

**ANALYSIS, DESIGN AND IMPLEMENTATION OF
IMPROVED POWER QUALITY CONVERTERS FED
ADJUSTABLE SPEED INDUCTION MOTOR DRIVES**

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ADJUSTABLE SPEED INDUCTION MOTOR DRIVES**

by

MADISHETTI SANDEEP
Department of Electrical Engineering

Submitted

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CERTIFICATE

This is to certify that the thesis entitled, “**Analysis, Design and Implementation of Improved Power Quality Converters fed Adjustable Speed Induction Motor Drives**” being submitted by **Mr. Madishetti Sandeep** for the award of the degree of Doctor of Philosophy is a record of bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Madishetti Sandeep has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results obtained here in have not been submitted to any other University or Institute for the award of any degree.

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ABSTRACT

Induction motor drives, the most widely used drives in industry, have been traditionally used in open-loop control applications, for reasons of cost, size, reliability, ruggedness, simplicity, efficiency, less maintenance, ease of manufacture and ability to operate in dusty or inflammable environments. However, due to the complexity of control methodologies for the induction machine, until recently, the DC machine has been the reigning champion of high performance adjustable speed applications. With developments in microprocessors /DSPs, power electronics and control theory, the induction machine can now be used in high performance adjustable or variable-speed and cost-sensitive applications, such as heating, ventilating and air conditioning (HVAC) systems, waste water treatment plants, blowers, fans, textile mills, rolling mills etc. Apart from their inherent advantages mentioned above, induction machines can also have additional merits such as energy efficiency, ease of control, reduction in inrush current compounded with increase in starting torque due to the advent of modern control techniques. The use of Adjustable Speed Induction Motor Drives (ASIMDs) has further increased due to their capability to achieve good dynamic performance using vector control (or field oriented control) and direct torque & flux control. With these control techniques, induction motor drives can achieve similar or even better performance than DC motor drives. These ASIMDs generally use a single-phase or three-phase uncontrolled AC-DC converter along with a capacitor filter at the front end (for rectifying the AC mains voltage and filtering the DC output), followed by a three-phase Voltage Source Inverter (VSI) for feeding the induction machine. Such type of utility interface suffers from power quality problems such as poor power factor, injection of current harmonics into the AC mains, variations in the DC bus voltage with fluctuations in the AC mains voltage, equipment overheating due to harmonic current absorption, voltage distortions at the

point of common coupling (PCC) due to the voltage drop caused by harmonic currents flowing through the system impedances, decreased rectifier efficiency, malfunction of sensitive electronic equipment, interference on telephone and communication lines due to high frequency switching etc.

Several international power quality standards such as IEEE-519, IEC 61000-3-2, etc. give guidelines to impose strict limits on the levels of the AC mains current and voltage harmonic injections. This has led to the development of various circuit configurations for power quality improvement in ASIMDs used in different applications.

The main objective of this research work is to design, model, simulate, develop and implement in hardware different Improved Power Quality Converters (IPQCs) for mitigating the power quality problems at the AC mains in ASIMDs. Detailed investigations on various IPQCs are carried out for a wide range of applications starting from small rating motor drives used in home appliances up to large rating motor drives used in electric traction.

Based on the application, the ASIMDs need unidirectional or bidirectional power flow. They can also be classified based upon the rating as low voltage and medium voltage ASIMDs. Three different topologies of unidirectional improved power quality AC-DC converters are designed and developed for the front end of ASIMD which target specific applications such as fans, pumps, air conditioners, refrigerators, blowers, paper mills and textile mills where regenerative braking is not mandatory. These converters are Minnesota rectifier, Vienna rectifier and Scott-transformer based rectifier.

Bidirectional power flow applications are where regenerative braking of ASIMDs is desired such as cranes, elevators, marine propulsion systems, tram cars, electric traction, electric vehicles and conveyor belts. Here, the regenerated energy during braking is fed back to the AC

mains. In medium voltage rating ASIMDs, the regenerated power can effect a sizable cost saving even if a small percentage of energy is regenerated. Two different topologies of improved power quality AC-DC converters with bidirectional power flow capability such as two-level Voltage Source Converters (VSCs), three-level VSCs are investigated in this research work. A direct power control scheme has been incorporated in these front end converters to have independent control of real and reactive powers so that unity power factor can be achieved if it is required to do so.

Different digital control techniques are proposed in place of a conventional PI controller for speed, torque and current control loops to achieve improved steady state and dynamic performances. Some of the control techniques that are implemented are Gain-scheduling of a PI controller and RST control technique.

