A New Ride-through Approach for Matrix Converter Fed Adjustable Speed Drives

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***Abstract* — In this paper, a new ride-through approach for matrix converter fed adjustable speed drives (ASDs) is discussed and the topology of conventional matrix converter is modified with the addition of three IGBTs and a dc-link capacitor. The proposed modification provides ride-through capability for matrix converter fed ASDs under a short term power interruption. During a power interruption, the matrix converter operates as a conventional PWM voltage source inverter with DC link and forces an immediate transition into the regenerating operation. The proposed scheme maintains rotor flux and keeps synchronization of matrix converter and motor during power outages. In the proposed ride-through approach, it is shown that the matrix converter is able to re-accelerate the motor to the reference speed without current transients. Simulation results are shown to demonstrate the advantages of the proposed scheme and preliminary experimental results are included.**

***Keywords*—matrix converter; ride-through; short term power interruption(STPI); regeneration; indirect space vector PWM (ISVPWM); embedded PWM voltage source inverter (VSI)**

I. INTRODUCTION

Matrix converter was first introduced by Venturini [1]. It has evolved into a direct AC-AC energy converter which converts the AC line voltage to a variable-voltage variable-frequency source without an intermediate DC link circuit and has the following advantages : total silicon solution; sinusoidal input and output waveforms; bidirectional power flow; controllable input power factor and high reliability. However, matrix converter is more sensitive to input power disturbances than a conventional PWM voltage source inverter since the source and output load are connected directly without any intermediate energy storage elements (dc-link).

With the rapid increase of adjustable speed drives (ASDs) in commercial and industrial facilities, the susceptibility of ASDs under power disturbances such as sags, swells, transients and short term power interruption (STPI) has become more important issue. According to a recent survey results, STPI for 0.5 ~ 5 sec and voltage sags of 10 % ~ 40 % below normal grid voltage for 3 ~ 30 cycles are the majority of power disturbances caused to costly industry process disruption [2]. Although several studies concerning ride-through capability under power disturbances have been proposed [2] [3] [7], these studies have focused on three phase PWM rectifier and/or PWM inverter. Reference [4] proposes an approach for matrix converter with limited ride-through capability. However, this approach has limitation to develop torque or motor flux during ride-through interval and needs speed and flux angle observers to re-energize the motor in the grid condition re-establishment.

This paper proposes a new ride-through approach for matrix converter fed ASDs under STPI. In the proposed approach, the topology of a conventional matrix converter is modified with the addition of three IGBTs and a dc-link capacitor. During a power interruption, the input grid is disconnected from the ASD by the selective turn-off of six (out of nine) bidirectional switches. It is shown that the three remaining bidirectional switches along with the additional IGBTs and dc-link capacitor, a PWM voltage source inverter (VSI) can be realized. The PWM VSI is then suitably controlled to maintain rotor flux and guarantee continuous operation of the ASD. Upon restoration of input grid, the control is simultaneously transferred to the matrix converter mode. Thereby the proposed strategy provides ride-through capability for matrix converter fed ASD and has the following advantages :

(1) It maintains rotor flux magnitude and keeps synchronization between matrix converter and motor during STPI.
(2) It allows matrix converter to re-accelerate the motor to the reference speed without experiencing current transients when normal grid condition is re-established
(3) It operates as an embedded PWM voltage source inverter with dc-link during STPI and uses space vector PWM to regenerate mechanical energy in the load inertia to electrical energy in the dc-link capacitor.
(4) Minimum addition of hardware and software is required to the conventional matrix converter structure.

Simulation and experimental results are shown to demonstrate the advantages of the proposed approach.

