Modulation Strategies for Indirect Matrix Converter: Complexity, Quality and Performance

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***Abstract*--In general, there are two main classifications in matrix converters. The most common known type is conventional matrix converter (CMC) or direct matrix converter (DMC). The other type is indirect matrix converter (IMC). A brief review for modulation strategies are provided in this work for modulation strategies in IMC. There are several popular modulation methods for IMC such as carrier-based modulation and space vector modulation (SVM). A sinusoidal current waveform is produced on the input and output sides to implement the modulation method. In the conclusion the modulation methods will compared based on performance, theoretical complexity, and some other parameters.**

Keywords---AC–AC conversion, carrier-based modulation, indirect matrix converter, pulse width modulation, space vector modulation.

I. INTRODUCTION

Matrix Converter (MCs) usually is made from an AC-AC converter which includes the array bidirectional switches. This array is useful to connect main power supply to the load. At this connection circuit, there is no DC-link or energy storage elements[1]. The MCs have a great demand because of their superior function such as: (1) dc link capacitor is removed, (2) a sinusoidal waveform at both input and output terminal, (3) bidirectional power-flow capability, (4) power factor at input side is adjustable, (5) less weight and volume in design, and (6) long life usage [2], [3].

Basically, there is no limitation of frequency for MCs, however the output amplitude is limited to be smaller than input. Modulation technique can be using for solved this limitation problem[4]. There are two modulation strategies commonly used for MCs[5] namely: (1) method for carrier based modulation [6], and (2) space vector modulation (SVM) [2].

This paper briefly explains the most relevant strategies in modulation for IMC and provides the complexity and performance comparison of modulation strategies.

II. IMC WORKING PRINCIPLE

Common circuits of MCs are usually known in two types of topologies i.e. (1) the conventional matrix converter (CMC) and (2) the indirect matrix converter (IMC). The first IMC topology was proposed by Kolar et al [7], and then developed by another researcher in [8]–[12], the basic principle of IMC are constructed from bidirectional current source rectifier (CSR) and voltage source inverter (VSI) without the use of any intermediate energy storage element[13][14], as shown in Fig. 1. Commutation in zero current for IMC applies together with the rectifier circuit and this circuit gives lower losses during switching and reliable topology.

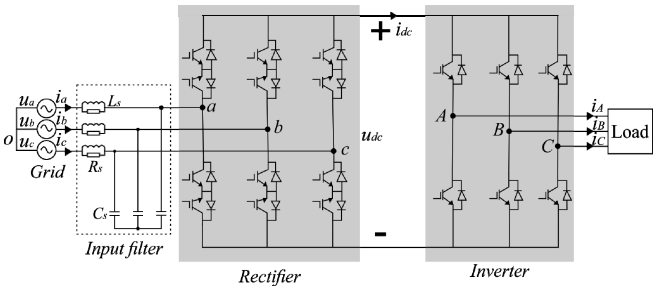

Fig. 1. Schematic diagram of IMC.

The indirect modulation separates each control on input current and output voltage side. The separation or it is also known as a decoupled strategy is carried out by decoupling transfer function **T** of MCs into first transfer function for rectifier and the second transfer function for inverter [15].

Where:
T = I * R

$$\begin{bmatrix} S_{aA} & S_{bA} & S_{cA} \\ S_{aB} & S_{bB} & S_{cB} \\ S_{aC} & S_{bC} & S_{cC} \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \cdot \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \quad (1)$$

In equation (1), inverter switches $S7$-$S12$ and rectifier switches $S1$-$S6$. Result to the product and sum of the input phases. As the equivalent circuit is observed from phase A of inverter output, then two switches $S7$ and $S8$ of phase A at half bridge are connected directly to phase a, b and c at input side through six switches on rectifiers[16].

