Review of Slip Power Recovery Scheme

Shiv Kumar[1], Ajay Kumar[2], Himanshu Gupta[3]

[1]Student, M. Tech, E-Max group of Institutions, Ambala, Haryana
[2]Associate Professor, Dept. of EE, Baddi University of Emerging Sciences & Technology, Baddi, HP
[3]Assistant Professor, Dept. of EE, E-Max group of Institutions, Ambala

Abstract— **Induction motors are the most commonly used motors in industrial motion control systems. Earlier, the nature of industrial applications of the induction motors were of constant speed mechanical drives due to difficult speed control systems but the recent advancement in power electronics components have pave the way for the development of power electronics based variable speed induction motor drives replacing dc drives. The slip power recovery scheme comprising Static Scherbius Drive provides speed control of slip ring induction motor below synchronous speed. The slip power recovery drives is used in very large-capacity pumps and fan drives, variable speed wind energy systems, shipboards VSCF (variable-speed/constant-frequency) systems, variable-speed hydro pumps/generators, utility system flywheel energy storage systems etc. In this paper various power quality problems created by use of power electronics components in this scheme and their remedies have been discussed. This survey paper will provide the insight of trends and technologies used in slip power recovery scheme.**

Keywords— **Slip power recovery scheme, Harmonics, Power factor, review**

I. INTRODUCTION

Induction motors are the most commonly used motors in industrial motion control systems. Earlier, the nature of industrial applications of the induction motors were of constant speed mechanical drives due to difficult speed control systems but the recent advancement in power electronics components have pave the way for the development of power electronics based variable speed induction motor drives replacing dc drives. The slip power recovery scheme comprising Static Scherbius Drive provides speed control of slip ring induction motor below synchronous speed. In this scheme, a portion of power available at the rotor is brought outside at very low frequency i.e. slip frequency & is converted into dc using three-phase bridge rectifier. The dc is filtered & fed to the line commutated inverter whose firing angle is set to a minimum value of 90º. This power is then transferred to source using recovery transformer. As the flow of power from rotor to rectifier is unidirectional due to diode-bridge, power can flow from rotor to bridge-side only. Thus, only sub-synchronous speed control is possible. Use of diode rectifier on the rotor side & line commutated inverter on the source side not only injects harmonics, low power factor & creates other power quality problems in the power source but also produces torque & speed pulsations on the shaft. Many techniques have been suggested in the literature to overcome such problems. This paper is a comprehensive study of some of those techniques & to look into latest trends for the remedies of such problems.

II. FORMER TECHNIQUES FOR IMPROVEMENT AND RECENT TRENDS

The basic concept of slip power recovery scheme was first presented by A. Lavi et al, in 1966 [1].

The analysis of the scheme using thyristors was reported by Shephard et al [2]. The main drawback of this scheme has been inferred as the poor power factor of the power system due to excessive reactive power drawn out of the source both by the motor as well as the line commutated inverter.

In order to overcome the drawbacks of poor power factor, several methods have been reported in literature.

W. Shephard et al, presented capacitive compensation approach [3]. In this paper the steady-state performance of a slip-energy-recovery scheme incorporating an induction motor and a static frequency changer is described. A considerable improvement in the low-speed efficiency is obtained at the expense of a poor power factor. Power-factor correction by the use of primary-side capacitance is found to increase slightly the 5th-harmonic component of the supply current and to double the torque/supply-current ratio. Compensation by the use of fixed secondary capacitance is found to give increased torque at low speeds, increased torque/supply-current ratio, higher efficiency at some speeds, better speed regulation, much improved step response to changes of control signal and good power-factor correction at low speeds.

S.K. Pillai et al, presented Static Scherbius Drive with chopper [4]. This scheme comprises a chopper inserted between the rectifier and the inverter bridges. The required speed control in the above scheme was obtained by time ratio control of the chopper unit for fixed value of firing angle of the inverter. However, it has been envisaged that in the absence of recovery transformer the current harmonic distortion in the supply system would increase.

