

# REVIEW OF SPEED-SENSORLESS VECTOR CONTROL OF PARALLEL CONNECTED INDUCTION MOTOR DRIVE FED BY A SINGLE INVERTER

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**Abstract-** *In this paper, speed-sensorless vector control of parallel connected induction motor drive fed by a single inverter is reviewed. In electric locomotives a few electric motors propel the train. The speed sensor used in traction drive had ultra low resolution rotary encoder and the detection time was high. It is difficult to realize a fine anti-slip and re-adhesion control by using speed sensor. In order to overcome this problem, speed-sensorless vector control is implemented in the drive system of electric motor coach where the speed is estimated by an estimator (observer). Multi motor drive system is employed in traction drives where two or three induction motors are controlled by a single inverter on account of cost effectiveness, compactness and lightness. Under unbalanced load conditions, there is a difference of the rotor angular velocities among the motors and the system becomes unstable. To make the system stable under unbalanced load conditions, average and differential currents flowing into the stator windings and rotor fluxes of induction motor were considered. In addition, in the speed control loop different speed controllers were used in various literatures. The main focus of this paper is on different types of speed controllers and control techniques which are applied to make the system stable under unbalanced load conditions in parallel connected induction motor drives fed by a single inverter. Multiphase multi motors used in traction applications are also discussed.*

**Key Words:** *electrical drives, sensorless control, vector control.*

## I. Introduction

Induction motors have higher power densities and are mechanically more robust, which make them the ideal motor in many industrial applications. Induction motor control can be classified into two types: scalar control and field oriented or vector control.

With the invention of field-oriented control (or vector control) in the late 1960's [1], the torque of the machine is controlled indirectly. In controlling

induction motor drives, speed transducers such as tacho-generators, resolvers or digital encoders are used to obtain speed information. They are usually expensive and speed sensor is not suitable for defective and aggressive environmental conditions. Sensorless vector control is suitable from the point of reliability of the equipment, cost effectiveness and less maintenance. In sensorless vector control, the speed of the induction motor is estimated from the measured terminal voltages and currents.

Sensorless vector control has been generally used to drive the induction motor accurately with one inverter driving one induction motor. In applications such as electric traction and steel processing, one inverter may drive multiple induction motors connected in parallel [2] on account of cost effectiveness, compactness and lightness, etc.

In most of the multiple induction motor drive systems 'single motor' vector control scheme was applied, which treats the parallel connected motors as one large induction motor. In some drive systems, speed sensor is attached to only one motor [3] properly chosen from among many motors. However, in these methods unbalances of torque and current make the system unstable. The above mentioned problem is overcome by the average and differential currents flowing into stator windings and rotor fluxes of two induction motors [4]-[5]. The main focus of this paper is on different types of speed controllers and control techniques which are applied to make the system stable under unbalanced load conditions in parallel connected induction motor drives fed by a single inverter.

The paper is organized as follows: different power semi conductor devices and control techniques used for traction drives are reviewed in section II. Sensorless vector control of induction motor drives with different estimators used to estimate the speed

and rotor fluxes of induction motor are discussed in section III. Parallel connected induction motor drive fed by a single inverter with different speed controllers used to control the speed of parallel connected induction motor drive system are discussed in section IV. Finally, this paper is concluded in section V.

## II. Traction drives

Classically, traction drives were implemented with electromechanical contactors and lossy rheostats to control the speed of DC series motor. Later, these rheostats were replaced by thyristorized controls. SCRs based chopper circuits with regeneration capability were used to control the speed of DC series motor used in traction drives [6]-[7].

By the early 1980s, power electronics had progressed to the stage where 3-phase induction motor became a serious and more efficient alternative to the DC series motor in traction applications because:

1. They are simpler to construct and they require no mechanical contacts to work (such as brushes).
2. They are lighter than DC motors for equivalent power.
3. Modern electronics allow induction motors to be controlled effectively to improve both adhesion and traction.
4. Induction motors can be microprocessor controlled to a fine degree and can regenerate current down to almost zero speed whereas DC regeneration fades quickly at low speeds.
5. They are more robust and easier to maintain than DC motors.

Voltage Source Inverters (VSI) fed three phase squirrel cage induction motors were used in traction applications [8]. An inverter configuration with an auxiliary shutoff circuit designed for traction and similar applications requiring high values of starting torque was presented by J.T. Salihi [9].