The necessary modeling and simulations are carried out in MATLAB environment using Simulink and SimPowerSystem block set toolboxes. A high speed DSP is used for implementing the drive system with IPQC in hardware. In every scheme, the simulated and experimental results are compared with each other and in most of the schemes and it is found that strict adherence to international power quality standards has been attained in IPQC fed ASIMD.

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- Fig. 3.23 Dynamic performance of the IRFOC based IM drive system during starting for reference speed of $N_r^*=1000$ rpm. (a) v_{abs} , i_{as} , V_{dc} and N_r , (b) i_{as} , V_{dc} , i_{ast} and N_r , (c) i_{as} , i_{bs} , i_{cs} and N_r , (d) i_{dst} , i_{qst} , i_{ast} and N_r .
- Fig. 3.24 Dynamics performance of the IRFOC based IM drive system during field weakening operation (a) i_{as} , V_{dc} and i_{ast} and N_r , (b) i_{dst}^* , i_{qst} , i_{ast} , and N_r .
- Fig. 3.25 Dynamic performance of the IRFOC based IM drive system for a sudden change in reference speed (a) v_{abs} , i_{as} , V_{dc} , and N_r , (b) i_{as} , i_{bs} , i_{cs} and N_r , (c) i_{dst} , i_{qst} , and N_r , (d) i_{ast} , i_{bst} , i_{cst} and N_r .
- Fig. 3.26 Dynamic performance of the IRFOC based IM drive for a sudden change in load torque (a) v_{abs} , i_{as} , V_{dc} and N_r , (b) i_{as} , V_{dc} , i_{ast} and N_r , (c) i_{dst} , i_{qst} , i_{ast} and N_r , (d) i_{ast} , i_{bst} , i_{cst} and N_r .
- Fig. 3.27 Harmonic spectra at the AC mains of the IRFOC based ASIMD with diode bridge rectifier at the AC mains under full-load condition (a) AC mains line voltage and line current, (b) three-phase AC mains power, (c) line current THD and (d) line voltage THD.
- Fig. 3.28 Harmonic spectra at the AC mains of the IRFOC based ASIMD with diode bridge rectifier at the AC mains under light-load (a) AC mains line voltage and line current, (b) three-phase AC mains power, (c) line current THD and (d) line voltage THD.
- Fig. 3.29 Variations of (a) THD and (b) PF at the AC mains of the diode bridge rectifier fed IRFOC of ASIMD for different load torques from light-load to full-load.
- Fig. 3.30 Harmonic spectra of stator current for IRFOC based IM drive with hysteresis current control at full-load (a & b) and light-load (c & d).
- Fig. 3.31 Dynamics of DTC based ASIMD with diode bridge rectifier at the AC mains during starting and sudden change in reference speeds.
- Fig. 3.32 Dynamics of DTC based IM drive with diode bridge rectifier at the AC mains during field weakening and sudden change in load torques.
- Fig. 3.33 AC mains line current harmonic spectrum for diode bridge rectifier fed DTC based IM drive at (a) 100% load torque and (b) 20% load torque.
- Fig. 3.34 AC mains line voltage harmonic spectrum for diode bridge rectifier fed DTC based IM drive at (a) 100% load torque and (b) 20% load torque.
- Fig. 3.35 (a) Variation of THD (%) with the load torque (%) and (b) PF variation with the load torque (%) at AC mains for diode bridge rectifier fed DTC based IM drive.
- Fig. 3.36 Steady state performance of the drive at rated speed and rated load torque (a) v_{abs} , i_{as} , V_{dc} and N_r , (b) i_{as} , i_{bs} , i_{cs} and N_r , (c) i_{as} , V_{dc} , i_{ast} and N_r , (d) i_{ast} , i_{bst} , i_{cst} and N_r , (e) i_{as} , i_{ast} , T_e and N_r , (f) i_{as} , i_{ast} , T_e and N_r , (g) v_{abst} , i_{ast} , T_e & N_r , (h) i_{ast} , ψ_{ast} , ψ_{bst} & N_r .

