Standard Clamp for Regenerative Braking in Matrix Converter Drive: More Electric Aircraft

Imayavaramban Munuswamy
School of Electrical and Electronics Engineering
The University of Nottingham
Nottinghamshire, England, UK
Email: Imayavaramban@ieee.org

Patrick W Wheeler
School of Electrical and Electronics Engineering
The University of Nottingham
Nottinghamshire, England, UK
Email: Pat.wheeler@nottingham.ac.uk

***Abstract*—This paper describes a novel method for braking regeneration in the Matrix Converter (MC) drive is proposed, called Standard Clamp Circuit (SCC) method for More Electric Aircraft (MEA). In earlier publications, Bi-Directional Switch (BDS) method and Input Power Clamp (IPC) method with Power Comparison (PC) technique and Input Voltage Reference (IVR) technique for regenerative braking or electrical braking in the Matrix Converter drive have been discussed. The electrical braking is important in many aerospace applications such as surface actuation and Air to Air (in-flight) refueling system. Therefore, the inherent regeneration capability of the Matrix Converter drive is not desirable for aerospace applications so it has to be avoided. In contrast to earlier methods, the proposed SCC method is using the existing standard clamp circuit in the Matrix Converter drive. The proposed methods are demonstrated through detailed simulation results.**

I. INTRODUCTION

This research is focused on aerospace applications, such as aircraft surface actuation control systems and Air to Air (in-flight) Refueling systems (AAR), where regeneration into the main supply is not allowed. The avoidance of regeneration is very important in aerospace applications. For example, When Air-Air Refuelling (AAR) the Tanker Aircraft (TA) hose trails and winds, the regeneration takes place in the Host Drum Drive Motor (HDDM). The air refuelling system in the TA [1] as depicted in the Fig 1. Air to air refuelling means the receiver aircraft receives the fuel from the Tanker Aircraft, as shown in Fig 2. It includes the refuelling hose which is controlled by the

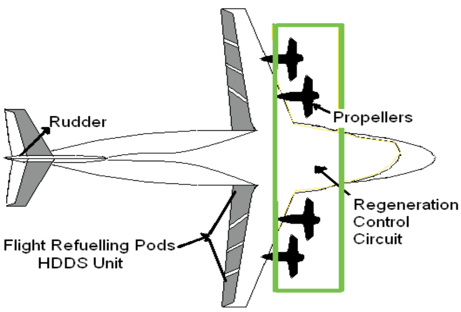

Fig 1. Host Drum Drive System of Tanker Aircraft (TA)

Host Drum Drive System (HDDS). This system is commanded by Refuelling Control Unit (RCU) by sending Aeronautical Radio Incorporated commands (ARINC). HDDS has three main components such as Motor Control Unit (MCU), Dump Resistor Pack (DRP) and two motors as shown in the Fig 3.

Fig 2. Tanker Aircraft Refueling Receiver Aircraft [1]

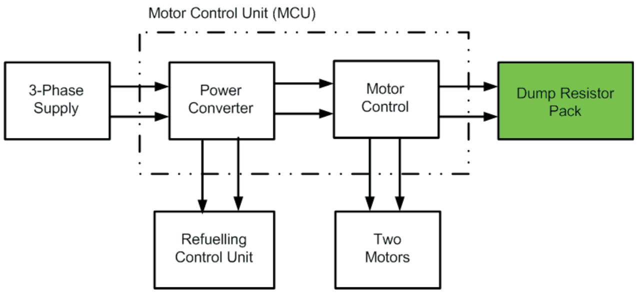

Fig 3. Schematic of Host Drum Drive System of TA

The MCU controls the motors based on RCU commands. For refuelling purpose the Tanker Aircraft refuelling hose trails and winds by Hose Drive Drum Motor. At the moment, the tension and retrieval of refuelling hose is controlled by MCU by changing the direction of motors speed. So that regeneration occurs in the motors. HDDS should able to dissipate the regenerated power otherwise it can cause two major problems:

1. Regeneration can increase the input supply to HDDS
2. Deactivate the control system of HDDS and the whole system become unstable.