Mittle et al, studied switching transients in static slip energy recovery drive [5]. This paper deals with the study of starting transients of a static slip-energy recovery drive. The non-linear equations of the system have been simulated on a digital computer and solved by the application of Runga-Kutta method. The effects of firing angle, load, system inertia and filter time constant on transient torques and speeds following a switching operation have been investigated.

Taniguchi et al, used power chopper in their scheme [6]. The paper deals with the applications of a chopper to the thyristor Scherbius which recovers slip power of a wound rotor induction machine. An analysis of the steady-state performance of this system is presented. The chopper improves in several characteristics of a conventional system. In particular, the low power factor, which is a disadvantage of the thyristor Scherbius, is significantly improved. A reasonable operation of the chopper can realise a shorter overlapping interval at the commutation of a thyristor inverter. The recovery current controlled by the chopper has the pulse-width modulated (PWM) waveform. Such a PWM wave-form can reduce the size of line filter for the waveform shaping. Theoretical and experimental results concerning the chopper controlled thyristor Scherbius system are presented.

Hilderbrandt applied Reference Frame theory to the analysis of a slip-recovery system [7]. Here, reference frame theory is used to establish the equations which can be used to predict adequately the dynamic and steady-state performance of a slip energy recovery system. The steady-state performance as predicted from this analysis is compared with that predicted from computer simulation. The errors of a previously published approach are discussed and the inaccuracy in predicting the steady-state torque-speed characteristics is illustrated. The stage is now set to develop linearized, small displacement equations which can be used for control system design

Zahawi et al, investigated the effect of rotor rectifier on motor performance in slip energy drives [8]. In this paper the influence of commutation overlap within the rotor rectifier upon motor power factor and peak attainable torque has been studied. This point is dealt with and it is also shown how the system performance can be predicted by largely analytical means, allowing fully for motor resistances, diode voltage drops, and the several possible rectifier overlap modes.

Doradla et al, presented a novel method to increase the supply power factor using multi-pulse-width modulation technique [9]. The ripples in the direct current were considerably reduced and the PWM converter harmonic current spectrum was shifted from lower order to higher order. A novel method of starting the drive was also explained.

Ioannides et al, investigated, a new control technique for the minimization of losses of a doubly-fed induction motor by using optimal control techniques [10]. The optimal control vector voltage leads to the improvement of overall drive performance and is a method of energy saving for industrial processes operating with variable loads in the low speed range.

Marques discussed active and reactive power controller for the slip power recovery drive [11]. Akpinar et al, proposed a modeling approach to predict the detailed operation of a slip recovery drive both in the steady state and in the transient state. The hybrid model retained the actual rotor states and the algorithm used a 4^{th} order Runga Kutta integration method [12].

Ionnides et al, discussed generalized optimization slip power recovery drives [13]. A generalized method for predicting the optimized performance of the doubly fed induction motor controlled by a voltage phasor at the rotor side, at any load conditions in slip power recovery drives, in the steady state is presented. The equations describing the model of the optimally controlled drive are deduced in terms either of the voltage phasor magnitude or of one of its components, direct or quadrature. These equations are simple and hence suitable for digitally controlled systems. The electromagnetic characteristics in the steady state are determined and discussed for the case in which the voltage phasor magnitude and the speed vary. The control covers the full operating ranges for speed, torque, and voltage phasor magnitude.

Baghzouz et al, presented a method to evaluate harmonic distortion in slip power recovery drives, while taking into account commutation overlap and dc current ripple [14]. This method predicted the voltage and current waveforms accurately and computed the individual harmonic components efficiently.

F. Liao et al, tried to recover the slip energy to the part of the stator winding to avoid use of recovery transformer [15]. A new speed control scheme for a wound-rotor induction motor utilizing feedback of the slip power to the stator winding by means of taps is described. It is shown that with this feedback system, the motor can be operated over a very wide range even to slips reaching 0.75. The new concept eliminates the need for a transformer. The selection of feedback point on the stator winding, the equivalent circuit, and the main parameters of this system are discussed. and these indicate that this system also has good performance in addition to its potential for lower cost.