II. PROPOSED RIDE-THRU SYSTEM IN MATRIX CONVERTER

A. Ride-through system configuration and PWM Strategy

Fig. 1 (a) shows a conventional three phase matrix converter with nine bidirectional switches. This topology allows any output phase *A, B, C* to be connected to any input phase *a, b, c*. Each of the nine bidirectional switches is constructed by connecting two IGBTs in back-to-back. Fig. 1 (b) shows common collector configuration which is usually chosen as lower power 3ϕ/3ϕ power module and each unidirectional IGBTs *SaA+* and *SaA-* represents positive conducting and negative conducting branch of the bidirectional switch *SaA*, respectively, by considering the direction of I_A in Fig. 1 (a) to be positive. Because the matrix converter topology is based on a direct connection between input grid and output load and has no reactive energy storage elements between them, matrix converter is not able to ride-through a momentary power interruption by using load inertia which most commercial PWM VSI-fed ASDs available on the market use as general solution for short power outages.

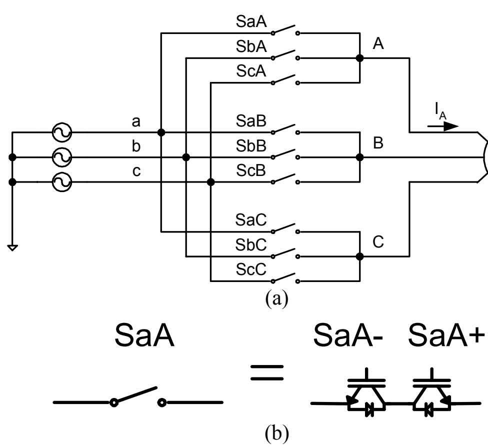


Fig. 1 (a) Conventional three phase matrix converter (b) Common collector configuration of bidirectional switch

The direct conversion of power available from constant voltage constant frequency input grid to variable voltage variable frequency output requires an advanced PWM control of the matrix converter switches (18 IGBTs). After careful consideration, the PWM control can be divided into rectifier control and inverter control section [5]. In the rectifier control section, the input current vector is controlled while the output line-to-line voltage vector is controlled via the inverter stage. Fig. 2 (a) shows input current switching hexagon where *a, b, c* indicate input phase voltage references and Fig. 2 (b) shows output voltage switching hexagon where *AB, BC, CA* indicate output line-to-line voltage references, respectively. Indirect

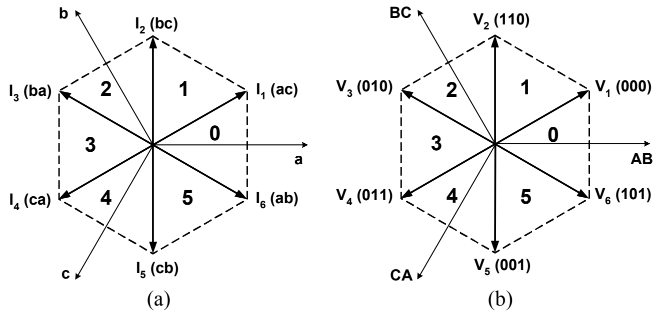


Fig. 2 (a) Input current switching hexagon (b) Output voltage switching hexagon

space vector PWM (ISVPWM) to reduce common mode voltage is adopted for the control of matrix converter [8].

Fig.3 shows the proposed ride-through system for matrix converter. This system consists of two parts. The first part is a conventional matrix converter module which operates under normal grid condition, normal mode. The second part is an add-on ride-through module which extends the matrix converter capability to achieve the ride-through under power interruption, ride-through mode. The three additional IGBTs (*SiA, SiB, SiC*) together with six IGBTs (*SaA+, SaA-, SaB+, SaB-, SaC+, SaC-*) and dc-link capacitor C_{dc} form a conventional standard VSI and use well-known space vector PWM. With 3 IGBTs *SaA-*, *SaB-* and *SaC-* fully turning on, each IGBT pair *SaA+* and *SiA, SaB+* and *SiB*, and *SaC+* and *SiC* are configured as phase *A, B, C* half-bridge arm of the VSI, respectively and the assembly of above 9 IGBTs and dc-link capacitor C_{dc} leads to embedded PWM VSI without rectifying stage. Thus C_{dc} is initially charged to the rated V_{dc}^* during the normal mode or recharged to V_{dc}^* after the ride-through mode via input line-to-line voltage V_{ab} or

