



MATRIX CONVERTER: A REVIEW

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ABSTRACT

Matrix Converter (MC) fundamentals and operation is described throughout this paper. This covers topological characteristics, MC types and basics of operation, implementation of discrete semiconductors as bidirectional switches, commercially available bidirectional switches modules packaging, bidirectional switches commutation schemes based on current and voltage direction as well as modulations strategies of MC based on related publications.

Keywords: matrix converter, review, bidirectional switch commutation, modulation, space vector modulation.

INTRODUCTION

The term “Matrix Converter” is initially stated by Venturini back in 1980 [1]. A Matrix Converter (MC) allows forward and reverse capability via an array of four quadrant, fully controllable bidirectional switches. A common three-phase to three-phase MC (3×3 MC) is capable of performing direct AC to AC voltage conversion without requiring any DC conversion in the process. This attribute promotes MC as an appealing alternative to the inverter.

Conventional inverter involves a two-stage power conversion. Input AC voltage is firstly rectified to DC voltage before inverted to desired output AC load voltage through a PWM inverter [2]. Unlike the inverter where conversion of AC to DC voltage is necessary, requirement for any smoothing electrolytic DC link capacitor is clearly absent in MC topology.

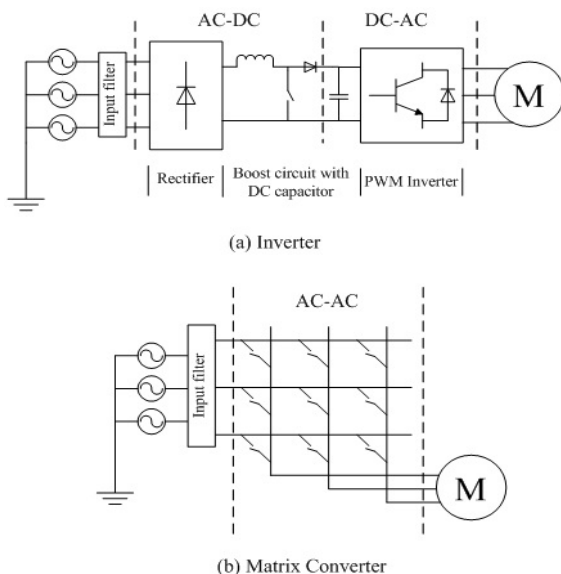


Figure-1. A comparison between inverter and MC in AC to AC conversion stage.

While providing high input power with unrestricted frequency operation, MC contributes to

reduced input current harmonics, more compact in size and higher efficiency in comparison to the inverter. An MC also perform AC to DC, DC to AC or even DC to DC conversion with the very same topology, depends on what type of source and load the MC is implying, either AC or DC [3]. Input and output connection phases of an MC are also arbitrary and not solely restricted to three-phase to three-phase connection.

MC evolved from Forced Commutated Cycloconverters (FCCC) [4]. Besides the FCCC, Naturally Commutated Cycloconverters (NCCC) is also a type of cycloconverters. The NCCC rely on discontinuous control-type switches like thyristors which turns off only when voltage difference between the outgoing and incoming switches is in correct polarity. In contrary to the NCCC, the FCCC switches use active-control switches like power transistors. Its switching can be actively turned off in any desired instance. The earlier version of the FCCC utilises thyristors similar with NCCC but with an additional external commutation circuit to realize bidirectional switches function. Table-1 below summarises the cycloconverters type.

Table-1. Types of cycloconverters based on its switching device type and output frequency.

	Naturally Commutated (NCCC)	Forced Commutated (FCCC)
Switching device	Discontinuous-type (Thyristors)	Actively-controlled (Power transistors)
Output frequency	Lower than input	Higher than input

MATRIX CONVERTER TYPES

MC is classified into conventional or Direct MC (DMC) and Indirect MC (IMC) [4]. The name given to each category is an indication of how the MC operates; either through direct or indirect means.