Borges et al, presented adaptive fuzzy techniques for improving performance of slip recovery drive [16]. In this paper one solution consists of adding two GTOs to the converter bridge, in order to transform it into a fully controllable inverter, which allows for independent control over voltage and displacement factor is given. When appropriately controlled, this converter is capable of producing reactive power in just the right amount to fully compensate the reactive power consumed by the power induction machine. Unity power displacement factor is then attainable over most of the operating range.

Borges et al, presented Adaptive fuzzy technique for control of slip recovery drive [17]. The fuzzy adaptive control is based on a three-level control structure. Each level, described by a set of linguistic fuzzy rules, is responsible for a specific task. Together, the three levels constitute a flexible adaptive control structure that manipulates the system variables, improving the drive performance as the system evolves.

Akpinar, et al, presented a technique for starting of a slip energy recovery induction motor drive from standstill position. This approach used a hybrid model which retained the actual rotor phase variables but transformed those of the stator, to examine the starting transients of a slip recovery drive system [18].

Akpinar et al, discussed starting transients in slip energy recovery induction motor drives [19].In this paper the starting resistor allows the peak motor torque to be developed at starting or for the starting currents to be limited to a prespecified value. The transients associated with the initial connection of the inverter can be limited by the appropriate choice of the inverter firing angle. A transient occurs when the resistor is finally disconnected because of the removal of a parallel current path. Both the overlap in the rotor rectifier and the harmonics reflected by the inverter have been included in the modeling and the computer program. This removes the need for correction factors to be used in the design of a practical drive.

Akpinar et al, presented an analytical technique on the rectifier output voltage in the slip energy recovery induction motor drives [20]. Since, this technique used hybrid dq/abc model, it was found to be a suitable method for harmonic analysis of current waveforms.

L. Refouli et al, presented detailed analysis of a step-down chopper controlled slip energy recovery induction motor [21]. This approach comprised a hybrid model of the induction motor including a chopper controlled drive.

Tang et al, discussed the stability of slip power recovery system [22]. The authors present a stability analysis of the doubly-excited machine with open-loop voltage control and open-loop current control in the rotor circuit. Possibilities of open-loop control are analyzed. Second, they present a unified model of a high-performance slip power recovery system composed of a field-orientation controlled doubly-excited machine, power converters and a DC bus in the rotor circuit. The stability of this composite system represented by a model is studied. Of special interest is when the system functions as a variable-speed motor drive system or as a variable-speed constant-frequency generating system

Marques presented a configuration for slip power recovery scheme using decoupled control of two different variables at the same time [23].. The use of PWM voltage converter on the line side allowed the possibility of controlling the reactive power in a wide range and also with low current harmonic contents

Marques evaluated performance of slip power recovery system by field and current space vectors [24]. In this paper the DC current intermediate circuit is replaced by a DC voltage link. A boost chopper is used to connect the diode rectifier to the DC link voltage inverter. The merits of the configuration presented are the cost, the control simplicity, the possibility of reactive power control in a wide range and the quasi optimum exploration of the Electrical Machine. It is also possible to compensate harmonic currents injected on the mains by the electrical machine.

Samahy et al, presented modeling and speed control scheme for the static Kramer drive [25].The growing need for efficient drive systems has given the static Kramer drive system a position of importance among variable speed drives. A mathematical model of this system is presented. This model is called a hybrid model. The hybrid model has been extended to include closed-loop speed control using PI controller. This model is used also to examine the system performance under free acceleration and closed-loop speed control conditions. Finally, laboratory tests are presented to confirm the validity of the mathematical model. These tests also show the ability of the PI controller to achieve a reliable closed-loop speed control of the static Kramer drive system.