The power semiconductor devices used in traction drives are series connected GTOs [10]-[11], IGBTs [12] and IGCTs [13]. The switching frequency of GTO traction inverters is 500 Hz or less and requires complicated gate drive circuits. But the switching frequency of high voltage IGBT varies from 500 to 1500 Hz or more in order to minimize harmonic currents. The 3.3 kV devices were the first IGBT designed for traction converters [14].

Selection and design of induction motor for traction applications fed by an inverter was discussed by John L.O. and Steven C.P. [15]. The main factors

considered for design of induction motor are number of poles (which gives the maximum torque per unit volume), rotor bar shape (to minimize skin effect and slip losses) and power factor. The inverter was operated in Pulse Width Modulation (PWM) mode in the constant torque region and in a Six-Step Square Wave (SSSW) mode in the constant power region. The performances of the induction motor were presented for both PWM mode and SSSW mode.

The electric traction drive architecture selected by traction equipment manufacturers for heavy-rail catenary systems with GTO power switches is shown in Fig. 1[16]. However, there are many significant variations in the details of the rectifier/inverter configuration selected for specific applications. These variations include the number of paralleled induction machines excited by each three-phase inverter, as well as the number of single-phase DC/AC rectifier units paralleled to supply the DC link.

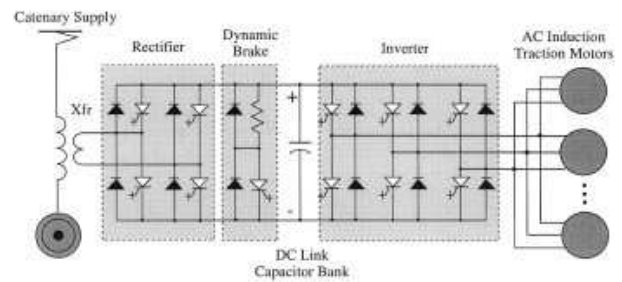


Fig. 1 Typical AC traction system

## III. Speed sensorless vector control

In controlling DC and AC motor drives, speed transducers such as tachogenerators, resolvers or digital encoders are used to obtain speed information. They are usually expensive. In defective and aggressive environments, the speed sensor might be the weakest part of the system. Further, it degrades the system's reliability. This has led to a speed-sensorless vector control. The term "sensorless" does not represent the lack of sensors entirely; it denotes that the speed and/or position sensor is missing. This feature decreases the cost of the drive system, reduces the size and no need of additional wiring for sensors or devices mounted on the shaft due to hostile environments such as high temperature, corrosive contacts, etc.

The speed sensor used in traction drive had ultra low resolution rotary encoder, such as 60 pulse/rev and the detection time was around 25ms [17]. It is difficult for a drive system of electric motor coach to realize a fine anti-slip and re-adhesion control by

using speed sensor. The implementation of sensorless vector control to electric motor coach with anti-slip and re-adhesion control was discussed in [18].

In speed-sensorless vector control, speed is estimated by an estimator. In general, an estimator is defined as a dynamic system whose state variables are estimates of the system of interest. A lot of speed observer systems were presented in the literature to estimate the rotor speed. Most popular methods are based on Luenberger theory [19] - [21], Extended Kalman filter [22] - [27], MRAS [28]-[32] and natural observer [33]. A Luenberger algorithm is more useful for industrial applications because of its simple structure. Adaptive scheme is used to estimate the rotor speed combined with state model. In the general observer approaches, the proper observer pole or gain selection is very difficult and a tedious task. The gain matrix constant  $k$  is chosen as 1 in [19] - [20] and  $k=0.5$  in literatures [4]-[5], [33]-[34] to make the calculations simple. The structure of the adaptive observer is shown in Fig. 2. It is used for estimating the state variables and unknown parameters together.