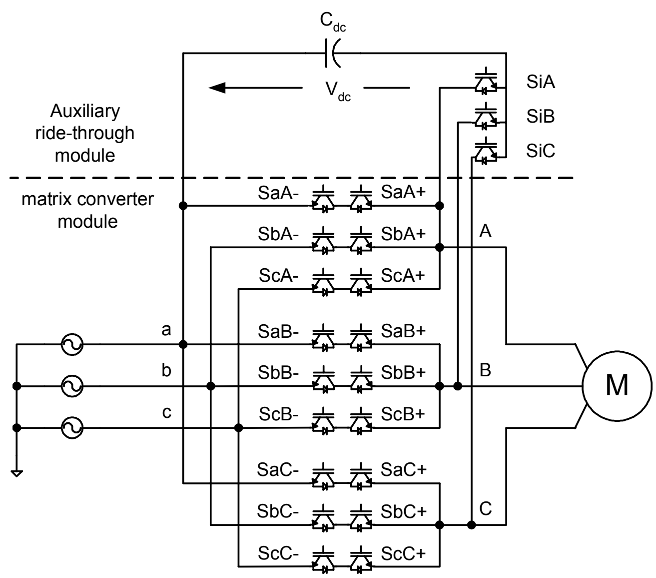
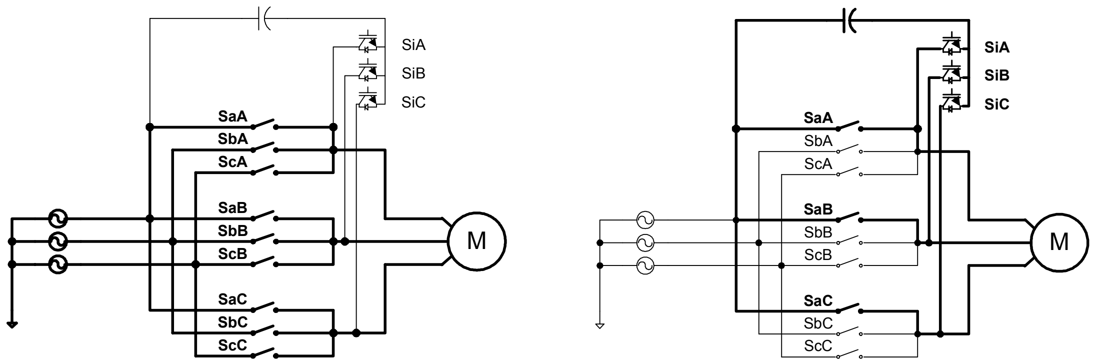


Fig. 3 Proposed matrix converter with ride-through module (*SiA, SiB, SiC* are add-on IGBTs)



(a) (b)

Fig. 4 (a) Normal mode (b) Ride-through mode

V_{ac} (when $V_{ab} > 0$ or $V_{ac} > 0$) and anti-paralleled diodes of 3 IGBTs (*SiA, SiB, SiC*).

B. Proposed Ride-through strategy

Both normal mode and ride-through mode are illustrated in Fig. 4. The bold lines in Fig. 4 (a) represent the working circuit parts during normal mode and normal grid condition and they represent matrix converter structure.

Indirect space vector modulation generates PWM patterns for 9 bidirectional switches, 18 IGBTs, in this mode. The bold lines in Fig. 4 (b) represent the working circuit parts during ride-through mode and momentary power interruption. They represent embedded PWM VSI structure which is the combination of added ride-through module and existing bidirectional switches in matrix converter module. During this mode, input grid is separated from motor and dc-link capacitor by turning off the bidirectional switches connected to input phase *b, c*. 6 IGBTs connected to phase *a* together with add-on 3 IGBTs and dc-link capacitor C_{dc} act as 3 phase PWM VSI. While the amount of stored energy in the dc capacitor is usually not sufficient to supply rated power to motor during a STPI, the mechanical energy of motor and load inertia is substantially higher. Thus, when the DSP controller detects the power interruption, it regulates the dc-link voltage V_{dc} by decreasing the speed of the drive. Subsequent regeneration is used to feedback energy from the motor inertia and maintains the dc-link voltage level at a preset value.