Amin presented neural network based tracking control system for slip energy recovery drive [26]. This paper studies the implementation of tracking control in a slip-energy recovery induction motor drive. Tracking control is investigated using an artificial neural network-based controller. In this system, the rotor speed can follow an arbitrarily prescribed trajectory. This trajectory may be different from the one used in training the network. The proposed system is capable of achieving accurate tracking control of the speed even when the nonlinear parameters of the motor and the load are unknown. These unknown nonlinear parameters are captured by the trained artificial neural network. The architecture and the training algorithm of the neural network are presented and discussed. The effectiveness of the proposed drive system is investigated using a laboratory model. Laboratory results confirm a very promising tracking control system. This system takes full advantage of the efficient slip-energy recovery induction motor drive.

Krause et al, undertook reference frame analysis of slip energy recovery system [27]. In this paper reference frame theory is used to establish the equations which can be used to predict adequately the dynamic and steady-state performance of a slip energy recovery system. The steady-state performance as predicted from this analysis is compared with that predicted from computer simulation. The errors of a previously published approach are discussed and the inaccuracy in predicting the steady-state torque-speed characteristics is illustrated. The stage is now set to develop linearized, small displacement equations which can be used for control system design.

Papathanassiou discussed commutation angle analysis of the slip energy recovery drive [28]. In this paper the variation of the rectifier commutation angle and the factors that determine its magnitude are investigated using a detailed hybrid abc-dq model of the SERD, the accuracy of which is validated by experimental results. The dependence of the commutation angle on the DC current and the operating slip is shown for a case study drive and practical relations are deduced which permit the evaluation and a-posteriori correction of the steady state error of simplified dq models, where the commutations and converter harmonics are ignored.

Errath et al, discussed conversion of a fixed speed drive to an adjustable speed drive using slip energy recovery system [29]. This paper describes the reason for the change, the function and also the economical advantages of an adjustable-speed drive in this application with the SER drive configuration. This paper also states and explains why this type of drive system is attractive. SER drive systems are accompanied by an availability almost unreachable using other configurations.

Knowles et al, presented analysis of Static Scherbius Drive with two IGBT sinusoidal current converters in the rotor circuit using hybrid dq model [30]. The analysis was based on a transformation of stator variables only to a frame of reference stationary with respect to the rotor. The analysis was based on a solution of system of equations for every possible converter switch combination.

Marques presented a numerical simulation method using dq induction-machine model for the slip power recovery system. The model used flux linkages as state variables and employed MATLAB/Simulink to integrate the equations, leading to an efficient computer program [31].

Amin presented dq model of Static Kramer Drive System [32]. In this paper, a mathematically efficient model of the static Kramer drive system is developed. This model is based on the reference frame theory.

Yoshika Kawabata et al, proposed a vector controlled inverter fed wound rotor induction motor for high power applications [33]. This configuration comprised a wound-rotor induction motor and two current-controlled Pulse Width Modulation (PWM) inverters. The outputs of two inverters were combined electromechanically in the machine and the motor speed corresponded to either the sum or the difference of the frequencies depending upon the situation.

G.D. Marques et al, presented a different circuit configuration in which a boost up chopper connected the rotor rectifier to a dc link of voltage controlled line commutated inverter connected in parallel with a capacitor [34]. This scheme gave rise to mains current harmonics of variable frequency which presented the problems of sub harmonics and inter harmonics. To overcome these problems, additional inductances were suggested to be connected on the ac side of rotor circuit to increase overlap angle. Another alternative could be to connect harmonic filter.

Tunyasrirut et al, presented adaptive Fuzzy-neuro controller for speed control of wound rotor induction motor with slip energy recovery [35]. In this paper, the authors proposed an adaptive fuzzy-neuro controller to control the speed of a wound rotor induction motor with slip energy recovery. An adaptive fuzzy-neuro controller has been designed by integrating two neural network models with a basic fuzzy logic controller. Using the back-propagation algorithm, the first neural network is trained as a plant emulator and the second neural network is used as a compensator for the basic fuzzy controller to improve its performance online. The function of the neural network plant emulator is to provide the correct error signal at the output of the neural fuzzy compensator without the need for any mathematical modeling of the plant. The scheme is applied to the control of the speed of the wound rotor induction motor process. Simulation and experimental results show that the adaptive fuzzy-neuro controller gives constant speed and good transient response without overshoot.