- Fig. 3.39 Dynamic performance of the drive during starting for reference speed of $N_r^*=1000$ rpm. (a) v_{abs} , i_{as} , V_{dc} and N_r , (b) i_{as} , V_{dc} , i_{ast} and N_r , (c) i_{as} , i_{bs} , i_{cs} and N_r , (d) Ψ_{st} , i_{ast} , T_e and N_r .
- Fig. 3.40 Dynamic performance of the drive during field weakening operation (a) i_{as} , V_{dc} , i_{ast} and N_r , (b) i_{as} , i_{bs} , i_{cs} and N_r , (c) Ψ_{st} , i_{ast} , T_e and N_r , (d) i_{ast} , ψ_{ast} , $\psi_{\beta st}$ and N_r
- Fig. 3.41 Dynamic performance of the drive for a sudden change in reference speed (a) v_{abs} , i_{as} , V_{dc} , and N_r , (b) i_{as} , i_{bs} , i_{cs} and N_r , (c) Ψ_{st} , i_{ast} , T_e and N_r , (d) i_{ast} , i_{bst} , i_{cst} and N_r
- Fig. 3.42 Dynamic performance of the drive for a sudden change in load torque (a) v_{abs} , i_{as} , V_{dc} , and N_r , (b) i_{as} , V_{dc} , i_{ast} , and N_r , (c) i_{ast} , i_{bst} , i_{cst} and N_r , (d) Ψ_{st} , i_{ast} , T_e and N_r , (e) i_{ast} , ψ_{ast} , $\psi_{\beta st}$ and N_r .
- Fig. 3.43 Harmonic spectra at the AC mains of the DTC based IM drive with diode bridge rectifier at the AC mains under full-load torque (a) AC mains line voltage and line current, (b) three-phase AC mains power, (c) line current THD and (d) line voltage THD.
- Fig. 3.44 Harmonic spectra at the AC mains of the DTC based IM drive with diode bridge rectifier at the AC mains under 20% load torque (a) AC mains line voltage and line current, (b) three-phase AC mains power, (c) line current THD and (d) line voltage THD.
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- Fig. 4.2 Third harmonic modulated two-switch IPQC (Minnesota rectifier) fed two-level VSI based ASIMD.
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- Fig. 5.2 Control structure of Minnesota rectifier control with RST current controller.
- Fig. 5.3 Control structure of indirect FOC of three-phase induction motor.
- Fig. 5.4 Block diagram of RST controller.
- Fig. 5.5 Block diagram of RST controller with saturation anti wind-up.
- Fig. 5.6 Frequency response of output PWM noise to output transfer function for RST and PI current controllers [PI gains: $K_{piL}=0.8$, $K_{iiL}=11$], [RST gains: $K_1=5$, $K_2=3$].
- Fig. 5.7 Frequency response of sensing noise to output transfer function for RST and PI current controllers [PI gains: $K_{piL}=0.8$, $K_{iiL}=11$], [RST gains: $K_1=5$, $K_2=3$].
- Fig. 5.8 Step response of RST and PI current controllers.
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- Fig. 5.10 MATLAB Simulink model of RST current controller based Minnesota rectifier fed FOC of IMD.
- Fig. 5.11 Power circuit of Minnesota rectifier.
- Fig. 5.12 MATLAB model of RST current controller based Minnesota rectifier controller.
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- Fig. 5.15 Laboratory prototype of Minnesota rectifier fed IRFOC of IM drive.
- Fig. 5.16 Reference and actual inductor current for (a) conventional PI current controller and (b) polynomial RST current controller based Minnesota rectifier
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- Fig. 5.18 Injected third harmonic current i_{3inj} , AC mains current i_{as} and diode rectifier input current i_{asr} .
- Fig. 5.19 Dynamics of RST current controller based Minnesota rectifier fed IRFOC of IM drive during starting and sudden change in reference speeds.
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- Fig. 5.21 AC mains line current harmonic spectrum for RST current controller based Minnesota rectifier at (a) full-load torque and (b) light-load torque.
- Fig. 5.22 AC mains line voltage harmonic spectrum for RST current controller based Minnesota rectifier at (a) 100% load torque and (b) 20% load torque.
- Fig. 5.23 AC mains line current harmonic spectrum for conventional PI current controller based Minnesota rectifier at (a) 100% load torque and (b) 20% load torque.
- Fig. 5.24 (a) AC mains current THD Vs load torque (%) plot and (b) AC mains PF Vs load torque (%) plot for both PI and RST current controllers based Minnesota rectifier fed IRFOC of ASIMD.
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- Fig. 5.26 Performance of the drive system under steady state at rated speed ($N_r^*=1430$ rpm) and load torque ($T_L=15$ Nm) (a) v_{abs} , i_{as} , V_{dc} , and V_{c2} , (b) v_{as} , i_{as} , V_{dc} and V_{c2} , (c) i_{as} , i_{bs} , i_{cs} and V_{dc} (d) v_{abs} , i_{as} , V_{dc} and i_{ast} , (e) N_r , i_{as} , V_{dc} , and V_{c2} , (f) N_r , i_{as} , V_{dc} and i_{ast} , (g) N_r , i_{ast} , i_{bst} and i_{cst} , (h) AC mains current i_{as} , diode rectifier input current i_{asbr} and injected current i_{3inj} .
- Fig. 5.27 Dynamic performance of the drive system during starting for a reference speed of $N_r^*=900$ rpm.
- Fig. 5.28 Dynamic performance of the drive system during field weakening operation (a) N_r , i_{as} , V_{c2} and V_{dc} , (b) N_r , i_{as} , i_{ast} , and V_{dc} .
- Fig. 5.29 Dynamic performance of the drive system for a sudden change in reference speed (a) N_r , i_{as} , V_{dc} and i_{ast} , (b) N_r , i_{ast} , i_{bst} and i_{cst} , (c) N_r , i_{as} , V_{dc} and i_{ast} , (d) v_{as} , i_{as} , V_{dc} and N_r .