The ‘direct’ operation was initiated by Venturini and Alesina with their “low frequency modulation matrix” mathematical modelling [5]. The designated modulation is directly multiplied with input voltage to obtain required output voltage, hence the “direct transfer function” term.



The DMC proposes single stage voltage and current conversions commonly through nine bidirectional switches. Figure-1(b) best illustrates topology of DMC where the source and load is directly connected to it. As connection phases are arbitrary in MC topology, a three-phase to three-phase MC is not the only option for a DMC.

The IMC features a slight topological difference in switches count where it typically utilizes six switches to operate. The indirect method of IMC is theoretically depicted by dividing its operation into a rectifier, a “fictitious” DC link and a single phase inverter [6].

The rectifier operates based on Current Source Rectifier (CSR) whereas the inverter operates as Voltage Source Inverter (VSI). It is noted that the DC link is just virtually made to exist to illustrate how it functions and it is not physically present in actual topology. The illustration on IMC concept based on three-phase to single-phase MC (3×1 MC) is shown in Figure-2.

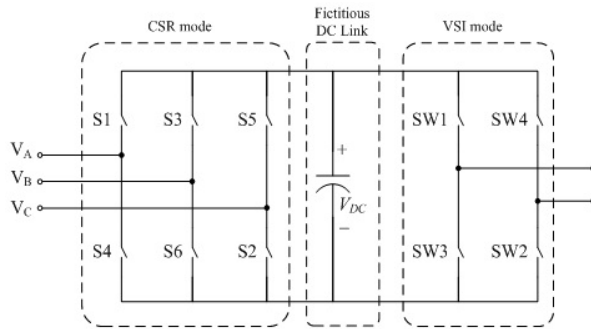


Figure-2. Illustration of IMC mode of operation.

The IMC can be divided into two mode of operations namely rectifier (CSR) mode of operation and inverter (VSI) mode of operation [6], [7]. The CSR mode is created to obtain dc voltage (VDC) from fictitious DC link and to maintain input power factor to near unity. A high frequency output voltage is expected to be generated from VSI mode after VDC is obtained earlier from CSR mode.

FUNDAMENTAL OPERATION

MC operates as a phase-voltage to phase-load connected converter. It is denoted by m to n ($m \times n$) matrix or m-connected phase voltage against n-connected phase load. For an instance, a practical 3×3 MC connected to an induction motor is referred as a “three-phase voltage connected to a three-phase load” MC [8].

The basic operation of an MC is generally the operation of a DMC and is comparable to a conventional VSI [9]–[11]. MC operates on the VSI principle of voltage source-fed and inductively connected load. Thus, MC modulation is based on PWM modulation strategy for a VSI. While MC is having more complicated commutation strategies for its bidirectional switches compared to unidirectional VSI, modulation techniques implemented on VSI can be as well applicable on MC with some

alteration and derivation to commute its bidirectional switches.

Huber and Borojevic proposes a fundamental Space Vector Modulation (SVM) based scheme to a 3×3 MC [8], [10]. The proposed method is based on Venturini direct approach. Figure-3 below illustrates a 3×3 MC with parameters to define this direct modelling.

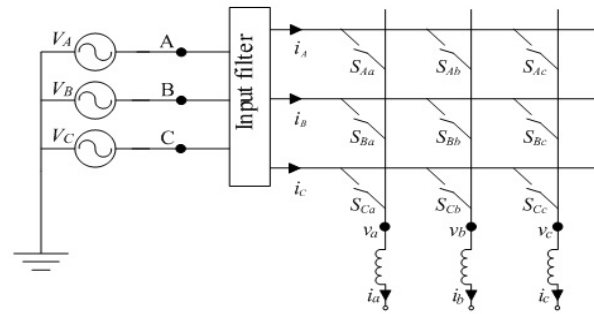


Figure-3. 3×3 MC with parameters.