Faiz et al, investigated the presence of sub harmonics of line frequency and simulated harmonics content of waveforms in various points of the drive at different speeds, based on hybrid model (dq/abc). The sinusoidal PWM technique was used in order to improve the power factor of the drive and weaker low-order harmonics to the supply [36].

Singh et al, presented the design of microprocessor based slip power recovery scheme using Intel 8085 microprocessor. The motor converter system was modeled in s-domain and was simple, flexible and straight-forward. However, the system was highly sensitive on the sampling time and became unstable if the value of sampling time was not carefully selected [37].

Azizi et al, investigated slip energy recovery method for speed control of slip ring induction motor by developing ac and dc side equivalent circuits in MATLAB/Simulink environment. The approach could be followed in close loop system to improve dynamic response [38]. Panda et al, presented a methodology for the rotor side control of a doubly-fed induction machine [39]. In this paper, a novel machine side converter (MSC) and associated control strategy for the DFIM is proposed which will replace one of the IGBT converters. The proposed converter consists of a thyristor bridge and a boost/buck-boost DC-to-DC interface. This converter is capable of bidirectional power flow and thus the machine can be controlled in both the super-synchronous and subsynchronous speed ranges. The proposed converter has the ability for successful commutation of the thyristors for all speeds of operation. Through the suitable control of the IGBT based front end converter (FEC), the composite system interfaces with the grid at nearly unity power factor. The FEC supports the power flow between the rotor circuit and the utility and in addition, it is made to work as an active filter to compensate for any additional harmonics injected by the stator of the machine to the utility. With the proposed power converter combination, the potential cost of the system is reduced without any major sacrifice in the system performance.

Mishra et al, presented a different approach in which three-phase ac supply was taken as input to the stator of the wound rotor induction motor and by further using a three-phase rectifier, ac supply was converted into dc [40]. The ripples from the rectified dc voltage were reduced by connecting a large capacitor filter across the output of the rectifier. The rectified dc voltage became input to a PWM controlled self-commutated three-phase bridge inverter. To recover the slip power from the rotor terminals, the rotor three-phase voltage was rectified using a three-phase diode bridge rectifier. This rectified voltage was stepped-up, using a step-up chopper, to the level of the dc voltage of the rectifier inverter set, feeding the stator winding of the slip ring induction motor.

Recently, adaptive sliding-mode controller for slip power recovery induction machine drive was developed by Soltani [41]. In this paper a robust nonlinear controller is presented for doubly-fed induction machine (DFIM) drives. The nonlinear controller is designed based on combination of Sliding-Mode (SM) and Adaptive-Backstepping control techniques. Using the fifth order model of DFIM in a stator d, q axis reference frames with stator currents and rotor fluxes as state variables, a SM controller is designed in order to follow a linear reference model. Then, the SM control and adaptive backstepping control approach are combined to design a robust composite nonlinear controller for DFIM that makes the drive system robust and stable against the parameters uncertainties and external load torque disturbance. In this drive system two back-to-back voltage source two level SVM-PWM inverters are employed in the rotor circuit, to make the drive system capable of operating in motoring and generating modes below and above synchronous speed. Computer simulation results obtained, confirm the effectiveness and validity of the proposed control approach.

Bonnet et al, developed a bi-converter structure to supply a doubly fed induction machine with two voltage source inverters (VSIs) feeding the stator and rotor windings [42]. This paper is a novel biconverter structure to supply a doubly fed induction machine (DFIM). Two voltage source inverters (VSIs) feed the stator and rotor windings. The outputs of the two VSIs are combined electromechanically in the machine.