III. GENERAL CLASSIFICATION OF MODULATION STRATEGIES FOR MCS

Fig. 2 shows the classification of modulation methods developed for the IMC. Basically the most well known modulation on MCs is Pulse width modulation (PWM). PWM is classified into two type of modulation strategies, i.e. carrier-based and space vector modulation (SVM) [5]. Carrier-based modulation method is the simplest approach, while the SVM method has an elegant and powerful solution for IMC. The modulation method for IMC was very interested to developed, several method was developed for IMC modulation method proposed in [6], [13], [17]–[21], [21]–[24]

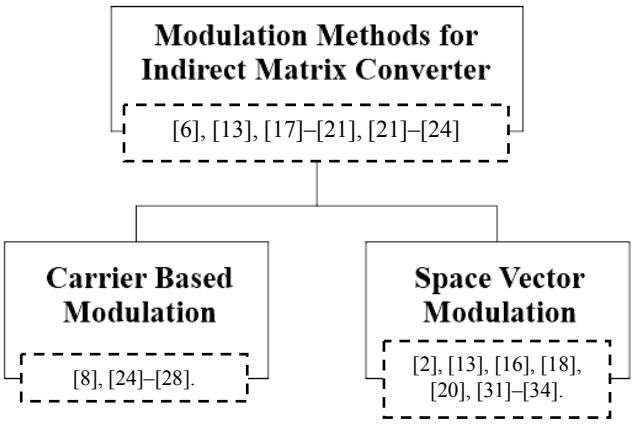

Fig. 2. Summary of modulation strategies for IMC.

IV. Carrier-Based Modulation for IMC

The first research about carrier-based modulation for MC was proposed by Yoon *et al* [6], by changing the carrier of slope and using voltage offset. By using this techniques, synthesize product of unity power factor in sinusoidal input currents and desired output voltages is implemented. A carrier based PWM for IMC was proposed by Wang [17], where the algorithm of the carrier-based modulation is enhanced in two techniques. The first technique makes a continuous modulation function for all throws based on the designed sinusoidal input current. The switching functions are intended to focus on the zero current commutation which has derived from the modulation functions. More details about this method can be found in [17] and [25]. Different research about carrier-based modulation also proposed in [8], [24]–[28].

V. Space Vector Modulation for IMC

SVM techniques for MCs are known in two different strategies. The first strategy is indirect space vector modulation taking the consideration of a virtual dc link and the second is direct space vector modulation presenting direct conversion [29], [30]. The first research about indirect space vector modulation or it is also known as indirect SVM was proposed by Borojevic *et al* [18], where matrix converter was constructed to combination circuit. This circuit, as it is shown in Fig. 3, synthesis CSI as current source inverter and VSI as voltage source inverter in the connection to a virtual dc link. Three phase inverter stage has six switches, *S7-S8 for* VSI and also other six switches, *S1-S6* for rectifier circuit [15]. Other research about indirect SVM method are also proposed in [2], [13], [16], [18], [20], [31]–[34].

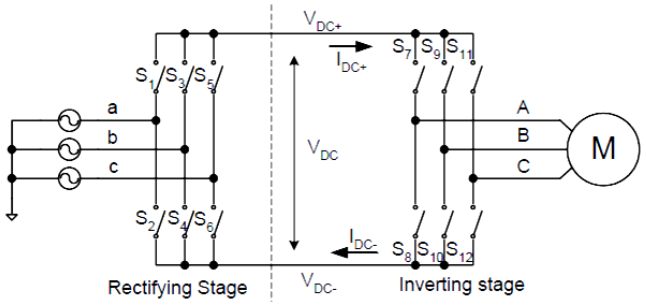

Fig. 3. The equivalent circuit for indirect modulation

Space vector PWM implemented rectifier-inverter in the indirect modulation technique. Three half bridges is not obligatory to follow as an output in this topology, so that only eight switches are possible to apply in the combinations. In Fig. 4(a), this proposed combination can be alienated into six active nonzero output voltage vectors i.e. V_1-V_6 and two zero output voltage vectors V_0.

The proposed virtual rectifier avoid an open circuit by using nine switching combinations. In this combination, six active nonzero input current vectors from I_1-I_6 and three zero input current vectors I_0 are implemented. The implementation scheme is shown in Fig. 4(a). Current I_1 (ab) gives indication that input phase a is bonded to the positive rail of the virtual DC-link VDC+ , then the input phase b is tied to the negative rail VDC−. The last connection scheme is shown in Fig. 4(b).

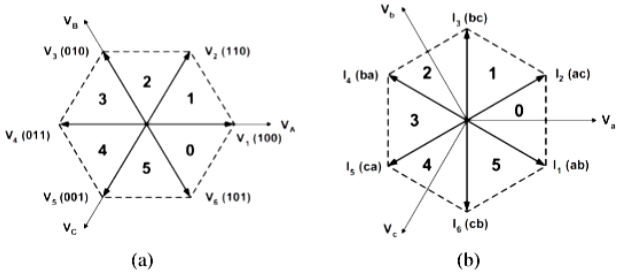

Figure 4: (a) inverter voltage hexagon. (b) rectifier current hexagon.