Based on this fundamental;

$$S_{Kj} = \begin{cases} 1, \text{switch } S_{Kj} \text{ closed} \\ 2, \text{switch } S_{Kj} \text{ open} \end{cases} \quad K = \{A, B, C\} \quad j = \{a, b, c\} \quad (1)$$

Expression of the above constraints is

$$S_{Aj} + S_{Bj} + S_{Cj} = 1 \quad j = \{a, b, c\} \quad (2)$$

Where the 27 possible switching states could be obtained for the MC with constraints mentioned in (2).

Expression of the load and source voltages (V_o and V_i) in vectors is

$$V_o = \begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix}, \quad V_i = \begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} \quad (3)$$

The relationship between load and input voltage is expressed as:

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \begin{bmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{Ac}(t) & S_{Bc}(t) & S_{Cc}(t) \end{bmatrix} \begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix} \quad (4)$$

$$V_o = TV_i$$

Where T is the instantaneous transfer matrix of the MC.

Vector form of input and output currents (i_i and i_o);

$$i_i = \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix}, \quad i_o = \begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} \quad (5)$$



$$i_i = T^T \cdot i_o \quad (6)$$

Where T^T is the transpose matrix of T .

Let T_{seq} defined as the period of one sequence cycle, let $m_{Kj}(t)$ be the duty cycle of switch S_{Kj} , defined as $m_{Kj}(t) = t_{Kj} / T_{seq}$ which can have the following values:

$$0 < m_{Kj} < 1 \quad K = \{A, B, C\} \quad j = \{a, b, c\} \quad (7)$$

The low frequency transfer matrix is defined by

$$M(t) = \begin{bmatrix} m_{Aa}(t) & m_{Ba}(t) & m_{Ca}(t) \\ m_{Ab}(t) & m_{Bb}(t) & m_{Cb}(t) \\ m_{Ac}(t) & m_{Bc}(t) & m_{Cc}(t) \end{bmatrix} \quad (8)$$

The low frequency component of the output phase voltage is given by

$$v_o(t) = M(t) \cdot v_i(t) \quad (9)$$

The low frequency component of the input current is

$$i_i = M(t)^T \cdot i_o \quad (10)$$

Venturini and Alesina approach synthesises signal generated from instantaneous input voltage (V_i) into a high-frequency at its low frequency component of the output voltage (V_o). Basically this method deals with the low frequency component of V_o .

BIDIRECTIONAL SWITCH

Semiconductor switch arrangements

Semiconductor switches are the main “building blocks” of an MC. The switches must be capable of operating in four quadrant operation while having the capability to block voltage and conduct current [12]. Each switches is made of an arrangement of transistor-diode pairs to realize bidirectional power flow.

Due to unavailability of single bidirectional switch in the market, realization of bidirectional switch is basically done by configuring conventional unidirectional power transistor such as Bipolar Junction Transistor (BJT) or Insulated Gate Bipolar Transistor (IGBT) with diodes into an arrangement. The bidirectional switches arrangements are illustrated as in Figure-4.

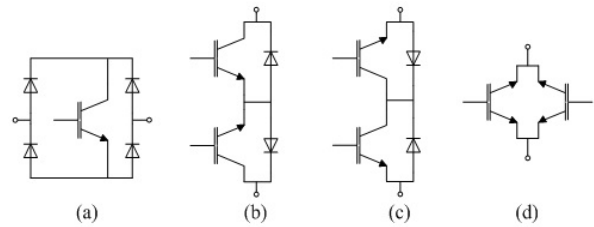


Figure-4. Bidirectional switch arrangement types. (a) Diode-bridge (DB). (b) Common-emitter (CE). (c) Common-collector (CC). (d) Reverse blocking IGBT (RB-IGBT).

Diodes are included in bidirectional switch arrangement to provide reverse blocking when required. DB configuration uses a single IGBT with four diodes. While having the advantage of using only one power transistor, this configuration contributes to high conduction losses as current flow involves three components of one transistor and two diodes [13].