- Fig. 5.30 Dynamic performance of the drive system for a sudden change in load torque (a) v_{abs} , i_{as} , V_{dc} and i_{ast} , (b) i_{as} , i_{bs} , i_{cs} and V_{dc} (c) N_r , i_{as} , V_{dc} and V_{c2} , (d) N_r , i_{as} , V_{dc} and i_{ast} , (e) v_{as} , i_{as} , V_{dc} and V_{c2} .
- Fig. 5.31 Harmonic spectra at the AC mains of the RST current controller based Minnesota rectifier fed VCIMD under full-load torque (100%) (a) AC mains line voltage and line current, (b) three-phase AC mains power, (c) line current THD and (d) line voltage THD.
- Fig. 5.32 Harmonic spectra at the AC mains of the RST current controller based Minnesota rectifier fed VCIMD under light-load torque (20%) (a) line voltage and line current, (b) three phase AC mains power, (c) line current THD and (d) line voltage THD.
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- Fig. 5.34 (a) Input AC mains current THD Vs load torque (%) plot and (b) Input AC mains PF Vs load torque (%) plot for both PI and RST current controllers based Minnesota rectifier fed FOC of IMD.
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- Fig. 6.11 Dynamic results of Scott-transformer IPQC fed three-level NPC inverter based SVM-IRFOC of IM drive with feed-forward control during starting and sudden change in reference speed.
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- Fig. 6.13 Harmonic analysis of AC mains currents of proposed drive system at (a) full-load torque and (b) light-load torque.
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- Fig. 6.15 THD (%) and PF with the load torque (%) for three-level NPC inverter fed SVMIRFOC of IM drive with proposed Scott-transformer IPQC.
- Fig. 6.16 Steady state waveforms at rated speed ($N_r^*=1430$ rpm) and load torque ($T_L=15$ Nm) (a) v_{abs} , i_{as} , i_{bs} and i_{cs} , (b) i_{as} , V_{dc} , V_{c2} and N_r , (c) i_{as} , V_{dc} , i_{ast} and N_r , (d) i_{ast} , i_{bst} , i_{cst} and N_r , (e) v_{sT1} , v_{sT2} , i_{L1} and i_{L2} .
- Fig. 6.17 Dynamic results of Scott-transformer IPQC fed three-level NPC inverter based IRFOC of IM drive during starting for a reference speed of 1000 rpm.
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- Fig. 6.20 Dynamic response of DC bus voltage under step increase in load torque (a) with feed-forward control and (b) without feed-forward control for proposed drive system for a sudden increase in load torque.
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- Fig. 6.22 Dynamic results under step increase in load torque with feed-forward control (a) v_{abs} , i_{as} , i_{bs} and i_{cs} , (b) secondary voltages of teaser and main transformer (v_{sT1} & v_{sT2}), inductor currents (i_{L1} & i_{L2})
- Fig. 6.23 AC mains line voltage (v_{cas}) and AC mains line current (i_{bs}), (b) input active power (P_s) and input reactive power (Q_s), (c) different power quality indices of proposed drive system at full-load torque (100%).
- Fig. 6.24 AC mains line voltage (v_{cas}) and AC mains line current (i_{bs}), (b) input active power (P_s) and input reactive power (Q_s), (c) different power quality indices of proposed drive system at light-load torque (20%).
- Fig. 6.25 (a) THD (%) and (b) PF variations with the load torque (%) for Scott-transformer PFC rectifier fed three-level NPC inverter based IRFOC of IM drive with feed-forward control.
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- Fig. 7.12 AC mains line current harmonic spectrum at (a) 100% & (b) 20% load torque.
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- Fig. 7.15 Steady state performance of the Vienna rectifier fed DTC based IM drive at rated speed ($N_r^*=1430$ rpm) and full-load torque ($T_L=15$ Nm) (a) v_{cas} , i_{bs} , i_{ast} , and N_r , (b) i_{bs} , N_r , V_{c2} and V_{dc} , (c) v_{cas} , i_{as} , i_{bs} and i_{cs} , (d) v_{cas} , i_{ast} , i_{bst} and i_{cst} .
- Fig. 7.16 Dynamics of the Vienna rectifier fed DTC based IM drive during starting at a reference speed of $N_r^* = 1000$ rpm (v_{abs} , i_{bs} , N_r and V_{dc}).
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- Fig. 7.18 Dynamics of Vienna rectifier fed DTC based IM drive for sudden change in reference speed (a)&(b) i_{bs} , V_{dc} , V_{c2} , and N_r , (c)&(d) N_r , i_{ast} , i_{bst} , and i_{cst} .
- Fig. 7.19 Dynamics of Vienna rectifier fed DTC based IM drive for a sudden change in load torque (a) & (b) i_{bs} , N_r , V_{dc} and V_{c2} , (c)&(d) N_r , i_{ast} , i_{bst} and i_{cst} .
- Fig. 7.20 Experimental results at the AC mains of the Vienna rectifier fed DTC based IM drive under full-load torque (a) AC mains line voltage and line current, (b) three-phase AC mains power, (c) line current harmonic spectrum and (d) line voltage harmonic spectrum.
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- Fig. 8.5 Block diagram of the total control system of speed and torque controller loops.
- Fig. 8.6 Bode plot of GS-PI speed and torque controllers based SVM-DTC for $k_{p\omega}=K_{p\omega max}$, $k_{i\omega}=K_{i\omega min}$ & $k_{pt}=K_{pt max}$, $k_{it}=K_{it min}$ (b) $k_{p\omega}=K_{p\omega min}$, $k_{i\omega}=K_{i\omega max}$ & $k_{pt}=K_{pt max}$, $k_{it}=K_{it max}$.
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- Fig. 8.13 Dynamic response of VF SVM-DPC based active front end VSC fed GS-PI controller based SVM-DTC during starting and sudden change in reference speed.
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- Fig. 8.21 (a) Starting response of i_{as} , DC bus voltage V_{dc} , stator current i_{ast} and N_r for conventional fixed gain-PI speed controller, (b) Starting response of proportional gain $k_{p\omega}$, integral gain $k_{i\omega}$, i_{ast} and N_r for GS-PI speed controller.
- Fig. 8.22 Response comparison during speed reversal (a) i_{as} , V_{dc} , i_{ast} and N_r for conventional fixed gain-PI speed controller (b) torque-loop proportional gain k_{pt} , integral gain k_{it} , i_{ast} and N_r for GS-PI torque controller during speed reversal.
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- Fig. 8.26 Response of (a) speed-loop proportional gain $k_{p\omega}$, integral gain $k_{i\omega}$, i_{ast} and N_r for step increase in reference speed from 1100 to 1430 rpm, (b) Response of v_{abs} , i_{as} , V_{dc} , N_r and (c) i_{ast} , i_{bst} , i_{cst} , N_r for step decrease in reference speed from 1430 to 1000 rpm.
- Fig. 8.27 Response of v_{abs} , V_{dc} , T_e and N_r during a step increase in load torque from 20% to 100% at $N_r^*=1430$ rpm for (a) fixed gain PI based SVM-DTC & (b) GS-PI based