VI. Comparison of the Modulation Strategies

The presentation of modulation strategy discussed in this paper will be compared by considering the following parameters, including: (1) Complexity appeared in theory, (2) current quality at load side, (3) dynamic behaviour and response, (4) resonance of input filter, and (5) performance of the system under unbalanced voltage condition at input side.

A. Theoretical Complexity

In terms of complexity, carrier-based modulation are considered as a simple technique to generate pulses for gate drive in bidirectional power switches, although they are involve many equations[35]. While the SVM method has very complex to implement if we compare this with the carrier-based method or any other control method[5].

B. Quality of Load Current

From several observation in[5], [6], [13], [16], [17], [19], [21], [23], [28], we found that the quality of load current of the carrier-based modulation method and SVM method for MCs is deliver the high quality current to the load. That means quality of load current is not a big problem in the context of MCs.

C. Dynamics Behaviour and Response

The dynamic behaviour and response are important result parameter for some modulation and control method. While the dynamic response of carrier-based modulation method and SVM method is pretty good. Therefore from several observation for dynamic response parameter, we found that the control method like a direct torque control (DTC) and predictive control method has a better result on dynamic response parameter[5],[36].

D. Resonance of Input Filter

The significant issue in MCs when it is implemented and operated is a resonance of the input filter. A very significant impact on the input filter performance is the characteristic of the modulation method[36]–[39], an important observation not previously concerned. As a result, the modulation method works with a fixed switching frequency, in this case SVM method, have made resonance decreased in the input filter. While a Carrier-based modulation method has the input current with strong resonances in the input filter. This behaviour can be significantly improved and it must be considered at input current side.

E. Performance of the System Under Unbalanced Input Voltage Condition.

One of the most significant issues in influencing the performance of MCs is the input voltage condition[40], because of direct power conversion which implies instantaneous power transfer. From several observation through reference[30], [40], [41], [42], we found that the SVM method has a better solution for solving the unbalanced input voltage condition, while the carrier-based modulation has respectable result, although the carrier-based modulation does not need any extra algorithm as the unbalanced condition occurred in input voltage [42].

Based on observations from several references for these modulation methods, we can observe and analysis the comparison of the carrier-based modulation and space vector modulation for IMC. The comparison of these modulation methods has presented in Table I.

TABLE I. Comparison of Modulation Strategies for IMC

Parameter	Modulation method for IMC	
	Carrier-Based Modulation	**Space Vector Modulation**
Theoretical complexity	very simple	very complex
Quality of load current	good	very good
Dynamic response	good	good
Resonance of input filter	medium resonance	very low resonance
Performance under unbalanced input voltage condition	respectable	very good

VII. Conclusion

In recent years the development of MCs area is still interesting, especially in the scope of modulation method for IMC. There are two modulation strategies generally used for MCs namely: carrier-based modulation and space vector modulation. These methods have a different theoretical principles and also different complexity stages.

With the results written in this paper, carrier-based modulation have advantages especially on the level of complexity, where this method has the lowest level of complexity when compared to other methods including the SVM method. While the SVM method has an elegant and powerful solution for IMC. For the future observation, the comparison and the assessment of the method may include more advanced technical aspect.

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References

[1] E. Yamamoto *et al.*, "Development of MCs and its applications in industry," *IEEE Ind. Electron. Mag.*, vol. 5, no. 1, pp. 4–12, 2011.

[2] D. Casadei, G. Serra, A. Tani, and L. Zarri, "Matrix converter modulation strategies: a new general approach based on space vector representation of the switch state," *Ind. Electron. IEEE Trans.*, vol. 49, no. 2, pp. 370–381, 2002.

[3] J. W. Kolar, T. Friedli, J. Rodriguez, and P. W. Wheeler, "Review of three-phase PWM AC-AC converter topologies," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 11. pp. 4988–5006, 2011.

[4] J. Lettl and D. Kuzmanovic, "Matrix Converter Induction Motor Drive Employing Direct Torque Control Method," *PIERS Online*, vol. 6, no. 8, pp. 711–715, 2010.

[5] J. Rodriguez, M. Rivera, J. W. Kolar, and P. W. Wheeler, "A review of control and modulation methods for matrix converters," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 58–70, 2012.