CE and CC is the most common and preferred arrangements used as bidirectional switches to operate an MC [12], [14]. CE are connected as anti-parallel IGBTs. Independent control of current direction is possible and conduction loss is reduced as only two current-carrying components are triggered one at a time. However, each switch cell based on these arrangements requires an isolated gate drive circuitry to commute the switches, therefore added to complexity of the MC switches commutation.

RB-IGBT is the most recent arrangement that improves CC and CE configurations as it eliminates the need for anti-parallel diodes. Only two transistors are aligned in anti-parallel instead of two transistors and two diodes as found in CC and CE arrangements. However, as it lowers conduction losses, application of RB-IGBT on DMC potentially lowers power transfer and degrades efficiency during converter operation, making it more suitable to be used in IMC, as reported by Friedli et. al [15]. The bidirectional switch arrangements can be simplified into following table:

Table-2. Comparison of bidirectional switches arrangements based on its components and conducting device.

Arrangements	DB	CE	CC	RB-IGBT
Components	IGBT	1	2	2
	Diodes	4	2	0
Conducting device	3	2	2	1

Bidirectional switch modules

Some researchers and manufacturers have taken steps to commercialize packaging of bidirectional switches modules. Dynex manufactured the DIM400PBM17-A000 IGBT bidirectional switch with 400A 1700V rating and configured in common-collector, n-channel enhancement



mode arrangement [16]. The switch is intended for MCs, brushless MCs as well as frequency converters. This switch is intended for applications with high thermal cycling capability.

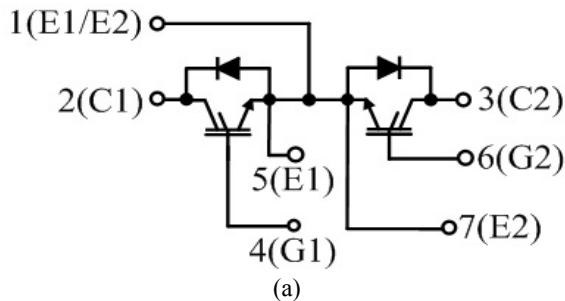


Figure-5(a). Dynex DIM400PBM17-A000 circuit configuration [16].

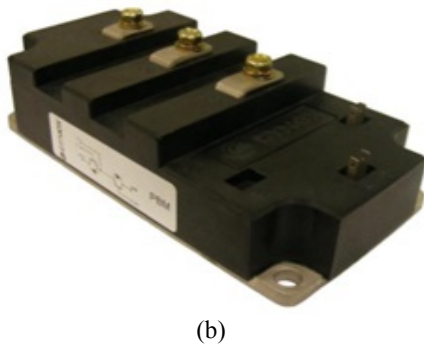


Figure-5(b). DIM400PBM17-A000 package [16].

Another example can be seen on SEMELAB company. An MC-IGBT bidirectional switch module is developed by SEMELAB with 360kVA (600V, 300A) rating for a project called Electrically Driven Advance Actuator system (EDAAS) [17]. The IGBT packaging is made available in 300V to 1800V range. It is claimed to be an excellent reliability module in terms of temperature cycling, humidity tested and passed elevated pressure testing. It comes as a plastic package/hermetic package, as seen in Figure-6 below.



Figure-6. SEMELAB bidirectional switch for the EDAAS project [9].

Some manufacturers accomplished developing a full MC power module consists of bidirectional switches. In 2001, the first MC package named EconoMAC is introduced into the market by EUPEC under the work of Hornkamp et. al. [18]. 18 diodes and 18 IGBTs are arranged in common-collector to realize 9 bidirectional switches. The EconoMAC is practically made for small 3×3 MC with 35A, 7.5kW rating. However, it can be adjusted to fit other $m \times n$ MC configuration. The nine CC-arranged bidirectional switches are configured to form a complete 3×3 MC. The module can also be customised to form a 3×1 or a 1×3 MC with its high level of integration to power circuit.