Currently, two-stage DC-Link converters are used in the MCU of HDDS. DC-Link converters are more weight and bulk. HDDS should be as light as possible. Because of above reasons Matrix Converter is recommended.

In earlier published methods, called Bi-Directional Switch (BDS) method and Input Power Clamp (IPC) method, have the following disadvantages: 1) The BDS method requires three Bi-Directional Switches in series with three resistors to dissipate the regenerative power. 2) The IPC method requires conventional diode bridge and a switch in series with a resistor.

Matrix Converter modulation is described in section 2. The conventional electrical Braking techniques and methods (BDS, IPC) are explained in section 3, 4 and section 5 respectively. Section 6 discusses the proposed method (SCC) for electrical Braking in the Matrix Converter drive and the comparison for all methods is discussed in Section 7. Simulation results and Experimental verification have been described in section 8.

II. MC Modulation and Vector Control

A. Space Vector Modulation

SVM was first used with matrix converters in [2-3] where this new PWM control technique for Matrix Converters was introduced based on the space vector representation of the voltages.

B. Vector Control

The concept of the Indirect Field Oriented Vector Control (IFOVC) is depicted in the Fig.4 [4-6]. The rotating reference frame is rotating at synchronous angular velocity (ω_e). This reference frame allows the 3-phase currents to be viewed as two 'dc' quantities under steady state conditions. The direct axis or real axis component is responsible for the field producing current (i_{sd}) and is ideally maintained constant up to the motor synchronous speed.

The q-axis component is responsible for torque producing current (i_{sq}). These two vectors are orthogonal to each other so that the field current and torque current can be controlled independently [5-6]. To obtain the stable operation, the reference voltages for space vector modulation are derived from output of speed and current control loops. The output of the speed controller (i^*_{sq}) is considered as reference for i_{sq}

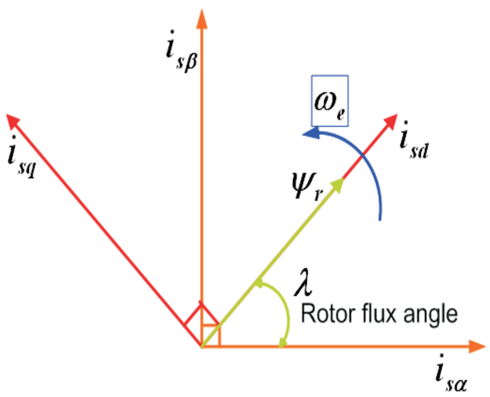

Fig 4. Field Orientation: Ψ_r is aligned with d-axis

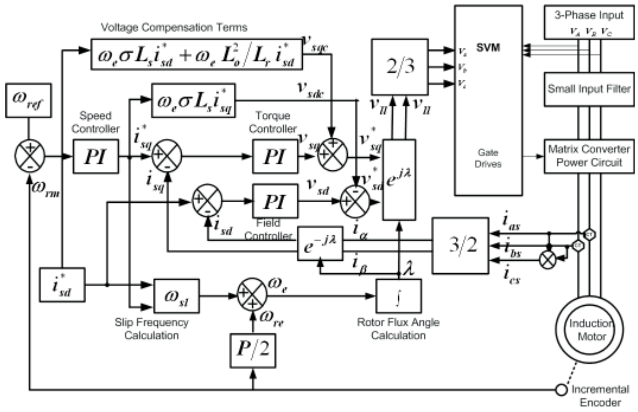

Fig 5. Closed Loop Indirect Field Oriented Vector Control (IFOVC) Scheme

because this value defines the torque produced by the motor. In case of current loop, a calculated constant value (60 % of the no load current) is used as a reference for the field producing current (i^*_{sd}). The outputs of the faster current controllers are summed with voltage compensation terms which are derived from the stator equation. Finally, the stator reference quantities are obtained from 2/3 transformation as shown in the Fig 5.