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- Fig. 8.29 Response of i_{as} , i_{ast} , Ψ_{st} and N_r for step change in load torque from 20% to 100% at $N_r^*=1430$ rpm for (a) fixed gain PI based SVM-DTC and (b) GS-PI based SVM-DTC.
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- Fig. 8.31 Response of V_{dc} , P_s , Q_s and N_r for (a) step increase in load torque from 20% to 70% and (b) step decrease in load torque from 70% to 20% at $N_r^*=1430$ rpm.
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- Fig. 8.37 (a) THD (%) and (b) PF with the load torque (%) for the proposed drive system.
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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital
ASIMD	Adjustable Speed Induction Motor Drive
CAN	Controller Area Network
CCS	Code Composer Studio
CPU	Central Processing Unit
CF	Crest Factor
DAC	Digital to Analog
DBR	Diode Bridge Rectifier
DC	Direct Current
DF	Distortion Factor
DPC	Direct Power Control
DPF	Displacement Power Factor
DSP	Digital Signal Processor
DTC	Direct Torque Control
FOC	Field Oriented Control
FLC	Fuzzy Logic Control
HVAC	Heating, Ventilation and Air Conditioning
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IPQC	Improved Power Quality Converter
IRFOC	Indirect Rotor Field Oriented Control
MATLAB	Matrix Laboratory
MCB	Miniature Circuit Breaker
MOSFET	Metal Oxide Field Effect Transistor
MRAS	Model Reference Adaptive Systems