The ride-through capability by using load inertia is controlled by PI regulator. This regulator regulates the dc-link voltage with acceptable steady-state performance during power interruption by changing the stator reference frequency accordingly. Fig. 5 shows the control block diagram for the proposed system. When the control is transferred to ride-through mode, the output of PI regulator is initially held at zero. Thus, ω_r will start decreasing from zero to negative value as soon as the PI regulator is enabled. This negative-going rotor frequency ω_r is added to stator reference frequency ω_s and resulted in stator ride-through frequency ω_o . The stator reference voltage V_o and angle θ_o proportional to *V/f* characteristic are used in the space vector PWM (SVPWM) block to generate 6 IGBT gate patterns of embedded PWM VSI [6]. During this interval, the drive continues to operate at almost zero torque and just regenerates a minor amount of power to cover the electrical losses in the entire drive. When the input grid is re-established and DSP controller detects the event, DSP controller transfers control to the indirect space vector PWM (ISVPWM) block for matrix converter and re-accelerates motor shaft speed from the stator ride-through frequency ω_o to the stator reference frequency ω_s without any discontinuity in the rotor flux. ISVPWM block generates 18 IGBT gate patterns for matrix converter and uses input grid voltage vector V_i to control input displacement power factor.

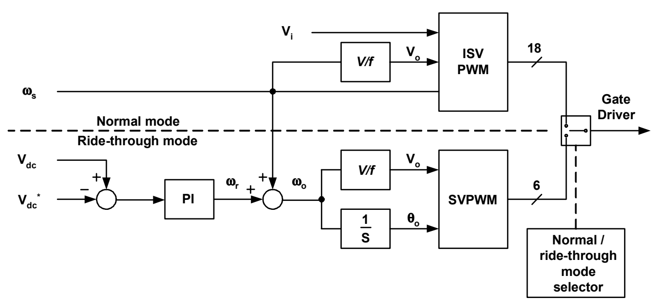


Fig. 5 Control block diagram of the proposed ride-through strategy

III. SIMULATION RESULTS

To illustrate the advantages obtained by the proposed ride-through approach, the matrix converter of Fig. 3 has been simulated in PSIM. The parameters of the induction motor used in the simulation are P=3HP, U_N=220V, f_N=60Hz, n_N=1710rpm, J=0.089kgm2, I_N=5.8A, T_N=11.9Nm, R_S=0.435Ω, R_R=0.816Ω, L_S=L_R=2mH, L_M=69.3mH and other simulation conditions are as follows :

Input grid : 220V, 60 Hz
Output frequency : 40 Hz
Switching frequency : 2 kHz
Dc-link capacitor C_{dc} : 500 µF
Acceleration ramp : 120 Hz/sec

Fig. 6 shows the ride-through operation without load torque, T_{load} = 0 Nm, during 400 msec short term power interruption. Fig. 6 (a) shows input grid is interrupted momentarily during 0.8 ~ 1.2 sec and Fig. 6(b) shows the motor phase current I_A of matrix converter flows continuously without transients after power outage and re-establishment. Fig. 6(c) shows V_{dc} is regulated well by regenerating load mechanical energy during outage and then back to its normal dc-link voltage level. Fig. 6(d) shows the motor maintains its shaft speed with small speed dip and continues its operation. Fig. 7 shows the proposed scheme performs a complete ride-through operation at 100% load torque. Fig. 7(b) shows motor phase current I_A supplies magnetizing current during outage and small amount of power for converter losses regardless of the required load torque during normal mode. Fig. 7(c) shows V_{dc} is regulated at 90 % of the predetermined dc-link voltage V_{dc}^* under100% load torque. Fig. 7(d) shows motor shaft speed decreases to 50% of reference speed by the difference between zero electromagnetic torque and 100% load torque during STPI and re-accelerates toward the reference speed with the acceleration ramp of 120Hz/sec after input grid re-establishment. It shows the possible duration of the ride-through operation depends on load torque as well as initial motor shaft speed level.

