Abstract—Hybrid matrix converters can potentially enable matrix converter in high-power applications that conventional matrix converters would not be able to attain. The hybrid matrix converter consists a main matrix converter that processes the bulk power conversion and an auxiliary back-back voltage source converter that improves the terminal power quality. Prior simulation study has successfully demonstrated that the superior spectral performance can be achieved. This paper is focused on the control scheme of the hybrid matrix converter operating under balanced and unbalanced conditions.

I. INTRODUCTION

Matrix converters have several advantages over traditional frequency converters. They are able to provide sinusoidal input currents and output voltages, smaller size, no large energy storage components required, and provide full control over the input power factor for any load[1][2].

Due to the qualities that the matrix converter provides, it has been a very attractive area of research over the recent years. The real development was started by Venturini and Alesina published in 1980[3][4], they first introduced the name "Matrix Converter" and provided a detailed mathematical model describing the behavior of the converter. Another modulation technique is based on a fictitious DC link connecting a current source bridge and voltage source bridge presented by Rodriguez[5]. This approach is known as the indirect transfer function approach. In 1989 the method of space vector modulation technique for matrix converters introduced by Huber[5]. In 1992 it was practically confirmed that the nine switches matrix converter shown in Fig.1, could be used effectively in vector control of induction motor[7]. However, the usage of the matrix converter was still limited due to the difficult current communication of bidirectional switches. Recently, many solutions have been presented to solve the communication problem of bidirectional switches, such as the four step method[8].

Matrix converters generate current harmonics that are injected back into the ac system. These current harmonics can result in voltage distortions that affect the operation of the AC system. On the other hand the voltage harmonics on the output side will cause a disturbance to the load which in most cases is an inductive load. In order to reduce these harmonics in the source current and the output voltage, passive filters are typically used to reduce the harmonics generated by the matrix converter. Different configurations of low pass passive filters have been proposed[9]. The size and design of these filters depend on many factors such as:
1- power quality requirements
2- power system harmonic content
3- converter switching frequency
4- converter modulation technique[10].

Passive filters seem to be an easy solution in low power applications of matrix converters. However, this is not the case when a matrix converter is introduced for high power interfaces, the optimal design of the passive filter would be a major challenge.

The first high power matrix converter is introduced by Yaskawa for wind power applications[11], in which the modular concept is used to cope with the various demands in the power grid. However, the modular concept is presented to be used in a very high voltage applications such as wind mills. In a prior paper the hybrid matrix converter is introduced to
operate at high power medium voltage demands. The topology used a conventional 9 bidirectional switch matrix converter combined with auxiliary back-back voltage source converter to improve the terminal power quality. However, the previous paper did not cover all the operation conditions that hybrid matrix converter might encounter. In this paper, a control scheme is provided for hybrid matrix converter operating under normal and abnormal conditions, such as unbalanced voltage source and unbalanced load.

The matrix converter is modulated using the low frequency modulation algorithm [12] and the active filters are controlled based on the instantaneous reactive power theory[13][14] and symmetrical component theory. This paper is organized as follows: following the introduction, section two present the hybrid matrix converter, section three present the modulation algorithms for the active filters under normal conditions, section four present the control scheme for active filter when hybrid matrix converter operate under abnormal conditions, section five shows the simulation results, finally conclusion and remarks end the paper.

II. PROPOSED HYBRID MATRIX CONVERTER

The operation of the matrix converter at high power has several advantages in efficiency, sizing, and reliability over the back-to-back converter inverter system[10]. Fig. 2 shows the proposed topology for matrix converter used for medium voltage high power applications.

The topology includes the conventional nine bidirectional switches matrix converter with a shunt active filter implemented on the input side and series active filter implemented on the output side. Both active filters consist of three phase inverters connected by a common DC link. The shunt active filter compensate the input current harmonic produced by the matrix converter and the series active filter compensate the output voltage harmonics. That means, the matrix converter is considered as a two type of harmonic sources, current harmonic source in the input side, and voltage harmonic source in the output side.