[6] Y. D. Yoon and S. K. Sul, "Carrier-based modulation technique for matrix converter," *IEEE Trans. Power Electron.*, vol. 21, no. 6, pp. 1691–1703, 2006.

[7] J. W. Kolar, M. Baumann, F. Schafmeister, and H. Ertl, "Novel Three-Phase AC-DC-AC Sparse Matrix Converter Part I : Derivation , Basic Principle of Operation , Space Vector Modulation , Dimensioning," *Appl. Power Electron. Conf. Expo. 2002. APEC 2002. Seventeenth Annu. IEEE*, 2002.

[8] K. Zhou and D. Wang, "Relationship between space-vector modulation and three-phase carrier-based PWM: A comprehensive analysis," *IEEE Trans. Ind. Electron.*, 2002.

[9] J. Holtz and U. Boelkens, "Direct Frequency Converter with Sinusoidal Line Currents for Speed-Variable ac Motors," *IEEE Trans. Ind. Electron.*, 1989.

[10] L. Wei and T. A. Lipo, "A novel matrix converter topology with simple commutation," *Conf. Rec. - IAS Annu. Meet. (IEEE Ind. Appl. Soc.*, 2001.

[11] J. W. Kolar, F. Schafmeister, S. D. Round, and H. Ertl, "Novel three-Phase AC-AC sparse matrix converters," *IEEE Trans. Power Electron.*, 2007.

[12] C. Klumpner and F. Blaabjerg, "Modulation method for a multiple drive system based on a two-stage direct power conversion topology with reduced input current ripple," *IEEE Trans. Power Electron.*, 2005.

[13] P. C. Loh, F. Blaabjerg, F. Gao, A. Baby, and D. A. C. Tan, "Pulsewidth Modulation of Neutral-Point-Clamped Indirect Matrix Converter," *IEEE Trans. Ind. Appl.*, vol. 44, no. 6, pp. 1805–1814, 2008.

[14] Lixiang Wei, T. A. Lipo, and Ho Chan, "Matrix converter topologies with reduced number of switches," in *2002 IEEE 33rd Annual IEEE Power Electronics Specialists Conference. Proceedings (Cat. No.02CH37289)*, 2002, vol. 1, no. 1, pp. 57–63.

[15] Han Ju Cha, "Analysis and Design Of Matrix Converters for Adjustable Speed Drives and Distributed Power Sources," *Texas A&M Univ.*, no. August, 2004.

[16] P. Chlebis, P. Simonik, and M. Kabasta, "The Comparison of Direct and Indirect Matrix Converters," vol. 1, no. January 2010, pp. 310–313, 2010.

[17] B. Wang and G. Venkataramanan, "A carrier based PWM algorithm for indirect matrix converters," in *PESC Record - IEEE Annual Power Electronics Specialists Conference*, 2006.

[18] D. Borojević, "Space Vector Modulated Three-Phase to Three-Phase Matrix Converter with Input Power Factor Correction," *IEEE Trans. Ind. Appl.*, vol. 31, no. 6, pp. 1234–1246, 1995.

[19] T. D. Nguyen and H.-H. Lee, "Modulation Strategies to Reduce Common-Mode Voltage for Indirect Matrix Converters," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 129–140, 2012.

[20] X. Li, Y. Sun, J. Zhang, M. Su, and S. Huang, "Modulation Methods for Indirect Matrix Converter Extending the Input Reactive Power Range," *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4852–

4863, 2017.

[21] M. Jussila and H. Tuusa, "Space-vector modulated indirect matrix converter under distorted supply voltage - Effect on load current," *PESC Rec. - IEEE Annu. Power Electron. Spec. Conf.*, vol. 2005, no. 1, pp. 2396–2402, 2005.

[22] T. Friedli, M. L. Heldwein, F. Giezendanner, and J. W. Kolar, "A high efficiency indirect matrix converter utilizing RB-IGBTs," *PESC Rec. - IEEE Annu. Power Electron. Spec. Conf.*, pp. 3–9, 2006.

[23] M. Jussila, M. Salo, and H. Tuusa, "Realization of a three-phase indirect matrix converter with an indirect vector modulation method," *IEEE 34th Annu. Conf. Power Electron. Spec. 2003. PESC '03.*, vol. 2, pp. 689–694.