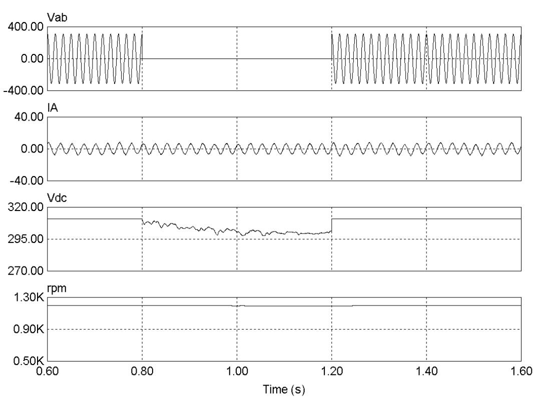


Fig. 6 Ride-through operation under zero load torque : from top to bottom (a) input line voltage V_{ab} (b) motor phase current I_A (c) dc-link voltage V_{dc} (d) motor shaft speed [rpm]

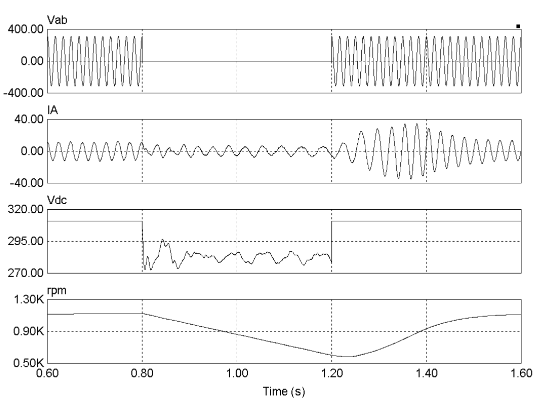


Fig. 7 Ride-through operation under 100% load torque : from top to bottom (a) input line voltage V_{ab} (b) motor phase current I_A (c) dc-link voltage V_{dc} (d) motor shaft speed [rpm]

IV. Hardware Implementation

To validate the theoretical analysis and simulation, a 230V, 3kVA matrix converter prototype (Fig. 9) was developed. The modulation strategy is an indirect space vector modulation running at 2 kHz with a double-sided switch pattern. Fig. 8 shows the block diagram of the matrix converter with ride-through capability. The prototype consists of a DSP board using TMS320LF2407, a FPGA board and Analog board for 4 step commutation and several functional digital logics programmed in Altera EPM7128S, a Gate driver & 7 isolated power supply board and a power board containing Eupec IGBT Matrix module (FM35R12KE3) and 3 discrete IGBTs (IRG4PH50KD) chosen for embedded PWM VSI, voltage and current sensors and snubbers.

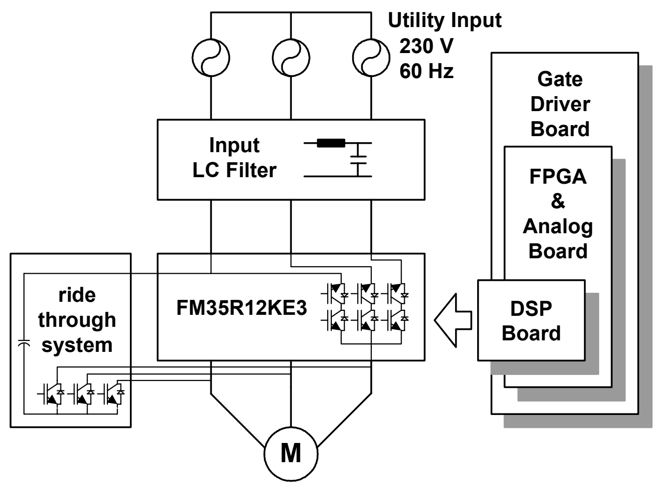


Fig. 8 Block diagram of 230V, 3kVA laboratory prototype matrix converter with ride-through capability