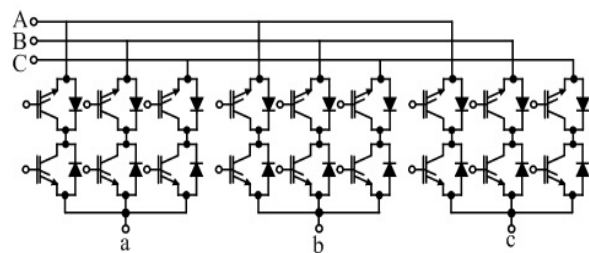


Figure-7. The EconoMAC based on 3×3 MC from EUPEC schematic diagram [9].

BIDIRECTIONAL SWITCHES COMMUTATION

MC has some operational limitations due to its bidirectional switching that need to be fully controlled to ensure safe operation. Commutation is referred to the control of turn-on and turn-off switching of the MC bidirectional switches [19]. The difference between an MC and a VSI is the absence of freewheeling diodes that can provide safer current commutation of the switches [8].

Bidirectional switches need to be commutated simultaneously. However this commutation realization would be difficult without making the input current short-circuited and interrupts current flow impressed on load [12]. Short-circuited at input terminals could cause the MC to malfunction due to overcurrent.

It is extremely important to ensure that no two bidirectional switches actively conducting at the same time (to prevent short circuit among input phases) and the switches are prohibited to be turned off all at once (to prevent voltage spike due to absence in inductive current path of the load [20]). Therefore, it is crucial to provide safe current commutation with extra gate drive circuitry to actively control the bidirectional switches.

Basic commutation

In basic current commutation strategy, it can be divided into two strategies, overlap current commutation and dead time commutation [8]. Incoming switch is fired before the outgoing switch is completely reached its off-stage in overlap current commutation. However, this method is not favorable as it needs a large inductor and additional switching period which consequently raise problem during further control scheme implementation. Dead time commutation in contrary offers a momentary



open circuit state where it creates a brief interval when no switch is conducting [21]. This strategy causes energy to dissipate during every commutation interval.

Commutation based on current direction

Commutation based on current direction offers two steps and four steps strategies [12]. The four steps strategy is explained by taking out the first array containing the first two switches as shown in Figure-7(a) [8], [19]. Its timing diagram of switching is presented in Figure-7(b). The load current is assumed to be in forward direction while the upper switch is in its off state. When the bottom switch needed commutation, outgoing current direction from the upper switch determines which device within that bottom switch need to conduct.

To be concise of the whole strategy, the direction of current flow (forward or reverse) is a key indication (the determining parameter) to decide which device between the IGBT and the diode in active switch is needed to be turned off to provide path for the current flow [20].

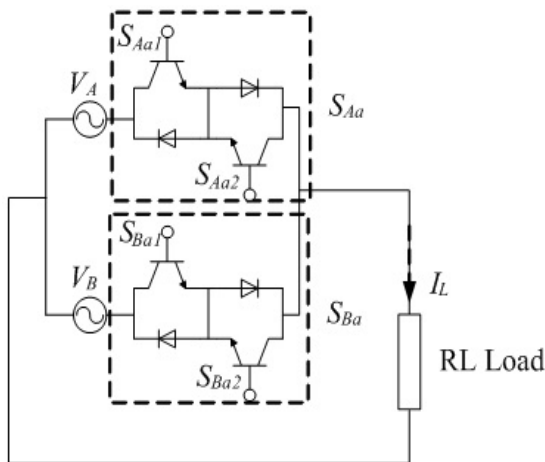


Figure-7(a). The first array of two switches [8].