[24] P. Kiatsookkanatorn and S. Sangwongwanich, "A unified PWM method for matrix converters and its carrier-based realization using dipolar modulation technique," *IEEE Trans. Ind. Electron.*, 2012.

[25] F. Gruson, P. Le Moigne, P. Delarue, A. Videt, X. Cimetiere, and M. Arpillière, "A simple carrier-based modulation for the SVM of the matrix converter," *IEEE Trans. Ind. Informatics*, 2013.

[26] L. M. Tolbert and T. G. Habetier, "Novel multilevel inverter carrier-based PWM method," *IEEE Trans. Ind. Appl.*, 1999.

[27] A. Hassanpoor, S. Norrga, H. P. Nee, and L. Angquist, "Evaluation of different carrier-based PWM methods for modular multilevel converters for HVDC application," in *IECON Proceedings (Industrial Electronics Conference)*, 2012.

[28] S. M. Ahmed, A. Iqbal, H. Abu-Rub, J. Rodriguez, C. A. Rojas, and M. Saleh, "Simple carrier-based PWM technique for a three-to-nine-phase direct ac-ac converter," *IEEE Trans. Ind. Electron.*, 2011.

[29] F. Gruson, P. Le Moigne, P. Delarue, M. Arpillière, and X. Cimetiere, "Comparison of losses between matrix and indirect matrix converters with an improved modulation," in *IEEE International Symposium on Industrial Electronics*, 2010.

[30] G. T. Chiang and J. I. Itoh, "Comparison of two overmodulation strategies in an indirect matrix converter," *IEEE Trans. Ind. Electron.*, 2013.

[31] M. Y. Lee, P. Wheeler, and C. Klumpner, "Space-vector modulated multilevel matrix converter," *IEEE Trans. Ind. Electron.*, 2010.

[32] D. O. Neacsu, "Space Vector Modulation - An Introduction," *IEEE Annu. Conf. Ind. Electron. Soc.*, 2001.

[33] J. Wang, B. Wu, D. Xu, and N. R. Zargari, "Indirect space-vector-based modulation techniques for high-power multimodular matrix Converters," *IEEE Trans. Ind. Electron.*, 2013.

[34] M. Hamouda, H. F. Blanchette, K. Al-Haddad, and F. Fnaiech, "An efficient DSP-FPGA-based real-time implementation method of SVM algorithms for an indirect matrix converter," *IEEE Trans. Ind. Electron.*, 2011.

[35] L. Helle, K. B. Larsen, A. H. Jorgensen, S. Munk-Nielsen, and F. Blaabjerg, "Evaluation of Modulation Schemes for Three-Phase to Three-Phase Matrix Converters," *IEEE Trans. Ind. Electron.*, 2004.

[36] M. Rivera, P. Correa, J. Rodríguez, I. Lizama, and J. Espinoza, "Predictive control of the indirect matrix converter with active damping," in *2009 IEEE 6th International Power Electronics and Motion Control Conference, IPEMC '09*, 2009.

[37] M. Rivera, C. Rojas, J. Rodríguez, P. Wheeler, B. Wu, and J. Espinoza, "Predictive current control with input filter resonance mitigation for a direct matrix converter," *IEEE Trans. Power Electron.*, 2011.

[38] M. Rivera, J. Rodriguez, B. Wu, J. R. Espinoza, and C. A. Rojas, "Current control for an indirect matrix converter with filter resonance mitigation," *IEEE Trans. Ind. Electron.*, 2012.

[39] J. I. Itoh, K. Koiwa, and K. Kato, "Input current stabilization control of a matrix converter with boost-up functionality," in *2010 International Power Electronics Conference - ECCE Asia -, IPEC 2010*, 2010.

[40] F. Blaabjerg, D. Casadei, C. Klumpner, and M. Matteini, "Comparison of two current modulation strategies for matrix converters under unbalanced input voltage conditions," *IEEE Trans. Ind. Electron.*, vol. 49, no. 2, pp. 289–296, 2002.

[41] J. I. Itoh, K. Koiwa, and K. Kato, "Input current stabilization control of a matrix converter with boost-up functionality," in *2010 International Power Electronics Conference - ECCE Asia -, IPEC 2010*, 2010, pp. 2708–2714.

[42] Y. Yoon and S. Sul, "Carrier-based modulation method for matrix converter with input power factor control and under unbalanced input voltage conditions," *Power Electron. Conf. APEC 2007*, pp. 310–314, 2007.