF) which detects the PCC direct and quadrature voltages $V_p^d, V_q^d, V_p^q, V_q^q$ and synchronization signal $\omega_t$. The dq component of the PCC voltage and output of the dc capacitor voltage balancing control $P_{avgw}$ and reactive power reference $Q'$ are fed as inputs into the converter phase current reference determination section. According to equation (9), the dq reference currents are calculated and converted into their respective stationary three phase currents $i_{ab}$, $i_{bc}$ and $i_{ca}$ as given in (10).

$$\begin{bmatrix} i_p^q \\ i_q^q \\ i_p^d \\ i_q^d \end{bmatrix} = \frac{2}{\omega_p^2(1 - k_{uv})} \begin{bmatrix} v_p^q - v_q^q \\ v_p^d + v_q^d \\ v_p^q + v_q^q \\ v_p^d - v_q^d \end{bmatrix} \begin{bmatrix} v_p^d \\ v_q^d \\ v_p^q \\ v_q^q \end{bmatrix} + \begin{bmatrix} \omega_p^d \\ \omega_p^q \\ \omega_q^d \\ \omega_q^q \end{bmatrix} \begin{bmatrix} P_{avgw} \\ P_{avgbc} \\ P_{avgca} \\ Q_{avg} \end{bmatrix}$$  \hspace{1cm} (9)
\[
\begin{bmatrix}
    l_{ab} \\
    l_{bc} \\
    l_{ca}
\end{bmatrix}
= \frac{\sqrt{2}}{3} \begin{bmatrix}
    1 & -1 & 0 \\
    1 & 0 & -1 \\
    0 & 1 & 1
\end{bmatrix} F \times G
\]  
(10)

Where the phase current components are;
\[
F = 2\sqrt{3}(x_d \cos\omega t + x_q \sin\omega t) + 3(x_d \cos\omega t - x_q \sin\omega t)
\]
\[
\sqrt{3}(x_q \cos\omega t - x_d \sin\omega t)
\]
\[
\sqrt{3}(x_q \cos\omega t + x_d \sin\omega t)
\]
\[
0
\]

where \(x_d = V_d^p + V_d^q \), \(x_q = V_d^q - V_d^p \), \(x_q = V_q^p \) and \(V_d^p \) and \(V_d^q \) are the oscillatory components of the voltage. The positive and negative sequence voltage components are expressed as \(V_d^p = \frac{2}{3}V_d \), \(V_d^q = \frac{2}{\sqrt{3}}V_d \) and \(\phi_{p} = 0\). The maximum value of the converter reference currents is determined by ensuring that the converter currents are not exceeded. The maximum current of the predicted current controller is defined in \((11a)\) and \((11b)\) as;
\[
l_{\text{max}} = \text{max}(l_{ab}, l_{bc}, l_{ca})
\]  
\(11a\)
\[
l_{\text{max}} = \text{max} \left( \frac{1}{\sqrt{3}}l_{\text{term}ab}, \frac{1}{\sqrt{3}}l_{\text{term}bc}, \frac{1}{\sqrt{3}}l_{\text{term}ca} \right)
\]  
\(11b\)

Where \(l_{\text{term}ab}, l_{\text{term}bc}, l_{\text{term}ca}\) are the oscillatory components of the converter phase currents. When the maximum current of the STATCOM is greater than the STATCOM rated current (i.e. \(l_{\text{max}} \geq I_{\text{rated}}\)) under severe fault conditions, the maximum current limit control scheme is activated to prevent overcurrent operation in the STATCOM. This STATCOM rated current \(I_{\text{rated}}\) is dependent on the converter power semiconductor switch current handling capability. This scheme is achieved by modifying the magnitude of the phase currents by using a limiting factor \(L_f\). The limiting factor;
\[
L_f = \begin{cases} 
1 & l_{\text{max}} \leq I_{\text{rated}} \\
\frac{l_{\text{rated}}}{l_{\text{max}}} & l_{\text{max}} \geq I_{\text{rated}} 
\end{cases}
\]  
(12)

The new phase current references for the single delta MMCC STATCOM is given in equation (13) as;
\[
\begin{bmatrix}
l_{ab} \\
l_{bc} \\
l_{ca}
\end{bmatrix}
= \frac{\sqrt{2}}{3} \begin{bmatrix}
1 & -1 & 0 \\
1 & 0 & -1 \\
0 & 1 & 1
\end{bmatrix} F \times G
\]  
(13)

The new converter current references, PCC voltages and converter currents are fed into the predictive current controller to generate the converter reference voltages. The individual phase dc capacitor balancing control is implemented to keep each sub-module capacitor within a particular phase balanced and this is achieved using a \(P\) regulator. The output of this controller is added to the converter reference voltages to generate the modulation signal of each sub-module. The phase-shifted PWM technique is applied in this paper. Individual phase dc capacitor balancing control and PS-PWM are extensively described in [20] and [25] respectively.