III. ACTIVE FILTER MODULATION UNDER BALANCED CONDITIONS

A. Input Current Conditioning

Considering the two waveforms at the input side, the three phase input voltage is always sinusoidal and the three phase current is extremely distorted because the matrix converter and the load are behaving non-linearly. The instantaneous three phase active power at the input side \( p_{in} \), can be given by

\[
p_{in} = V_{in} \cdot I_{in}, \tag{1}
\]

where “\( \cdot \)” denotes the internal product of the two vectors. Equation (7) can also expressed in the conventional detention of power,

\[
p_{in} = I_A V_A + I_B V_B + I_C V_C. \tag{2}
\]

The instantaneous input reactive power vector of the three phase system can be expressed as

\[
q_{in} = V_{in} \times I_{in}, \tag{3}
\]

where ”\( \times \)” denotes the cross product of the voltage and current vectors. \( q_{in} \) can also be expressed

\[
q_{in} = \begin{bmatrix} q_A \\ q_B \\ q_C \end{bmatrix} = \begin{bmatrix} V_B & V_C \\ I_B & I_C \\ V_C & V_A \\ I_C & I_A \\ V_A & V_B \\ I_A & I_B \end{bmatrix}, \tag{4}
\]

and

\[
q_{in} = \|q_{in}\| = \sqrt{q_A^2 + q_B^2 + q_C^2}. \tag{5}
\]

Respectively we can analysis the source current into an active component \( I_{in-p} \), and reactive component \( I_{in-q} \) in which

\[
I_{in-p} = \begin{bmatrix} I_{A-p} \\ I_{B-p} \\ I_{C-p} \end{bmatrix} = \frac{p_{in} \cdot V_{in}}{V_{in} \cdot V_{in}}, \tag{6}
\]

\[
I_{in-q} = \begin{bmatrix} I_{A-q} \\ I_{B-q} \\ I_{C-q} \end{bmatrix} = \frac{q_{in} \cdot V_{in}}{V_{in} \cdot V_{in}}, \tag{7}
\]

note that the resultant current vector from the addition of the two currents \( I_{in-p} \) and \( I_{in-q} \) is always equal the source current \( I_{in} \). Another thing to notice is that the instantaneous power produced from \( V_{in} \cdot I_{in-p} \) equal to the input power \( p_{in} \), and the instantaneous power produced from \( V_{in} \cdot I_{in-q} \) is always equal to zero. From this observation we can tell that \( I_{in-q} \) is not contributing to any power transmission from the source to the load. In fact if we made the instantaneous reactive current \( I_{in-q} \equiv 0 \) the current \( I_{in} \) will be transmitting the same instantaneous active power \( p_{in} \) with unity power factor.

![Fig. 2. Proposed Hybrid Matrix Converter](image-url)
Respectively, the instantaneous active power \( p_{\text{in}} \) can be analyzed into two components,

\[
p_{\text{in}} = \bar{p}_{\text{in}} + \tilde{p}_{\text{in}},
\]

where \( \bar{p}_{\text{in}} \) is the direct component of the instantaneous active power and it represents the energy flow in one direction from the source to the matrix converter, and \( \tilde{p}_{\text{in}} \) represents the oscillatory component of the instantaneous active power and it represents the energy exchanged between the source and the matrix converter. By eliminating the current component that produces \( \tilde{p}_{\text{in}} \), the source current will be sinusoidal. It is important to note that we do not need an energy storing component to compensate the reactive power \( q_{\text{in}} \), because \( q_{\text{in}} \) represents the energy exchange among the three phases, while an energy storing component is required for compensating the oscillatory real power \( \bar{p}_{\text{in}} \), because \( \bar{p}_{\text{in}} \) is the real power exchanged between the source and the matrix converter.

Knowing this, we can generate the compensation current by selecting the appropriate power portion to be eliminated. The three phase compensation current could be expressed as

\[
I_{\text{comp}}^* = \frac{p_{\text{C}}^* \cdot V_{\text{in}}}{V_{\text{in}} \cdot V_{\text{in}}} + \frac{q_{\text{C}}^* \times V_{\text{in}}}{V_{\text{in}} \cdot V_{\text{in}}},
\]

where \( p_{\text{C}}^* \) and \( q_{\text{C}}^* \) can be assigned from \( \bar{p}_{\text{in}} \) and \( q_{\text{in}} \) respectively, depending on our compensation objectives.