III. CONCLUSION AND FUTURE WORK

Thus summarizing, the performance of slip power recovery scheme with various topologies has been thoroughly studied and the outcomes have been discussed here. It is found that the inverter & converter inject harmonics to the power system resulting in low power factor, torque and speed pulsations, limited speed range operation & higher switching losses etc. Various techniques have been suggested by number of authors to overcome one and/or many problems. Each technique is unique and having its advantages & disadvantages with respect to power quality, complexity, cost, size & application. It has been observed that multilevel inverters generate output voltages with very low distortion (fewer harmonic) with lower switching frequency compared to the conventional inverters.

Hence, instead of conventional inverter, use of higher order multi-level inverter is suggested for the performance improvement of the scheme [43] [44] [45].

REFERENCES

1. A. Lavi, R.J. Polge, "Induction Motor Speed Control with Static Inverters in the Rotor", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-85, No. 1, Jan 1966, pp. 76-84.
2. W Shepherd, J Stanway, "Slip Power Recovery in an Induction Motor by the use of a Thyristor Inverter", *IEEE Transaction on Industry and General Applications*, Vol. IGA-5, No. 1, Jan/Feb 1969, pp. 74-82.
3. W Shepherd and A.Q. Khalil, "Capacitive, Compensation of Thyristor Controlled Slip-Energy Recovery System", *Proceedings IEEE, Vol. 117, No. 5, May 1970*, pp. 948-956.
4. S.K. Pillai, K.M. Desai, "A Static Sherbius Drive with Chopper", *IEEE Transaction on Industrial Electronics and Control Industrial Instrumentation*, Vol. IEC-24, No. 1, Feb 1977, pp. 24-29.
5. V.N. Mittle, K. Venkatesan, S.C. Gupta, "Switching Transient in Static Slip-Energy Recovery Drive", *IEEE Transaction Power Apparatus and System*, Vol. 98, July/August 1979, pp. 1315-1320.
6. K. Taniguchi, H. Mori, "Application of a Power Chopper to the Thyristor Scherbius", *IEEE Proceedings*, Vol. 133, Pt. B, No. 4, July 1986, pp. 225-229.
7. M.S. Hilderbrandt, "Reference Frame Theory applied to the Analysis of a Slip-Recovery system", *Purudue University* 1986.
8. B.A.T. Al Zahawi, B.L. Jones, W. Drury, "Effect of Rotor rectifier on motor performance in Slip Energy drives", *Canadian Electrical Engineering Journal*, Vol. 13, No. 1, 1987.
9. S.R. Doradla, S. Chakravorty, K.E. Hole, "A new Slip Power Recovery Scheme with Improved Supply Power Factor", *IEEE Transaction on Power Electronics*, Vol. 3, No. 2, April 1988, pp. 200-207.
10. Maria G. Ioannides, John A. Tegopoulos, "optimal efficiency Slip-Power Recovery Drive", *IEEE Transactions on Energy conversion*, Vol. 3, No. 2, June 1988.
11. G.D. Marques, "Synthesis of active and reactive Power Controllers for the Slip Power Recovery drive", in *Proceedings EPE* 1989, Vol. 2, Aachen, Germany, Oct. 1989, pp. 829-833.