5. Current Rating Requirement of Delta-connected STATCOM under Asymmetrical Conditions

The phase current analysis is considered since this inter-cluster balancing technique only influences the maximum current requirement while the voltage requirement is unaffected by the unbalanced condition. The negative sequence current is applied to balance the dc capacitors and also inject reactive power to the grid. According to equation (11), the maximum current of the delta connected STATCOM is influenced by the degree of voltage unbalance \(K_v\) and the negative sequence voltage phase angle \(\phi_{BN}\). Fig. 5(a) highlights this relationship. As the degree of voltage unbalance \(K_v\) increases, the maximum phase current either increases or decreases depending the negative sequence voltage phase angle \(\phi_{BN}\). Fig. 5(b) shows how the maximum current of the SDBC varies with \(\phi_{BN}\). The maximum and minimum values of \(I_{\text{max}}\) occurs at \(\phi_{BN} = \pi/6\) and \(\phi_{BN} = 7\pi/6\) respectively. The fault ride-through capability for the average power balancing technique shows that the \(K_v\) and \(\phi_{BN}\) influences the maximum current to be injected to the grid.

Comparing this inter-cluster balancing method to the zero-sequence current injection method, the maximum current of the SDBC using zero-sequence current injection method includes a component of the zero-sequence current. As \(K_v\) increases, the \(I_{\text{max}}\) value will mainly be contributed by zero-sequence current

Fig. 4. Reactive power injection using average power balancing control with maximum current protection of MMCC based STATCOM
maximum $I_{\text{max}}$ [18]. Comparing the maximum currents under zero-sequence current technique $I_{\text{max,0}}$ to the average power balancing technique $I_{\text{max,APB}}$, $I_{\text{max,0}} \approx 3\sqrt{2}I_{\text{max,APB}}$. Given;

$$I_{\text{max,APB}} = \frac{\sqrt{2}}{9\rho_{\phi}(1-k_{\phi})}$$

$$I_{\text{max,0}} = \frac{1}{3}\sqrt{2\rho_{\phi}(1-k_{\phi})}$$

This shows that the average power balancing inter-cluster technique requires less current compared to the zero-sequence current injection method. This high current requirement of the SDBC STATCOM using zero-sequence current technique has limited the use of this topology particularly under asymmetrical unbalanced voltage condition.

### 6. Results and Discussion

The effectiveness of the proposed reactive power and inter-cluster voltage control strategy under unbalanced grid voltage condition is investigated in MATLAB SIMULINK. A single delta bridge cell (SDBC) MMCC STATCOM is connected directly to a 2kV grid to provide reactive power support before/during/after voltage sag spells. The system setup is shown in Fig. 1, where four three-level H-bridge sub-modules are cascaded per cluster. Tables I and II show the system and controller parameter respectively. The control parameters were chosen based on the cutoff frequency of 10Hz and phase margin of 60°. The control strategy verified in this simulation is shown in Fig. 4. In this investigation, STATCOM reactive power reference injected into the grid is 0.15Mvar.

#### 6.1 One-phase 50% voltage sag

### Table 1. System parameter.

| Parameter             | Symbol | Value |
|-----------------------|--------|-------|
| Grid voltage          | $V$    | 2000V |
| Grid frequency        | $f$    | 50Hz  |
| AC filter inductor    | $L_s$  | 8mH   |
| Cascaded number       | $n$    | 4     |
| Sub-module dc voltage | $V_{DC}$| 1000V |
| Sub-module dc capacitance | $C_a$ | 1.12mF |
| Carrier frequency     | $f_c$  | 1000Hz|

### Table 2. Controller parameters.

| Symbol | QUANTITY  | Value |
|--------|-----------|-------|
| $k_{p_Cin}$, $k_{i_Cin}$ | Overall DC voltage control | 2, 20 |
| $k_{p_Cap}$, $k_{i_Cap}$ | Inter-cluster control | 1, 10 |
| $k_{p_Cvs}$ | Intra-cluster control | 0.8  |

### Fig. 5. MMCC current rating requirement

(a) Relationships between maximum current, degree of voltage unbalance and negative sequence voltage phase angle.

(b) Relationship between maximum current and degree of unbalanced voltage for $\phi_{VN} = \pi/6, \pi/3, \pi/2$ and $7\pi/6$.