### B. Output Voltage Conditioning

The continuous current requirement of the matrix converter at the output side makes it a perfect fit to apply the series active filter to compensate the output voltage harmonics. By using the dual approach of the instantaneous reactive power theory we can define an instantaneous active output power and instantaneous reactive output power as

\[
p_{\text{out}} = V_{\text{out}} \cdot I_{\text{out}},
\]

\[
q_{\text{out}} = V_{\text{out}} \times I_{\text{out}}.
\]

In turn, we define the instantaneous active output voltage vector \( V_{\text{out} - p} \) and instantaneous reactive output voltage vector \( V_{\text{out} - q} \) as

\[
V_{\text{out} - p} = \begin{bmatrix} V_{a-p} \\ V_{b-p} \\ V_{c-p} \end{bmatrix} = \frac{p_{\text{out}} \cdot I_{\text{out}}}{I_{\text{out}} \cdot I_{\text{out}}},
\]

\[
V_{\text{out} - q} = \begin{bmatrix} V_{a-q} \\ V_{b-q} \\ V_{c-q} \end{bmatrix} = \frac{q_{\text{out}} \times I_{\text{out}}}{I_{\text{out}} \cdot I_{\text{out}}},
\]

Note that the upper script \( ^{\text{1}} \) denotes the fundamental component of the output current. In most cases, series active filters is used in applications were the current is sinusoidal. However, this is not the case in the matrix converter and it is a required further control effort to extract the fundamental component of the output current.

Similar observation can be made in the series active filter. The addition of the two voltage vectors \( V_{\text{out} - p} \) and \( V_{\text{out} - q} \)

always equal the output voltage \( V_{\text{out}} \). The instantaneous power produced from \( V_{\text{out} - p} \cdot I_{\text{out}} \) is equal to the to the output power \( p_{\text{out}} \), and the instantaneous power produced from \( V_{\text{out} - q} \cdot I_{\text{out}} \) always equals zero.

The instantaneous output active power has a similar envelop to the instantaneous input active power, the only difference is the switching losses. We can also define an oscillatory component of the instantaneous output active power and the corresponding component of output voltage that causes this oscillation. By selecting the appropriate portions of power to be compensated we can write the equation of the compensating voltage as

\[
V_{\text{comp}}^* = \frac{p_{\text{C}}^* \cdot I_{\text{out}}^1}{I_{\text{out}}^1 \cdot I_{\text{out}}^1} + \frac{q_{\text{C}}^* \times I_{\text{out}}^1}{I_{\text{out}}^1 \cdot I_{\text{out}}^1},
\]

where \( p_{\text{C}}^* \) and \( q_{\text{C}}^* \) can be assigned from \( p_{\text{out}} \) and \( q_{\text{out}} \) according to our one’s compensation objectives.

The control circuits of the two active filters are shown in fig.6. Circuit (a) includes computational circuits for the instantaneous input reactive power \( q_{\text{in}} \), instantaneous oscillatory component of the input active power \( p_{\text{in}} \), and instantaneous reactive component of the input current \( I_{\text{in} - q} \), instantaneous oscillatory component of the input active current \( I_{\text{in} - p} \). Circuit (b) includes computational circuits for the instantaneous output reactive power \( q_{\text{out}} \), instantaneous oscillatory component of the output active power \( p_{\text{out}} \), and instantaneous reactive component of the output reactive power \( \tilde{I}_{\text{out}} \), instantaneous oscillatory component of the output active voltage \( V_{\text{out} - p} \). Circuit (c) shows the fundamental component extraction from the output current. It’s important to mention that using the Fourier analysis method of extracting the fundamental component of the output current is not effecting the response of the control circuit, because Fourier analysis method has faster response than the instantaneous reactive power theory method. The Fourier analysis method required an accurate information about the fundamental component frequency. This will not cause any problem because we always have an accurate information about the output fundamental frequency.
IV. General Cases Including Distortion and Imbalance in the Voltages and Currents

A. Unbalanced Voltage Source

In the previous section the assumption is made that the source voltage is balanced, meaning the amplitudes of the three phase voltages are equal to each other and there is a 120° phase shift among them. In case of unbalanced voltage source, further analysis needs to be considered to obtain the correct compensation current for the input stage of the matrix converter.