12. E. Akpinar, P. Pillay, "Modeling and Performance of Slip Energy Recovery Induction Motor drive", *IEEE Transaction on Energy Conversion*, Vol. 5, No. 1, March 1990.
13. Maria G. Ioannides, John A. Tegopoulos, "Generalized Optimization Slip Power Recovery drives", *IEEE Transaction on Energy Conversion*, Vol. 5, No. 1, March 1990.
14. Y. Baghzouz, M. Azam, "Harmonic Analysis of Slip Power Recovery Drives", 90/CH 2935-5/90/0000 © 1990 *IEEE*.
15. F. Liao, J.I. Sheng, A.L. Thomas, "A New Energy Recovery Scheme for Doubly fed, Adjustable-Speed Induction Motor drives", *IEEE transaction on Industry Applications*, Vol. IA-27, No. 4, July/Aug. 1991, pp. 728-733.
16. L.E. Borges, K. Nakashima, G. Lainbert Torres, V. Ferreira da Silva, Guy Olivier, Georges-E April, "Improving Performance of Slip Recovery Drive: An Approach using Fuzzy Techniques", 0-7803-0453-5/91, *IEEE* May 1991.
17. L.E. Borges da Silva, B.L. Torres, V.F. da Silva, "Adaptive Fuzzy Techniques for Slip Recovery Drive Control"' 0-7803-0236-2/92, *IEEE* Feb. 1992.
18. E. Akpinar, P. Pillay, A. Ersak, "Starting Transients in Slip Energy Recovery Induction Motor", *IEEE Transactions on Energy Conversion*, Vol. 7, No. 1, March 1992.
19. E. Akpinar, P. Pillay, "Starting Transients in Slip Energy Recovery Induction Motor Drives-Part 2: Flowchart and Performance", *IEEE Transactions on Energy Conversion*, Vol. 7, No. 1, March 1992.
20. E. Akpinar, MIEEE, P. Pillay, MIEEE, A. Ersak, MIEEE, "Calculation of the Overall Angle in the Slip Energy Recovery Drives using a dq/abc Model", *IEEE Transactions on Energy Conversion*, Vol. 8, No. 2, June 1993.
21. L. Refoufi, P. Pillay and M.R. Harris, "A Step-Down Chopper-Controlled Slip Energy Recovery Induction Motor Drive", *IEEE Transactions on Energy Conversion*, Vol. 8, No. 3, Sept. 1993, pp. 396-403.
22. Y. Tang, L. Xu, "Slip Power Recovery System Stability", *IEEE Industry Application Magazine*, May/June 1995.
23. G.D. Marques, "Performance Evaluation of the Slip Power Recovery System with a D.C. Voltage Intermediate Circuit and a LC Filter on the rotor", 0-7803-3334-9/96 © 1996 *IEEE*.
24. G.D. Marques, "Performance Evaluation of the Slip Power recovery system by field and current space vectors", in *Proc. PEMC* '96, Budapest, Hungary, 1996.
25. A.A. El-Samahy, Avir M.A. Amin, E.T. El-Tanahy, A.A. Sayed, "Modeling and Speed Control Scheme for the Static Kramer Drive", *Proceedings of the IEEE International Conference on Industrial Technology*, 1996.
26. Avir M.A. Amin, "Neural Network-Based Tracking Control System for Slip Energy Recovery Drive", *IEEE Catalog* Number: 97 TH 8280, 1997.
27. P.C. Krause, O. Wasynczuk, M.S. Hildebrandt, "Reference Frame Analysis of a Slip Energy Recovery System", *IEEE transaction on Energy Conversion*, Vol. 13, No. 1, March 1998, pp. 21-26.
28. S.A. Papathanassiou and M.P. Papadopoules, "Commutation Angle Analysis of the Slip Energy Recovery Drive", *IEEE transaction on Energy Conversion*, Vol. 13, No. 1, March 1998, pp. 21-26.