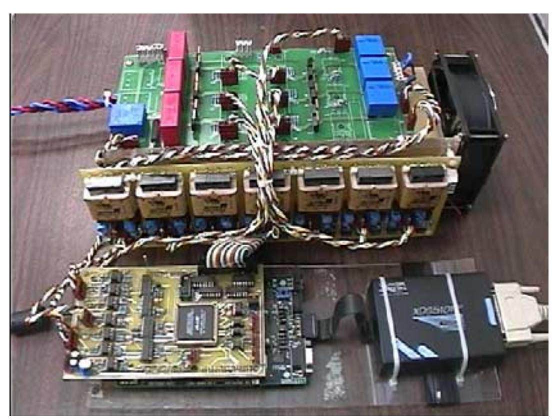


Fig. 9 230V, 3 kVA laboratory prototype matrix converter

V. EXPERIMENTAL RESULTS

In the experiment, 208V, 2HP general purpose induction motor is operated with constant voltage-frequency ratio and 2 kHz switching frequency. A separate functional test for matrix converter module and ride-through module has been carried out. Fig. 10 shows the output current I_A and output lint-to-line voltage V_{AB} when matrix converter module is running at 30 Hz. It is seen the matrix converter module supplies sinusoidal output current with low harmonic contents and the output line-to-line voltage reflects 360 Hz peak envelope of input source voltage. The Fig. 11 shows an acceleration of motor from 5 Hz to 30 Hz at no loaded condition. The auxiliary ride-through module has been tested with the same load and input condition with extra B6 type rectifier to verify its feasibility. Fig. 12 shows the output current I_A and output line-to-line voltage V_{AB} running at 30 Hz and 300V dc link voltage is provided by extra B6 rectifier. Preliminary experiment about mode change between normal mode and ride-through mode has been done with 500 msec short term power interruption and three phase passive reactor load. Fig. 13 shows STPI detector signal (trace 1), input line-to line voltage V_{ab} (trace 2), output load current I_A (trace 3) and output line-to-line voltage V_{AB} (trace 4) when input grid is interrupted momentarily during 500 msec. AC power source (California Instruments) is used to generate a custom defined three-phase voltage system. While STPI detector signal is “1”, the ride-through module supplies the load from dc-link capacitor and extra B6 rectifier. STPI signal is generated by real time STPI detect algorithm programmed in DSP and value “1” indicates momentary power interruption occurs. During normal grid condition that STPI signal is “0”, the matrix converter module supplies the load. Output current I_A flows continuously without any transients between mode changes caused by power outage and re-establishment. Additional experimental results will be presented in the conference.

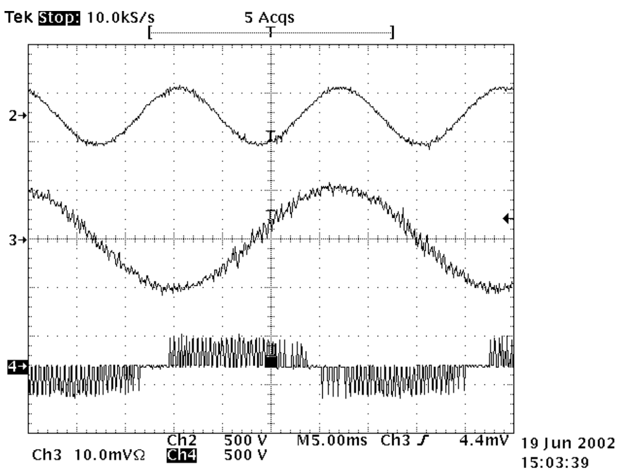


Fig 10 Matrix converter module operation. (2 : input voltage V_{ab}, 3: output current I_A [5A/div] 4: output line-to-line voltage V_{AB})