### Fig. 6. Simulation results of SDBC-MMCC STATCOM

(e) Sub-module capacitor voltages

(f) Grid voltage magnitude
To test the effectiveness of the control strategy, a 50% voltage sag on phase A lasting for a duration of 0.2s before the grid voltage fault is cleared out is investigated. The maximum current protection scheme is activated to protect STATCOM once the converter currents exceed the rated current \( I_{\text{rated}} \). The simulation results are shown in Fig. 6.

Fig. 6(a) shows the PCC voltage waveform experiencing asymmetrical fault of 50% voltage amplitude reduction in phase A for 0.2s. Fig. 6(b) shows the converter output voltage waveforms with amplitude reduction in phases \( V_{\text{cap}} \) and \( V_{\text{cav}} \) resulting from the 50% reduction in phase A voltage. Fig. 6(c) shows the waveform of STATCOM line currents, and these currents are unbalanced. Fig. 6(d) shows the STATCOM phase currents; it is seen that the maximum phase current \( I_{\text{max}} \) increases from 40A to 48A during the fault condition and decreases back to 40A after the fault has been cleared out. This maximum current is lower than the rated current of the STATCOM device \( I_{\text{rated}}=50A \), thus STATCOM is operated without activating overcurrent protection. Fig. 6(e) shows the submodule dc capacitor voltages across all the clusters. These dc capacitor voltages are kept balanced because of the average power balancing control applied across the STATCOM phases.

Fig. 6(f) highlights the effectiveness of the reactive power support provided by STATCOM to the grid voltage. Without reactive power compensation provided by STATCOM, the current drawn by the load at PCC causes the PCC voltage to drop to 1850V due to the grid impedance. But with compensation, the grid voltage at PCC is maintained at 2kV. Also, the magnitude of the grid voltage during unbalanced voltage fault is higher than when no reactive power support is provided by STATCOM by 7.5%. This shows that this proposed method improves the unbalance voltage condition by increasing the voltage amplitude.

7. Conclusion

This paper has presented a reactive power control strategy for the delta configured MMCC as STATCOM operating under asymmetric voltage conditions. The inter-cluster average active power across each phase and the reactive power to be injected to the grid has been analyzed in dq frame. The reference currents expressions for achieving inter-cluster power balancing and reactive power compensation have been presented. These reference current expressions have shown that the degree of voltage unbalance and the phase angle of the negative sequence voltage influences the current rating of the delta-connected STATCOM, especially under asymmetric voltage unbalance condition. A maximum current limit control scheme has been proposed which ensures safe operation of STATCOM within its rated current limits irrespective of the asymmetric voltage condition. The proposed method has been seen to offer superior current requirement compared to the zero-sequence current technique, by \( 3\sqrt{3} \) less than the current requirement of zero sequence technique under the same asymmetric condition. Finally, the proposed method has been validated by the simulation results to provide a continuous injection of reactive power to the grid and sub-module dc capacitor voltage balancing under asymmetric voltage fault condition.

6.2 Two-phase 50% voltage sag.

To highlight the usefulness of the proposed control strategy towards over-current protection, a two-phase 50% voltage sag condition lasting for 0.2s in both phases A and B are tested as shown in Fig. 7(a). Fig. 7(b) shows the converter STATCOM output voltages. Fig. 7(c) shows the STATCOM maximum phase current \( I_{\text{max}} \) rises from 40A to 65A due to the fault condition. This maximum phase current is operating above the rated current \( I_{\text{rated}}=50A \), resulting in maximum phase current protection scheme activation to protect STATCOM operation. It is seen that the STATCOM phase currents magnitude is limited to the rated current. Fig. 7(d) shows the STATCOM line currents to be unbalanced. Fig. 7(e) shows the sub-module capacitor voltages of the STATCOM to be balanced due to the average power balancing control strategy. Without the implementation of the over-current protection scheme, injection of a large amount of current above the rated current will affect the STATCOM sub-module capacitors. Also, various power semiconductor switches will be damaged resulting from excessive thermal breakdown. With the over-current protection activated whenever the STATCOM maximum current exceeds the rated current, safe operation of the device is guaranteed with the average power balancing cluster control maintaining their dc capacitor voltages balanced. Also, with the over-current protection scheme activated, the STATCOM still provide reactive power support during the unbalance voltage grid fault. The results have shown that the response of the proposed method to transient changes is about 5ms.

![Graph](image)

Fig. 7. Simulation results of SDB-C-MMCC STATCOM under phase A and B 50% sag.

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