The unbalanced voltage source may include positive, negative, and zero sequence components according to the symmetrical component theory. The symmetrical component transformation is applied on both the input voltage and current to determine the sequence components.

\[
\begin{bmatrix}
V_{in0} \\
V_{in+} \\
V_{in−}
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
1 & 1 & 1 \\
1 & \alpha & \alpha^2 \\
1 & \alpha^2 & \alpha
\end{bmatrix} \begin{bmatrix}
V_A \\
V_B \\
V_C
\end{bmatrix},
\]

where the subscripts "0", "+", and "−" correspond to the zero, positive, and negative sequences, respectively. The complex number in the transformation matrix corresponds to the phase shift in the three phase system, \(\alpha = e^{j120°} = e^{j\frac{2\pi}{3}}\).

\[
\begin{bmatrix}
I_{in0}^n \\
I_{in+}^n \\
I_{in−}^n
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
1 & 1 & 1 \\
1 & \alpha & \alpha^2 \\
1 & \alpha^2 & \alpha
\end{bmatrix} \begin{bmatrix}
I_A^n \\
I_B^n \\
I_C^n
\end{bmatrix},
\]

where "\(n\)" denotes the harmonic order.

The time domain equivalent voltage and current can be derived from the phasors given by (15) and (16). By synthesizing the symmetrical components, the \(a−b−c\) input voltages can be written as:

\[
V_A = \sqrt{2}V_{in0}\sin(\omega t + \phi_0) + \sqrt{2}V_{in+}\sin(\omega t + \phi_+) + \sqrt{2}V_{in−}\sin(\omega t + \phi−)
\]

\[
V_B = \sqrt{2}V_{in0}\sin(\omega t + \phi_0) + \sqrt{2}V_{in+}\sin(\omega t + \phi_+) - \frac{2\pi}{3} + \sqrt{2}V_{in−}\sin(\omega t + \phi−) + \frac{2\pi}{3}
\]

\[
V_C = \sqrt{2}V_{in0}\sin(\omega t + \phi_0) + \sqrt{2}V_{in+}\sin(\omega t + \phi_+) + \frac{2\pi}{3} + \sqrt{2}V_{in−}\sin(\omega t + \phi−) - \frac{2\pi}{3}
\]

Similarly, the instantaneous input line currents are found to be:

\[
I_A^n = \sqrt{2}I_{in0}^n\sin(\omega t + \phi_0) + \sqrt{2}I_{in+}^n\sin(\omega t + \phi_+) + \sqrt{2}I_{in−}^n\sin(\omega t + \phi−)
\]

\[
I_B^n = \sqrt{2}I_{in0}^n\sin(\omega t + \phi_0) + \sqrt{2}I_{in+}^n\sin(\omega t + \phi_+) - \frac{2\pi}{3} + \sqrt{2}I_{in−}^n\sin(\omega t + \phi−) + \frac{2\pi}{3}
\]

\[
I_C^n = \sqrt{2}I_{in0}^n\sin(\omega t + \phi_0) + \sqrt{2}I_{in+}^n\sin(\omega t + \phi_+) + \frac{2\pi}{3} + \sqrt{2}I_{in−}^n\sin(\omega t + \phi−) - \frac{2\pi}{3}
\]

The input current is the result of adding the results of all the time domain currents from each harmonic.

\[
I_k = \sum_{n=1}^{\infty} I_k^n \quad k = (A, B, C).
\]

The above description allows us to analyze the three phase unbalanced system in to two three phase balanced systems pulse zero sequence component. In the matrix converter case we will not consider the zero sequence component to be compensated in order to maintain a 0.866% voltage transfer ratio of the matrix converter.