III. Techniques to Detect Regeneration in MC

Two techniques [7] for detecting regeneration in Matrix Converter motor drives are presented in this section. The first technique is the Power Comparison technique (PC) where the motor output power is used as a reference for the Regeneration Control Circuit (RCC). The second technique is the Input Voltage Reference (IVR) technique, which is similar to dynamic braking technique used in DC-Link converters.

A. Power Comparison (PC) Technique

With regard to Power Comparison (PC) technique, the output power calculation is important. The absolute value of the calculated output power can be used as reference for both electrical Braking methods.

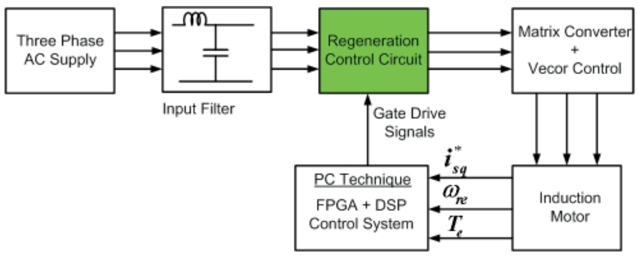

Fig 6. Block Diagram of the Power Comparison (PC) Technique for Electrical Braking Methods

The output power (P_o) of the converter is calculated from the torque producing current (i^*_{sq}) and measured rotor speed

(ω_{re}). Generation of gate drive signals is required for the switches in the Regeneration Control Circuit (RCC) for both dissipation methods, as shown in Fig 6. Power dissipation through the resistors in the Regeneration Control Circuit (RCC) is directly proportional to the duty cycle of switches, as shown in equation 1,

$$P_{dis} \propto D \tag{1}$$

where, D = Duty cycle of the bi-directional switches and P_{dis} = Power dissipation of the resistors.

The duty cycle calculation requires the maximum electrical braking power (P_{mb}) to be calculated, as shown in equation 2. The duty cycle of the switches is less than or equal to unity under all operating conditions.

$$P_{mb} = T_{me}\omega_{mre} \tag{2}$$

where, T_{me} = the maximum electromagnetic torque and ω_{mre} = the maximum motor speed.

The design of braking resistor (R_b) depends upon the maximum power under the regeneration, as shown in equation 3 and equation 4,

$$P_{in,max} = V_{in}^{2} \;/\; R_b \tag{3}$$

$$I_b = V_{in} / R_b \tag{4}$$

Where the braking current (I_b) and input power ($P_{in,max}$) are directly proportional to the input voltage. The braking resistor design also depends on the braking time, the thermal capacity of the resistor and heat sink. The value of braking current must also be less than the current rating of switches in the Regeneration Control Circuit (RCC).

B. Input Voltage Reference (IVR) Technique

In the Input Voltage Reference (IVR) technique, the voltage across the input filter capacitor is measured and compared to the supply voltage. The IVR technique can be used to detect the regeneration in the Matrix Converter for electrical Braking methods. Generation of control signals is required for the switches in Regeneration Control Circuit (RCC), as shown in Fig 7.

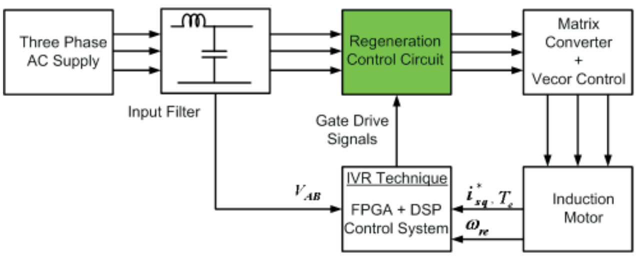

Fig 7. Block Diagram of the Input Voltage Reference (IVR) Technique for Electrical Braking Methods

The duty cycle variation is directly proportional to the increase in the line to line voltage across the input filter capacitor of the Matrix Converter under regeneration with respect to the output power (P_o), as shown in the equation 5.

$$V_{AB} \propto P_o \propto D \tag{5}$$

here V_{AB} is line to line voltage across the input filter capacitor.