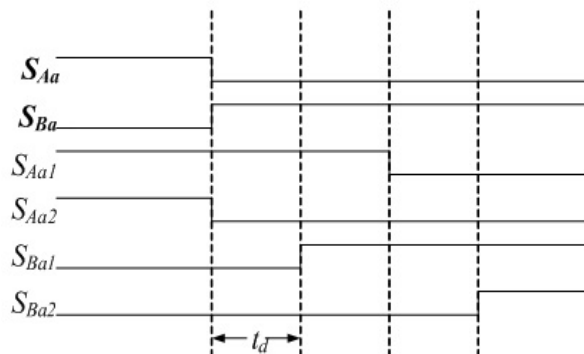


Figure-7(b). The timing diagram based on (a) [8].

Commutation based on voltage direction

As commutation based on current direction senses the direction of outgoing current, for this commutation, input voltage direction in contrary is the main subject. The commutation happens either shortly

after the turn-off of the first conducting device or after the following device is turned-on [19].

MODULATION SCHEMES

Modulation of MC refers to overall control of the MC, combining individual switches commutations into one MC system that needs to be well-controlled. Venturini defined “modulation” as a procedure to generate appropriate firing pulses to each bidirectional switches present in MC [1].

Thorough modulation and control techniques applied for MC is covered in [22]. This includes the implementations of scalar or direct method of Venturini and Alesina [5], Pulse Width Modulation based (PWM-based) techniques as well as Model Predictive Control (MPC) techniques [7], [9], [22]–[24]. The available modulation techniques can be summarised as in Figure-8.

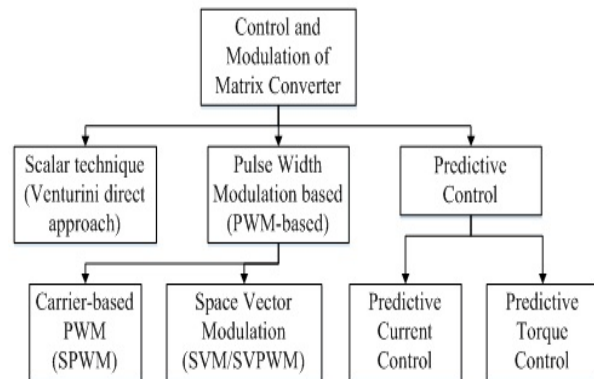


Figure-8. Summary of modulation for MC [22].

Scalar Technique

Venturini direct method is categorized under scalar technique [1]. It offers the simplest way to modulate MC as it involves direct multiplications of input voltage/source voltage with its instantaneous transfer matrix from the bidirectional arrangements in the MC, denoted as T , to obtain the output voltage. Mathematical modelling of this early version of modulation has been discussed in FUNDAMENTAL OPERATION section.

PWM-based – Sinusoidal PWM

Basic PWM-based modulation is carrier-based PWM modelled for a three-phase to single-phase MC (3×1 MC); called the sinusoidal PWM (SPWM) [22], [23]. This modelling can be further extended to 3×3 or multilevel MCs as desired. This method is simplified into Figure-9.

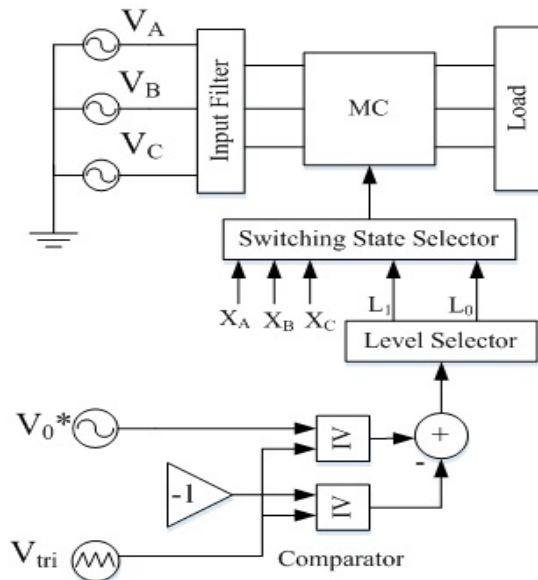


Figure-9. Sinusoidal PWM (SPWM) [22].