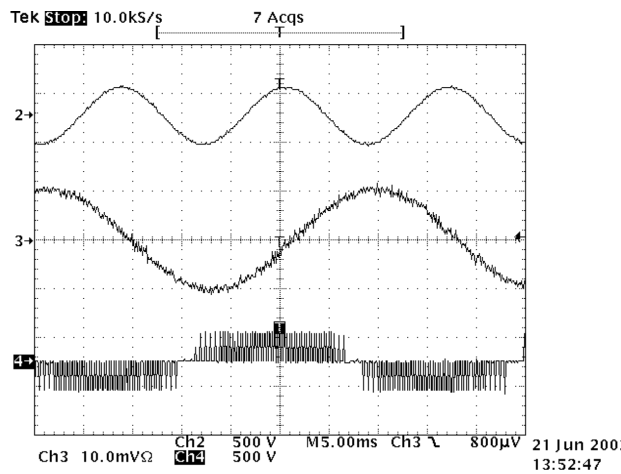


Fig 12 Ride-through module operation (2 : input voltage V_{ab}, 3: output current I_A [5A/div] 4: output line-to-line voltage V_{AB})

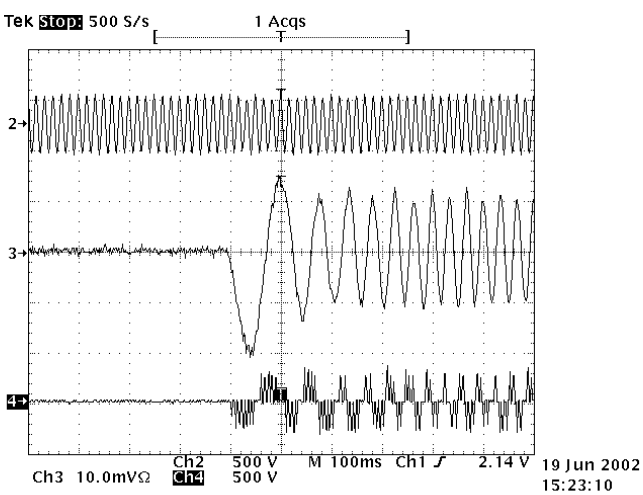


Fig 11 Motor Acceleration by matrix converter module (2 : input voltage V_{ab}, 3: output current I_A [5A/div] 4: output line-to-line voltage V_{AB})

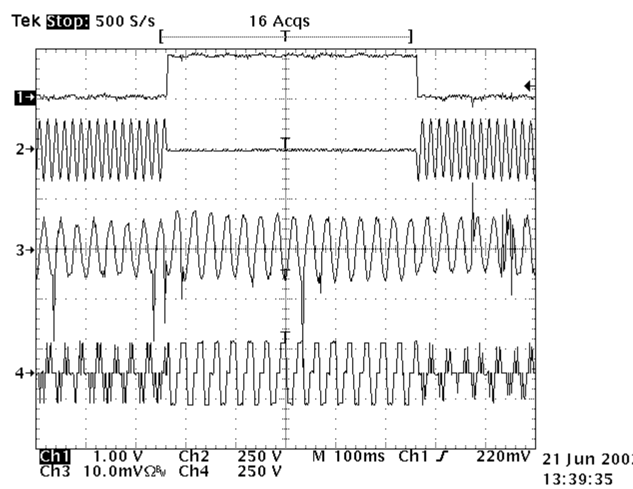


Fig. 13 Mode changes between normal mode and ride-through mode (1: STPI detector signal (0: normal mode, 1: ride-through mode) 2: input voltage V_{ab}, 3: output current I_A 4: output line-to-line voltage V_{AB})

V. Conclusion

In this paper, a new ride-through system for matrix converter has been proposed. The proposed system has been shown to maintain the rotor flux and synchronization between the motor and matrix converter during momentary power interruption. It has been shown that by regenerating the mechanical energy stored in load inertia and storing it to dc-link capacitor in the embedded PWM VSI part, successful ride-through operation can be attained. Further, the matrix converter has been shown to re-accelerate the motor to the reference speed without any current transients when normal grid condition is recovered. The duration of the ride-through operation depends on initial motor shaft speed level, load torque type and load inertia and this approach is well acceptable for variable torque load such as fan, pump and compressor. The feasibility of the proposed ride-through system has been verified through simulation and experiments.

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