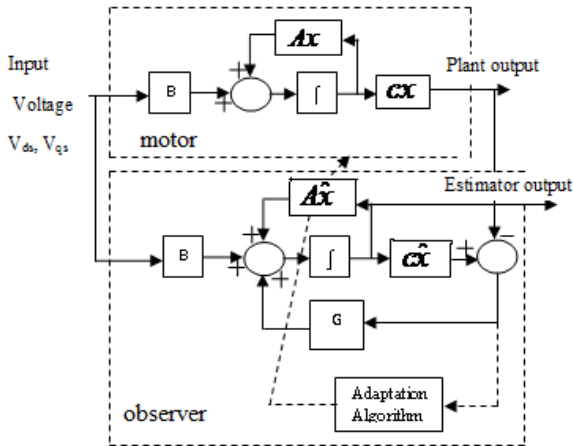


Fig.2 Block diagram of a speed adaptive observer

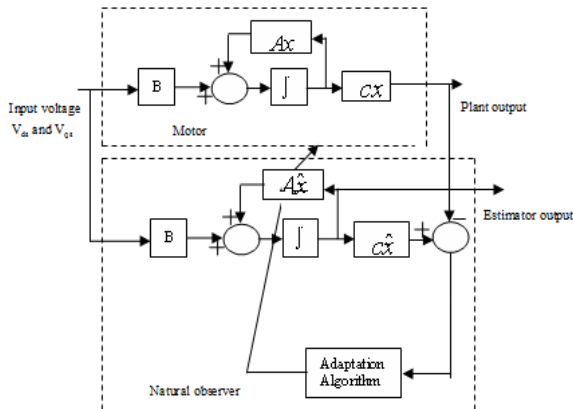


Fig. 3 Block diagram of a natural observer

The block diagram representation of a natural observer is shown in Fig. 3. It has the natural characteristics of the actual motor under the same conditions of load torque and input voltage. Its convergence is as fast as that of the motor in reaching its steady state, which is fast enough for most applications.

#### IV. Parallel connected induction motor drive

In locomotive or in electric multiple units, a few electric motors propel the train. In each bogie, one, two or three motors may exist. Each motorized car has two bogies. In each bogie, each axle is propelled by one electric motor [35]-[36]. Each bogie carries one or two inverters and each inverter drives two induction motors which are connected in parallel. In most of the high speed train, 1.2-MW induction motors are used. The shaft output power of induction motor used in Indian traction drive system is 1.15MW [37]

The motor torque is transmitted from the motor shaft to the wheels using two gears and few couplings. The motor is fixed to the car body. In Indian traction drives WAP -5 locomotives, two induction motors connected in parallel are driven by single inverter. Traction motors are suspended in the bogie frame and connected to the gear box (Two inverter-four induction motors). Motors transmit their energy to the driving axels through the gear box. The force from the driving axels is transmitted to the contact point between the wheel tread and the rail.

The ratings of induction motors connected in parallel remain same. The system is stable when the rotor speed and the current taken by both induction motors are same i.e. circulating current is zero. Whenever there is a deviation in the rotor angular velocity of induction motors, the current drawn by both induction motors differ and the circulating current increases. The causes for the differences of the rotor angular velocities among the motors are:

1. Mismatch between machine characteristics
2. Under full load- different slip characteristics
3. Mismatch between wheel diameters

Under unbalanced load conditions, if average currents flow through the stator windings and rotor fluxes were considered, the speed of one induction motor increases and the speed of other induction motor decreases continuously. This makes the system unstable.

To make the system stable, average and differential current flowing through the stator windings and rotor fluxes are considered. In the

speed control loop, different speed controllers and control techniques were used to determine the torque reference and current references.

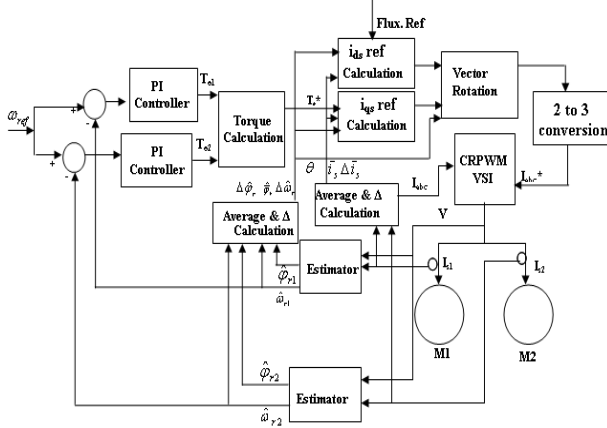


Fig. 4 Configuration of parallel connected dual induction motor drive

Fig. 4 shows the configuration of the parallel connected induction motor drive system. The main components are speed and rotor flux estimator, calculation block of two reference current values ( $i_{ds}$  and  $i_{qs}$ ) and Current Regulated Pulse Width Modulated (CRPWM) voltage source inverter. The estimators are either adaptive load torque estimation with natural observer or Luenberger observer. Speed is estimated from the measured terminal voltages and currents in both estimators. The torque reference of each induction motor is calculated from the difference between reference speed and estimated speed by using PI controllers. The speed controllers used in various references are P, PI or combination of both P & PI etc.