As its name implies, a 'carrier' signal denoted in Figure-9 as V_0^* which is a sinusoidal high frequency triangular signal (V_{tri}) is compared with a sinusoidal reference signal [23]. Eqn. (1) defines the switching state selector which must be satisfied according to Table-3. The states of input voltages are identified by the parameters X_A , X_B and X_C and L_1 and L_0 refer to output voltage levels.

$$N = 16x_A + 8x_B + 4x_C + 2L_1 + L_0 \quad (11)$$

Logic value 1 will be selected by respective input voltage parameters if condition given by Table-3 is satisfied while value 0 is selected whenever the condition is not satisfied. L_0 is selected if output voltage reference is less than or equal 0 and L_1 is selected if the output voltage reference is above zero.

Table-3. States of phase input voltages and output voltages.

Condition	Value
$V_A > V_B$	$X_A = 1$
$V_B > V_C$	$X_B = 1$
$V_C > V_A$	$X_C = 1$
$V_0 \leq 0$	L_0 selected
$V_0 > 0$	L_1 selected

PWM-based – Space Vector PWM

Modern MC modulation is based on space vector theory which presents a complex plane representation of voltage, current or flux that were originally used for AC machine dynamic behavior modelling [19]. The basic modulation based on space vector implementation is referred to as Space Vector Modulation (SVM) as earlier conducted by Huber and Borojevic [10]. Space vector

planes exist in voltage vector and current vector [25]. Figure-10 shows the representation of space vector in a plane based on input current vectors.

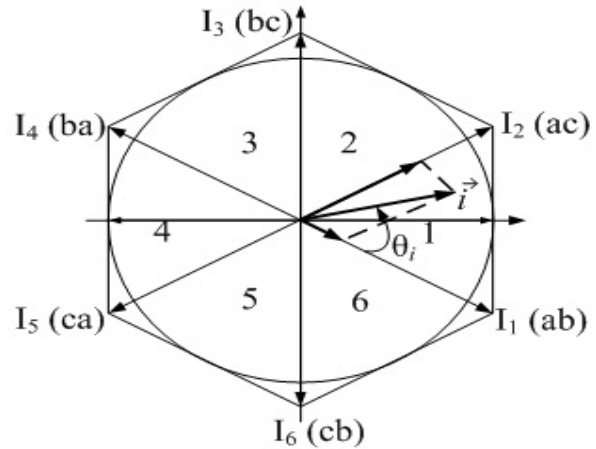


Figure-10. Vector plane based on input current [26].

The SVM referred to instantaneous space vector representation of input and output voltage and currents in α, β plane where phases input voltages vectors, normally denoted as V_A , V_B and V_C have 120° differences in space. Most SVM-based method resulted in the same desired output voltages but respect to its Total Harmonics Distortion (THD), peak-to-peak ripple and switching losses, the performance of each method would differ [27] [28].

The area enclosed between each vector is called sectors [27]. Using Figure-10 as an example, the input voltage vectors consist of six sectors, namely sector 1 until sector 6. Sector 1 for an instance, is located in between vector 1 and 2. The available vectors 1 until 6 are the active vectors while zero vectors are referring to vector 7 until 9. Two adjacent active vectors and a zero vector where it makes a 'sector' are always used to synthesize the input current vector.

CONCLUSIONS

MC topology and its fundamentals has been described in this paper. MC could perform AC-AC, AC-DC, DC-AC or DC-DC conversions, depending on source and load the MC is connected to. There are two types of MC, namely the DMC and IMC. Both are classified based on direct and indirect control methods. MC fundamental operation is analogous to a unidirectional VSI, but MC operates in bidirectional way, thus its modulation is more complex. Its fully controllable bidirectional switches need commutation strategies either through current or voltage direction to appropriately commute the switches to allow power flow. Conventional SPWM can basically modulate an MC, other than implying PWM based on space vector theory or predictive control method. Considering its interesting characteristics in contrast of its complex commutation and modulation, MC is worth to be applied in various applications in future power electronics market.



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