Fig. 4 shows the two balanced systems (positive sequence system \(V_{in+} = [V_{A+} V_{B+} V_{C+}]^T\), \(I_{in+} = [I_{A+} I_{B+} I_{C+}]^T\) and the negative sequence system \(V_{in−} = [V_{A−} V_{B−} V_{C−}]^T\), \(I_{in−} = [I_{A−} I_{B−} I_{C−}]^T\)) can be compensated in two different control loops, then the total compensating current will be the addition of the compensating current of the positive sequence system and the compensating current of the negative sequence system.

\[
I_{comp+}^* = p_{C+}^* \cdot \frac{V_{in+}}{V_{in+} \cdot V_{in+}} + q_{C+}^* \cdot \frac{V_{in+}}{V_{in+} \cdot V_{in+}},
\]

\[
I_{comp−}^* = p_{C−}^* \cdot \frac{V_{in−}}{V_{in−} \cdot V_{in−}} + q_{C−}^* \cdot \frac{V_{in−}}{V_{in−} \cdot V_{in−}},
\]

\[
I_{comp}^* = I_{comp+}^* + I_{comp−}^*.
\]
B. Unbalanced load

In case of when different loads are connected to the matrix converter, each load will draw a different amount of current leading to a linearly independent three phase output current. The decomposition of the output voltage and current into it’s symmetrical component is as follows:

$$
\begin{align*}
\begin{bmatrix}
V_{n_{out0}} \\
V_{n_{out+}} \\
V_{n_{out-}}
\end{bmatrix} &= \frac{1}{3} \begin{bmatrix}
1 & 1 & 1 \\
1 & \alpha & \alpha^2 \\
1 & \alpha^2 & \alpha
\end{bmatrix} \begin{bmatrix}
V_n \\
V_a \\
V_b
\end{bmatrix}, \quad (23)
\end{align*}
$$

$$
\begin{align*}
\begin{bmatrix}
I_{n_{out0}} \\
I_{n_{out+}} \\
I_{n_{out-}}
\end{bmatrix} &= \frac{1}{3} \begin{bmatrix}
1 & 1 & 1 \\
1 & \alpha & \alpha^2 \\
1 & \alpha^2 & \alpha
\end{bmatrix} \begin{bmatrix}
I_n \\
I_a \\
I_b
\end{bmatrix}, \quad (24)
\end{align*}
$$

The time domain equivalent voltage and current can be derived from the phasors given by (23) and (24). By synthesizing the symmetrical components, the $a-b-c$ voltage and current can be written as:

$$
\begin{align*}
V_a^n &= \sqrt{2}V_{n_{out0}}\sin(\omega t + \phi_0) + \sqrt{2}V_{n_{out+}}\sin(\omega t + \phi_+ ) + \sqrt{2}V_{n_{out-}}\sin(\omega t + \phi_- ) \\
V_b^n &= \sqrt{2}V_{n_{out0}}\sin(\omega t + \phi_0) + \sqrt{2}V_{n_{out+}}\sin(\omega t + \phi_+ ) + \frac{2\pi}{3} + \sqrt{2}V_{n_{out-}}\sin(\omega t + \phi_- ) + \frac{2\pi}{3} + \sqrt{2}V_{n_{out-}}\sin(\omega t + \phi_- ) - \frac{2\pi}{3}, \\
V_c^n &= \sqrt{2}V_{n_{out0}}\sin(\omega t + \phi_0) + \sqrt{2}V_{n_{out+}}\sin(\omega t + \phi_+ ) + \frac{2\pi}{3} + \sqrt{2}V_{n_{out-}}\sin(\omega t + \phi_- ) + \frac{2\pi}{3} + \sqrt{2}V_{n_{out-}}\sin(\omega t + \phi_- ) - \frac{2\pi}{3},
\end{align*}
$$