29. R.A. Errath, J.G. Santillana, "Conversion of a Fixed Speed Drive to an Adjustable Speed Drive using Slip Energy Recovery System", *Proceedings of the 1998 IEEE/PCA Cement Industry Technical*, May 1998, pp. 107-127.
30. C. Knowles-Spittle, B.A.T. Al Zahawi, N.D. Mac Isaac, "Simulation and Analysis of 1.4 MW Static Scherbius Drive with Sinusoidal Current Converters in the Rotor Circuit", Power Electronics and Variable Speed Drives, 21-23 Sept. 1998, Conference Publication No. 456, *IEEE* 1998.
31. G.D. Marques, "Numerical Simulation method for the slip power recovery system", *IEE Proc.-Electro. Power Application*, Vol. 146, No. 1, January 1999.
32. Amir M.A. Amin, "D-Q model of the Static Kramer Drive System", 0-7803-5662-4/99, *IEEE* April 1999.
33. Y. Kawabata, E. Ejiogu, T. Kawabata, "Vector Controlled Double Inverter Fed Wound Rotor Induction Motor Suitable for High Power Drive", *IEEE Transaction on Industry Applications*, Vol. 35, No. 5, Sept./Oct. 1999, pp. 1058-1066.
34. G.D. Marques, P. Verdelho, "A Simple Slip-Power Recovery System with a D.C. Voltage Intermediate Circuit and Reduced Harmonics on the Mains", *IEEE Transaction on Industry Electronics*, Vol. 47, No. 1, Feb. 2000, pp. 123-132.
35. S. Tunyasrirut, J. Ngamwiwit, T. Furuya, Y. Yamamoto, "Adaptive Fuzzy-Neuro Controller for Speed Control of Wound Rotor Induction Motor with slip Energy Recovery", 0-7803-6355-8/00, *IEEE* Aug. 2000.
36. Javed Faiz, H. Barati, Eyup Akpinar, "Harmonic Analysis and Performance Improvement of Slip Energy Recovery Induction Motor Drives", *IEEE Transactions on Power Electronics*, Vol. 16, No. 3, May 2001.
37. B.K. Singh, K.B. Naik, "Design of Microprocessor Based Closed-loop Slip Power Recovery Control of Slip Ring Induction Motor Drive", 0-7803-7233-6/10, *IEEE* 2001.
38. H. Azizi, A. Vahedi, M.A.S. Masoum, "Study of Slip Energy Recovery of Induction Motor Drive using MATLAB/SIMULINK".
39. D. Panda, E.L. Banedict, G. Venkataramanan and Thomas A. Lipo, "A_Novel Control Strategy for the Rotor Side Control of a Doubly-Fed Induction Machine", 0-7803-7116-X/01, *IEEE* Oct. 2001.
40. A.K. Mishra, A.K. Wahi, "Performance Analysis and Simulation of Inverter fed Slip –Power Recovery Drive", Vol. 85, Sept. 2004.
41. J. Soltani, A. Farrokh Payam, "A Robust Adaptive Sliding-Mode Controller for Slip Power Recovery Induction Machine Drive", 1-4244-0449-5/06, *IEEE* May 2006.
42. Bonnet, F. Vidal, P.E. Pietrzak-David, M., "Dual Direct Torque Control of Doubly Fed Induction Machine", *IEEE Transactions on Industrial Electronics*, Vol. 54, pp. 2482-2490, Oct. 2007.
43. Masaoud, A.; Hew Wooi Ping; Mekhilef, S.; Taallah, A.S., "New Three-Phase Multilevel Inverter With Reduced Number of Power Electronic Components," *Power Electronics, IEEE Transactions on power electronics*, vol.29, no.11, pp.6018,6029, Nov. 2014
44. Edpuganti, A.; Rathore, A.K., "Optimal Low Switching Frequency Pulsewidth Modulation of Nine-Level Cascade Inverter," *Power Electronics, IEEE Transactions on power electronics*, vol.30, no.1, pp.482,495, Jan. 2015 doi: 10.1109/TPEL.2014.2298239
45. Zhao, H.; Jin, T.; Wang, S.; Sun, L., "A Real-Time Selective Harmonic Elimination Based on A Transient-free, Inner Closed-Loop Control for Cascaded Multilevel Inverters," , *IEEE Transactions on Power Electronics*, vol.PP, no.99, pp.1,1

Shiv Kumar is a student of M. Tech Electrical Engineering, E-Max group of Institutions, Ambala. He graduated from Kurukshetra University, Kurukshetra. His research interest includes power electronics, electrical machines and electrical drives systems.

Ajay Kumar is an Associate Professor in the Department of Electrical Engineering, Baddi University, Baddi, India. He graduated from Kurukshetra University, Kurukshetra, did his masters in Power Electronics & Drives from M M University, Mullana. His research interest includes power electronics, electrical machines, drives and wind energy systems. He is a life member of ISTE.