NPC	Neutral Point Clamped
PCB	Printed Circuit Board
PCC	Point of Common Coupling
PF	Power Factor
PFC	Power Factor Correction
PI	Proportional plus Integral
PPC	Power PC
PWM	Pulse Width Modulation
RST	Regulation, Steady state error, Tracking
RTI	Real Time Interface
RTW	Real Time Workshop
SVM	Space Vector Modulation
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
UPF	Unity Power factor
VF	Virtual Flux
VOC	Voltage Oriented Control
VSC	Voltage Source Converter
VSI	Voltage Source Inverter

LIST OF SYMBOLS

$A(s)$	Denominator of open-loop transfer function
a	Overload factor
α - β	Two-phase stationary axes
α^{st} - β^{st}	Two-phase stationary axes fixed on stator
$B(s)$	Numerator of open-loop transfer function
C	DC bus capacitor/capacitance (F)
C_k	Constant
C_1, C_2	DC bus capacitors/capacitance (F)
C_{out}	Low pass filter capacitance (F)
$C(s), F(s)$	Transfer function of control and filtering parameters
$\sin\theta_e, \cos\theta_e$	Unit vectors of rotor flux angle θ_e
$\sin\theta_{\psi s}, \cos\theta_{\psi s}$	Unit vectors of virtual flux angle $\theta_{\psi s}$
$\sin\theta_{\psi st}, \cos\theta_{\psi st}$	Unit vectors of stator flux angle $\theta_{\psi st}$
D	Duty Ratio
D_1, D_2	Diodes of Scott-transformer IPQC and Minnesota IPQC
D_p	PWM noise
D_s	Sensing noise
D_y	load disturbance
d - q	Direct and quadrature axes rotating at synchronous speed
d^{st} - q^{st}	Stator direct and quadrature axes
d^r - q^r	Rotor direct and quadrature axes
ΔI_{LP}	Peak to peak AC mains/inductor current ripple (A)
ΔV_{cl}	Peak to peak capacitor voltage ripple (V)
e_c	Error between $V_{dc}/2$ and lower capacitor voltage V_{c2}
e_d	Error between the reference and actual direct axis stator currents
e_ω	Speed error between reference (ω_r^*) and sensed speed (ω_r)
e_{ps}	Error between the reference and actual input active powers (P_s^* and P_s)
e_{qs}	Error between the reference and actual input reactive powers (Q_s^* and Q_s)

e_q	Error between the reference and actual quadrature axis stator currents
e_t	Torque error between generated (T_e^*) and estimated torque (T_e)
η	Constant which decides the rate at which the ρ changes from 0 to 1
e_v	DC bus voltage error between reference (V_{dc}^*) & sensed DC bus voltage (V_{dc})
f_{sw}	Switching frequency (Hz)
$H_{\psi st}$	Output of flux hysteresis controller
H_{T_e}	Output of torque hysteresis controller
$HB_{\psi st}$	Flux hysteresis bands
HB_{T_e}	Torque hysteresis bands
i_{3h}	Third harmonic modulated inductor current (A)
I_{3hP}	Peak of third harmonic modulated inductor current (A)
i_{3inj}	Third-harmonic injected current (A)
I_{3inj}	rms value of third-harmonic injected current (A)
I_a	DC machine armature current (A)
$i_{\alpha s}^*, i_{\beta s}^*$	Reference stationary two phase $\alpha\beta$ components of AC mains current (A)
$i_{\alpha s}, i_{\beta s}$	Stationary two phase $\alpha\beta$ components of AC mains current (A)
$i_{\alpha st}^*, i_{\beta st}^*$	Reference stationary two phase $\alpha\beta$ components of stator current (A)
$i_{\alpha st}, i_{\beta st}$	Two-phase stator currents (A)
$i_{as}^*, i_{bs}^*, i_{cs}^*$	Reference AC mains three-phase currents (A)
i_{as}, i_{bs}, i_{cs}	AC mains three-phase currents (A)
i_{asb}	Phase 'a' bridge current (A)
$i_{ast}^*, i_{bst}^*, i_{cst}^*$	Reference three-phase stator currents (A)
$i_{ast}, i_{bst}, i_{cst}$	Three-phase stator currents (A)
I_c^*	Reference current to compensate the difference between two capacitor (A)
I_{dc}^*	Reference DC bus current (A)
I_{dcf}^*	Reference DC bus current with feed-forward term (A)
i_{ds}, i_{qs}	Direct and quadrature component of AC mains current (A)
i_{dst}^*, i_{qst}^*	Reference direct and quadrature component of stator current (A)
i_{dst}, i_{qst}	Direct and quadrature component of stator current (A)
I_f	DC machine field current (A)