IV. Bi-Directional Switch Method

The power circuit for the BDS method [7] Regeneration Control Circuit (RCC) is shown in Fig 8. The Regeneration Control Circuit (RCC) is introduced across the input filter capacitors (C_{AB}, C_{BC} and C_{AC}). The Regeneration Control Circuit (RCC) is responsible for power dissipation when regeneration takes place in the MC motor drive.

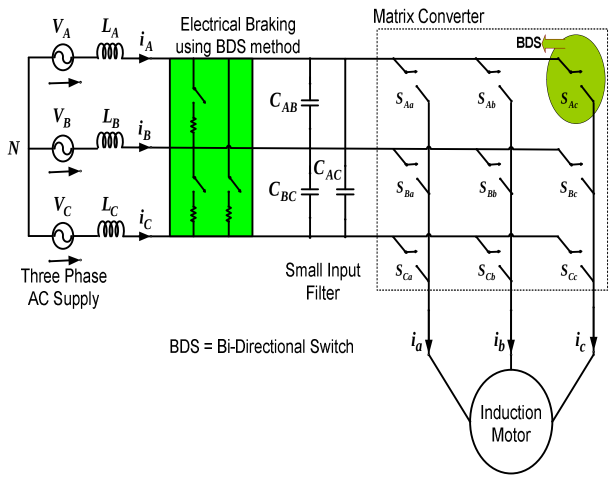

Fig 8. Electrical Braking with a Matrix Converter Motor Drive using the Bi-Directional Switch (BDS) Method

V. Input Power Clamp Method

The Input Power Clamp (IPC) method [8] is used for Braking the electrical energy in a Matrix Converter motor drive. The IPC method requires only one Braking resistor and switch, compared to three switches in series with three resistors for the BDS method

Electrical Braking Circuit or Regeneration Control Circuit (RCC) for the Input Power Clamp (IPC) method is located across the input filter capacitors (*CAB*, *CBC* and *CAC*). The schematic for the Input Power Clamp (IPC) method circuit is shown in Fig 9.

To control the switch in the Regeneration Control Circuit (RCC), a reference signal is generated using either the Power Comparison (PC) technique or the Input Voltage Reference (IVR) technique.

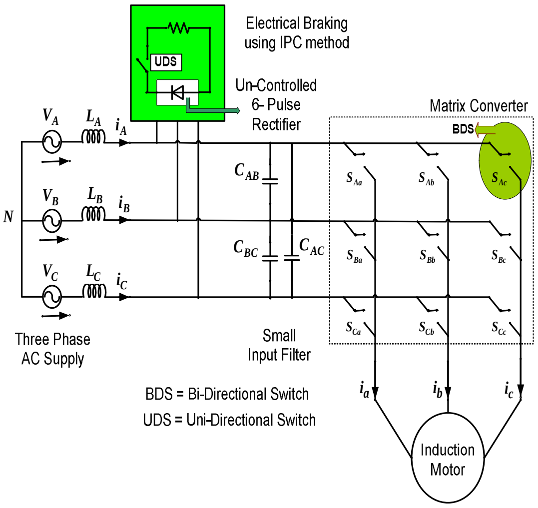

Fig 9. Electrical Braking with a Matrix Converter Motor Drive using the Input Power Clamp (IPC) Method

VI. Proposed Method: SCC

Similar to the BDS method and the IPC method [8], the proposed Standard Clamp Circuit (SCC) method is using two techniques to detect the regeneration in the Matrix Converter drive. These are: 1) Power Comparison (PC) Technique [4] and 2) Input Voltage Reference Technique. However, here the PC technique is only considered and the simulation results of the SCC method with PC technique are discussed. The block diagram for Standard Clamp Circuit is shown in Fig 10. The electrical Braking circuit is for Standard Clamp Circuit is shown in Fig 11.