Similarly, the instantaneous line currents are found to be

$$
\begin{align*}
I_a^n &= \sqrt{2}I_{n_{out0}}\sin(\omega t + \phi_0) + \sqrt{2}I_{n_{out+}}\sin(\omega t + \phi_+ ) + \sqrt{2}I_{n_{out-}}\sin(\omega t + \phi_- ) \\
I_b^n &= \sqrt{2}I_{n_{out0}}\sin(\omega t + \phi_0) + \sqrt{2}I_{n_{out+}}\sin(\omega t + \phi_+ ) + \frac{2\pi}{3} + \sqrt{2}I_{n_{out-}}\sin(\omega t + \phi_- ) + \frac{2\pi}{3} + \sqrt{2}I_{n_{out-}}\sin(\omega t + \phi_- ) - \frac{2\pi}{3} \\
I_c^n &= \sqrt{2}I_{n_{out0}}\sin(\omega t + \phi_0) + \sqrt{2}I_{n_{out+}}\sin(\omega t + \phi_+ ) + \frac{2\pi}{3} + \sqrt{2}I_{n_{out-}}\sin(\omega t + \phi_- ) + \frac{2\pi}{3} + \sqrt{2}I_{n_{out-}}\sin(\omega t + \phi_- ) - \frac{2\pi}{3}
\end{align*}
$$

then the output voltage is the result of adding all the harmonics together

$$
V_{k^n} = \sum_{n=1}^{\infty} V_k^n \quad k = (a, b, c). \quad (27)
$$

The control process is similar to the one we have in case of unbalanced source voltage, utilizing the output voltage and current into it’s symmetrical component leaving us with two balanced systems, (positive sequence system $V_{o_{out+}} = [V_{a+} V_{b+} V_{c+}]^T$, $I_{o_{out+}} = [I_{a+} I_{b+} I_{c+}]^T$) and the negative sequence system $V_{n_{in-}} = [V_{a-} V_{b-} V_{c-}]^T$, $I_{n_{in-}} = [I_{a-} I_{b-} I_{c-}]^T$). The two balanced systems can be compensated into two different control loops as shown in Fig.5. The total compensating voltage will be the addition of the compensating voltage of the positive sequence system and the compensating voltage of the negative sequence system.

$$
\begin{align*}
V_{comp+} &= V_{o_{comp+}} = \mu_{c+} \cdot I_{o_{out+}}^* + \mu_{c+} \cdot I_{o_{out+}}^*, \\
V_{comp-} &= V_{o_{comp-}} = \mu_{c-} \cdot I_{o_{out-}}^* + \mu_{c-} \cdot I_{o_{out-}}^*, \\
V_{comp} &= V_{o_{comp+}} + V_{o_{comp-}}.
\end{align*}
$$

V. SIMULATION RESULTS

A simulation model of the hybrid matrix converter shown in Fig.2 is built using MATLAB Simulink. In the shunt active filter a hysteresis current controller is used to track the instantaneous change of the inverter current and compare it back with the reference current.

It is necessary to control the voltage of the DC link capacitor by adding the power loss caused by the inverter switches. The active filter generates harmonics at its switching frequency, and it is necessary to filter out these harmonics, typically a small coupling inductor is connected in series with the inverter output to eliminate these high frequency harmonics. Fig.6, shows the input current and the output voltage after the compensation in the case of a balanced source voltage and load, in the same phase with the input voltage which means that all the reactive power has been compensated effectively. The compensation of the oscillatory component of the input active power results in the sinusoidal shape of the input current. The same explanation can be made for the output voltage. Fig.7, shows the output result of compensating the source current when the supply voltage is not balanced. The simulation shows that a sinusoidal input current can be achieved. Fig.8, shows the simulation in the case of an unbalanced load being fed by the matrix converter.
VI. CONCLUSION AND REMARKS

In this paper, a general control scheme for the hybrid matrix converter control operating under different conditions (normal condition, unbalanced source voltage, and unbalanced load).

The analysis of the input and output power shows that the instantaneous reactive power theory can be applied in determining the compensation current of the input side and the compensation voltage for the output side of the matrix converter. Further analysis needs to be considered when the Hybrid Matrix Converter operates under abnormal conditions, those analyses include the symmetrical component theory.

The proposed topology is very efficient in medium voltage high power applications in which the conventional solution of passive filters is not effective. The Hybrid Matrix Converter reduces the energy storing components, size, and provides higher reliability. The proposed topology can be utilized for mitigating the effect of voltage sag, especially when the matrix converter is used to drive sensitive loads.

REFERENCES