i_{L1}, i_{L2}	Sensed Inductor currents (A)
I_{LP}	Peak AC mains/inductor current (A)
i_p	Primary current of voltage sensor (A)
i_s	AC mains current (A)
i_{sense}	Current to be sensed (A)
i_{sensor}	Sensor output current (A)
$I_{strated}$	Rated stator current (A)
J	Moment of inertia (Kg/m ²)
K	Optimal amplitude of injected third harmonic current for Minnesota rectifier
$(k), (k-1)$	$(k)^{th}$ and $(k-1)^{th}$ sampling instants
K_1, K_2	Constants
K_a	DC machine EMF constant
K_{pc}, K_{ic}	Proportional and integral gains of mid-point DC bus voltage PI controller
K_{pd}, K_{id}	Proportional and integral gains of the direct axis stator current controller
K_{pe}, K_{ie}	Proportional and integral gains of the PI controller for speed estimator
K_{pi}	Proportional gain of current controller
$K_{p\omega max}, K_{p\omega min}$	Maximum and minimum values of speed loop proportional gain $k_{p\omega}$
K_{pps}, K_{ips}	Proportional and integral gains of the active power PI controller
K_{pq}, K_{iq}	Proportional and integral gains of the quadrature axis stator current controller
K_{pqs}, K_{iqs}	Proportional and integral gains of the reactive power PI controller
K_r	Constant decides the rate at which the $k_{p\omega}$ changes from $K_{p\omega max}$ to $K_{p\omega min}$
k_{pt}, k_{it}	Torque-loop proportional and integral gains
K_{pt}, K_{it}	Proportional and integral gains of torque PI controller
K_{pv}, K_{iv}	Proportional and integral gains of DC bus voltage PI controller
$k_{p\omega}, k_{i\omega}$	Speed-loop proportional and integral gains
$K_{p\omega}, K_{i\omega}$	Proportional and integral gains of speed PI controller
L_1, L_2	DC bus inductors/inductance (H)
L_b	Boost inductor/inductance (H)
L_i	Interfacing inductor/inductance (H)
L_{lr}	Rotor leakage inductance (H)

L_{lst}	Stator leakage inductance
L_m	Magnetizing inductance (H)
L_r	Rotor self-inductance (H)
L_{st}	Stator self-inductance (H)
N	DC bus mid-point
ω	AC mains frequency (rad./sec)
ω_s	Synchronous speed (rad./sec)
ω_{sl}	Slip speed (rad./sec)
ω_r	Rotor speed (rad./sec)
$\hat{\omega}_r$	Estimated rotor speed (rad./sec)
P	Number of poles
P_a	Pole of open-loop transfer function
P_s	AC mains active power (W)
P_s^*	Reference AC mains active power (W)
φ	Optimal phase angle of injected third harmonic current ($^\circ$)
Ψ_a	DC machine flux produced due to armature current I_a (Wb)
$\psi_{ar}, \psi_{\beta r}$	Two-phase rotor flux vectors (Wb)
$\hat{\psi}_{ar}, \hat{\psi}_{\beta r}$	Adaptive two-phase rotor flux vectors (Wb)
$\psi_{as}, \psi_{\beta s}$	AC mains two-phase virtual flux (Wb)
$\psi_{ast}, \psi_{\beta st}$	Two-phase stator flux (Wb)
ψ_{dr}, ψ_{qr}	Direct and quadrature axes components of rotor flux (Wb)
Ψ_f	DC machine flux produced due to field current I_f (Wb)
Ψ_r	Rotor flux magnitude (Wb)
$\vec{\psi}_r$	Rotor flux vector
Ψ_r^*	Reference rotor flux magnitude (Wb)
Ψ_{rated}^*	Rated reference rotor flux magnitude (Wb)
Ψ_{st}	Stator flux magnitude (Wb)
$\vec{\psi}_{st}$	Stator flux vector
Ψ_{stated}^*	Rated reference stator flux magnitude (Wb)
M	Measuring point