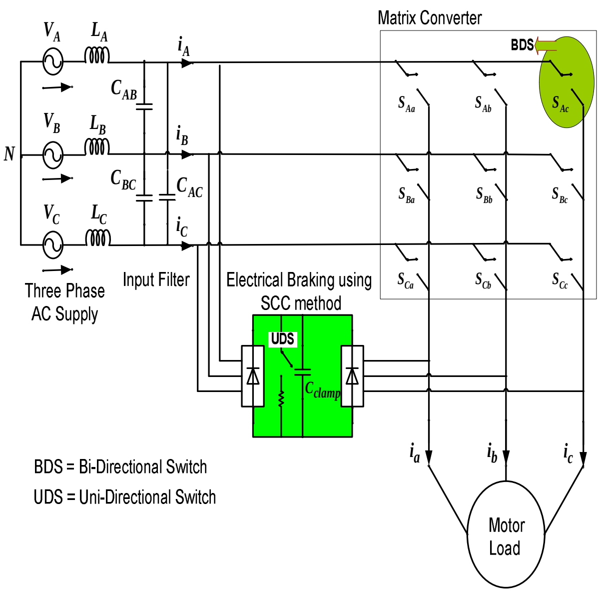

Fig 10. The Proposed Standard Clamp Circuit Method

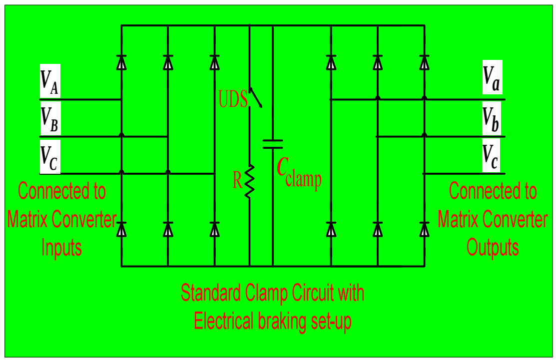

Fig 11. Electrical Braking circuit or Regeneration Control Circuit for SCC Method

Power dissipation through resistor is directly proportional to duty cycle of UDS, is already given in equation (1). To prove the performance of the proposed SCC method for electrical braking in the MC drive, a 2.2kW vector controlled induction motor fed by MC drive is considered.

VII. Comparison

BDS method, IPC method and SCC method

When compared to earlier methods, as described in Table 1, called the BDS method and Input Power Clamp (IPC) method, no auxiliary hardware is required for SCC method for electrical braking in the Matrix Converter drive. The BDS method [7] has three drawbacks:

1. It requires three BDS in series with three resistors.
2. Also it requires complex control platform which controls 6 PWM for electrical braking.
3. This circuit increases size, weight and cost.

Similarly the IPC method has two main drawbacks:

1. It requires conventional uncontrolled diode rectifier and Uni-Directional Switch with a resistor.
2. Separate Control platform for a PWM for electrical braking is required.
3. This circuit increases the size, weight and cost

The proposed SCC method requires only one UDS switch in series with a resistor for Electrical Braking in the MC drive.

Table 1: Comparison of BDS, IPC and SCC

Factors	BDS method	IPC method	SCC method
Switches	3 (BDS)	1 (UDS)	1 (UDS)
Resistors	3	1	1
Diodes	0	6	0
Weight, Size and Cost	Considerably increased	Bit increased	Remains same
Implementation	Complicated	Not complicated	Simple

VIII. SIMULATION RESULTS

To predict and verify the performance of the proposed methods for avoiding regeneration in a Matrix Converter, a simulation study is carried out using SABER software [9].

A. Regeneration

The regeneration can be demonstrated by reversing the speed using the step response as shown in the Fig 12. In this application a step is applied at 1.2 (secs). Fig 12 shows the speed transient and the developed torque in the induction motor for a no load speed reversal (from +188.5 rad/s to -188.5 rad/s) using vector control.

The output current waveforms of the Matrix Converter in the Fig 13 indicate that the speed reversal change from motoring mode to regenerating mode is smoothly achieved. During the step transient (the acceleration and deceleration of the speed), the torque producing current (i_q) of the induction motor reaches the maximum limit 35 Amps. The control of dq-currents (i_d, i_q) with no coupling effects is demonstrated. During regeneration the phase opposition (180◦ phase displacement) between the input phase voltages and input phase currents (i_A, i_B, i_C) can be seen in Fig 14.

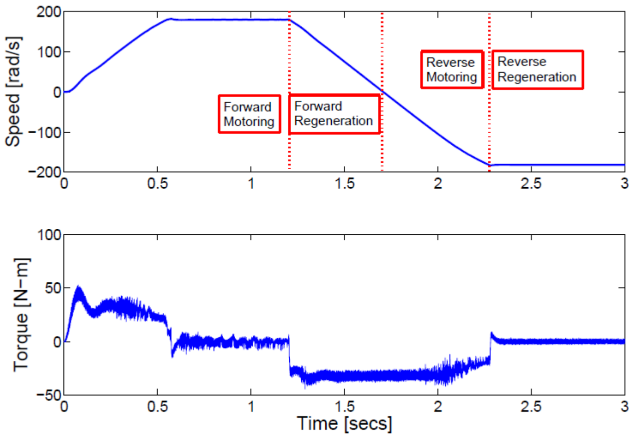

Fig 12. Speed and Torque of the Vector Controlled IM in Regeneration. V_{in} = 240 V, q = 0.75 and f_s = 10 kHz

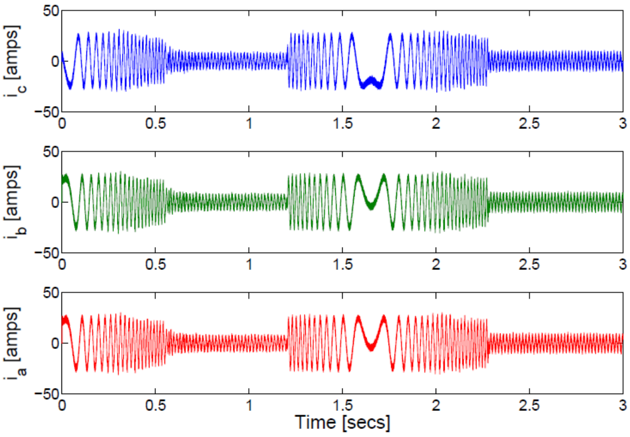

Fig 13. Output Currents of the Matrix Converter in Regeneration V_{in} = 240 V, q = 0.75 and f_s = 10 kHz

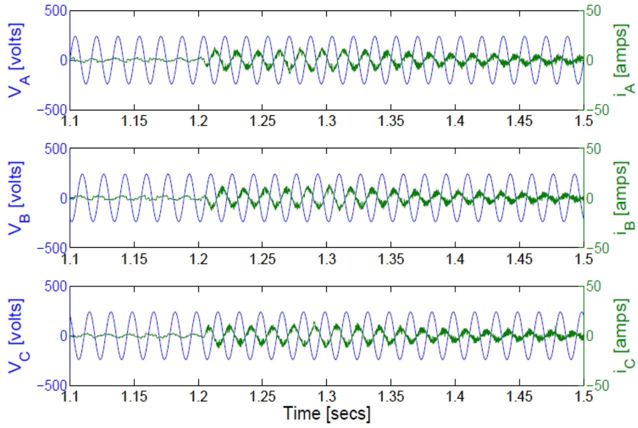

Fig 14. Phase Opposition between Input Phase Voltages and Input Phase Currents of the MC during the Regeneration V_{in} = 240 V, q = 0.75 and f_s = 10 kHz

In order to verify the regenerative energy dissipation, the input phase powers are calculated using input phase voltages and the input phase currents. The phase relationship between the input phase voltages (V_A, V_B, V_C) and input phase currents (i_A, i_B, i_C) whilst avoiding regeneration is shown in the Fig 15. These results can be compared to those in Fig 14.