m	Modulation index
m_{tria}	Triangular waveform amplitude
N_r^*	Reference rotor speed (rpm)
N_r	Rotor speed (rpm)
\widehat{N}_r	Estimated rotor speed (rpm)
N_{rrated}	Rated rotor speed (rpm)
Q_s	AC mains reactive power (W)
Q_s^*	Reference AC mains reactive power (W)
R_l, R_o	Coefficients of polynomial $R(s)$
R_l	Primary resistance of voltage sensor (Ω)
$R(s), S(s), T(s)$	Polynomials
R_f	Op-amp feedback resistance (Ω)
R_{L1}, R_{L2}	Resistance of inductor L_1 and L_2 (Ω)
R_m	Measurement resistance (Ω)
ρ	Decides the variation of $k_{i\omega}$ value from 0 to $K_{i\omega max}$
R_{out}	Low pass filter resistance (Ω)
R_r	Rotor resistance (Ω)
R_{st}	Stator resistance (Ω)
S_1, S_2	IGBT switches of Minnesota rectifier and Scott-transformer IPQC
S_{as}, S_{bs} and S_{cs}	Front end converter switching states
S_{ast}, S_{bst} and S_{cst}	Inverter switching states
ε	Local variable
ε_ψ	Flux error between adaptive and reference models
S_{yp}	PWM noise sensitivity function
S_{ys}	Sensing noise sensitivity function
S_{yy}	load noise sensitivity function
θ	phase angle of AC mains phase 'a'
θ_e	Rotor flux position (radians)
θ_r	Rotor speed position (radians)
$\theta_{\psi r}$	Rotor flux position (radians)

$\theta_{\psi s}$	Phase angle of the virtual flux vector (radians)
$\theta_{\psi st}$	Phase angle of the stator flux vector (radians)
θ_{sl}	Slip speed position (radians)
T_1-T_6	Six switches of two-level inverter feeding induction motor
t	Recover time of the DC bus voltage
$t_1, t_2, t_3, t_4,$	Triangular regions
t_{1o}, t_{2o}, t_{0o}	On times
T_{d1}, T_{d2} and T_{d0}	Dwell times
T_c, T_f	Parameter defines the control and filtering
T_e^*	Generated electromagnetic torque or developed torque (Nm)
$T_e^*(k), T_e^*(k-1)$	Generated electromagnetic torque at k^{th} and $(k-1)^{th}$ instants (Nm)
T_e	Electromagnetic torque or developed torque (Nm)
T_{FL}	Full-load torque (Nm)
T_L	Load torque (Nm)
T_r	Rotor time constant (s)
T_{Lrated}	Rated load torque (Nm)
T_{max}	Maximum load torque (Nm)
T_s	Sampling time
T_{sw}	Switching cycle ($=1/f_{sw}$)
u_{as}, u_{bs}, u_{cs}	Unit amplitude of AC mains phase voltages
v^*	Reference voltage vector
$ v^* $	Magnitude of reference voltage vector v^*
v_{ADCmax}	Maximum voltage that can be withstood by the ADC channels
\vec{V}_1 to \vec{V}_6	Inverter voltage vectors
V_1 to V_6	Inverter switching states
V_a	DC machine armature voltage (V)
v_{as}, v_{bs}, v_{cs}	AC mains phase voltages (V)
$v_{abs}, v_{bcs}, v_{cas}$	AC mains line voltage (V)
$v_{asconv}, v_{bsconv}, v_{csconv}$	Three phase front end converter voltages (V)
$v_{asconv}, v_{\beta sconv}$	Two-phase front end converter voltages (V)

$v_{as}^*, v_{\beta s}^*$	Reference two-phase AC mains voltages (V)
$v_{as}, v_{\beta s}$	Two-phase AC mains voltages (V)
$v_{asc}^*, v_{\beta sc}^*$	Reference two-phase AC mains voltages with capacitor balance compensator
$v_{ao}, v_{\beta o}$	Virtual two-phase vectors
$v_{abst}, v_{bcst}, v_{cast}$	Stator phase voltages (V)
$v_{ast}^*, v_{\beta st}^*$	Reference two-phase stator voltages (V)
$v_{ast}, v_{\beta st}$	Two-phase stator voltages (V)
v_{as}, v_{bs}, v_{cs}	Stator phase voltages (V)
V_{dc}^*	Reference DC bus voltage (V)
V_{dc}	Sensed DC bus voltage (V)
i_{dst}^*, i_{qst}^*	Reference direct and quadrature component of stator voltage (V)
V_{mph}	Peak of the per phase supply voltage (V)
v_{offset}	Offset voltage (V)
v_{out}	Output voltage of second op-amp (V)
v_{out1}	Output voltage of first op-amp (V)
v_s	Input AC mains voltage (V)
v_{sconv}	Front-end converter voltage (V)
v_{sensor}	Sensor output voltage (V)
v_{sph}	Input phase voltage (V)
v_{sT1}, v_{sT2}	Transformer secondary voltage (V)
x_1 and x_2	Two integers
y, r	Input and output of the system
ξ	Local variable