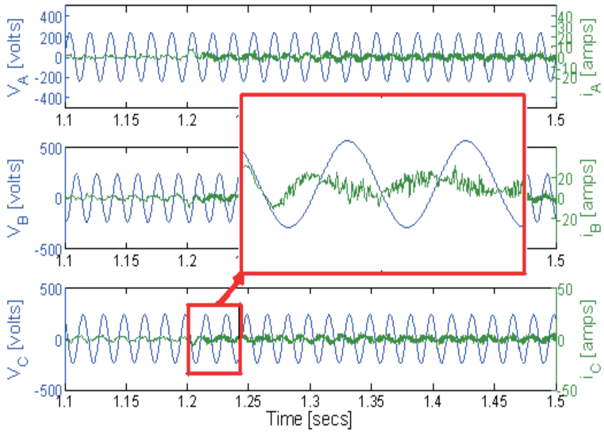

Fig 15. Phase Relationship between Input Phase Voltage and Input Phase Current in the BDS Method with the PC Technique V_{in} = 240 V, q = 0.75 and f_s = 10 kHz

B. Proposed Standard Clamp Circuit Method

The Standard Clamp Circuit method with PC technique is discussed. Similar to BDS and IPC method power dissipation through resistor, is directly proportional to duty cycle of UDS, is given in equation 1. The simulation results for generating a PWM for UDS using SCC method and electrical braking in Matrix Converter drive are shown in Fig 16 and Fig 17 respectively.

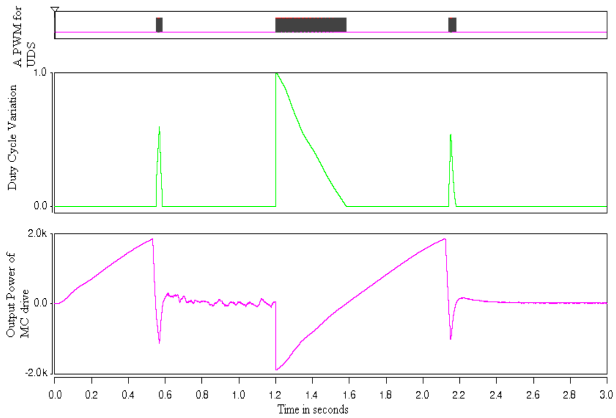

Fig 16. Pulse for RCC, Duty Cycle Variation and Output Power for the SCC Method with the PC Technique. V_{in} = 240 V, q = 0.75 and f_s = 10 kHz

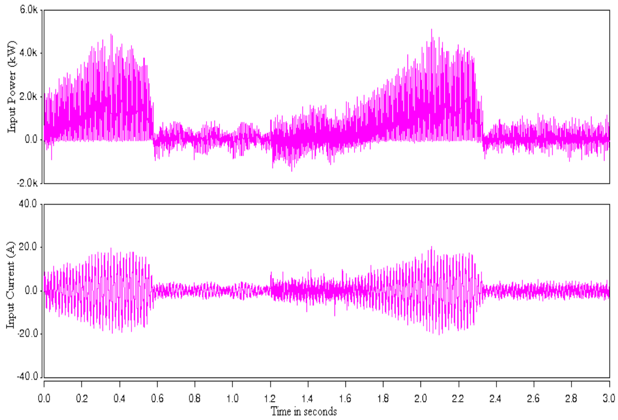

Fig 17. Input Phase Power and Input Phase Current for the SCC Method with the PC Technique V_{in} = 240 V, q = 0.75 and f_s = 10 kHz

IX. Conclusion

Even though all three methods (BDS, IPC and SCC) can produce good results, the Standard Clamp Circuit method with Power Comparison technique is preferable because no auxiliary hardware is required. Hence, the weight, size and cost of the Matrix Converter are considerably reduced. Therefore, the Matrix Converter with SCC method is recommended to aerospace applications where regeneration into the supply is not allowed. Finally, the novel Regeneration Control Circuit (RCC) using Bi-Directional Switch (BDS) method for avoiding regeneration with a Matrix Converter motor drive has been demonstrated. The obtained experimental results are similar to the simulation results as explained in the section 8. From these experimental results, it is concluded that electrical Braking with a Matrix Converter drive is feasible.

References

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