Fig. 5 shows the current flowing in the parallel connected induction motor [5]. When the loads on motors are unbalanced,  $i_{s1}$  does not equal to  $i_{s2}$ .  $\bar{i}_s$ , the average of  $i_{s1}$  and  $i_{s2}$  flowing in each stator winding and  $\Delta i_s$ , the current flowing directly from motor 1 into motor 2.

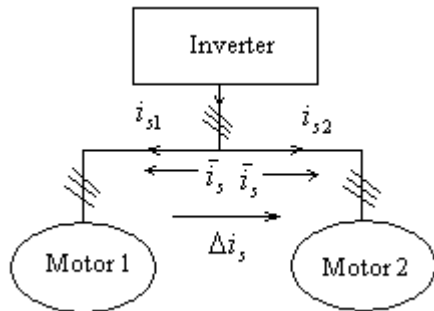


Fig. 5 Current flow for parallel connected induction motor

In [4]-[5], [38]-[46] adaptive observers were used to estimate the rotor flux and speed of the induction motors connected in parallel. In [34], natural observer was used to estimate the speed of parallel connected induction motor drive. Different types of speed controllers were used to make the system stable in parallel connected induction motor drive fed by a single inverter.

#### Case (i) Four induction motors in parallel

The behaviour of four induction motors fed by a single inverter was simulated focusing on one wheel slip phenomenon [39]. Different angular velocities caused by wheel diameter error were avoided by regulating the fluxes of all motors remain the same. Rotor resistance variation was compensated using d and q-axes induced voltages. The angular velocity of the slowest motor was selected as the reference velocity in acceleration, and that of the fastest motor was selected in braking. Simulation and hardware results were presented under step change in load, step change in speed, rotor resistance variation of 50% and the wheel diameter error of 0.5%. Speed was measured by a speed sensor.

Single inverter fed parallel connected induction motor drive for shinkansen rolling stock traction was discussed in [40]. Single pulse mode was used in high speed range and PWM mode was used for low and medium speed operations. Stator flux oriented vector control was used to avoid over magnetizing of the motor at light load. Simulation and hardware results were presented under PWM mode and single pulse mode for four induction motors connected in parallel fed by a single inverter. Rotor angular velocity of each induction motor is detected by a speed sensor.

M.Taniguchi et al presented simulation results of 4 motors drive system and the general equation for 'n' number of motors connected in parallel [41]. Two more P controllers were included in the speed loop in addition to the PI controllers used in the existing methods to improve the performance under unbalanced load conditions. In [40] - [41], sensorless vector control algorithm was used and adaptive observer was used to estimate the speed and rotor fluxes of both induction motors.

#### Case (ii) Three induction motors in parallel

Three induction motors with parallel stator windings fed by a single inverter was discussed in [42]. The average and differential currents flowing into the stator windings and rotor fluxes were used to

make the system stable under unbalanced load conditions. The sampling period for observer was 250  $\mu$ s. Simulation results were presented under different running conditions to prove the effectiveness of the proposed method. PI and P controllers were used in the speed control loop. Sensorless vector control algorithm was used and adaptive observer was used to estimate the speed and rotor fluxes of both induction motors.

#### *Case (iii) Two induction motors in parallel*

Sensorless vector control of parallel connected dual induction motor drive based on the dynamic model was presented by P. M. Kelecy and R. D. Lorenz [43]. Mean and differential torques were controlled during the transient and steady state. The average electromagnetic torque was controlled by q-axis stator current and the differential torque was controlled by d-axis stator current rather than rotor flux. A Motorola DSP 56001 was served as a digital controller for current regulated PWM inverter. Experimental results were provided under balanced and unbalanced load conditions. The speed of both induction motors were estimated using discrete Luenberger observer.

Parallel connected dual induction motor drive fed by a single inverter was presented in [44]-[48]. The ratings of both induction motors were different in [44] and same in [45]. PI and P-type controllers were used in the speed control loop for motor 1 and motor 2 respectively. The system was stable under unbalanced load conditions as average and differential stator current and rotor fluxes were considered. In [46], PI type speed controller was used in both induction motors and the ratings were also same. Hardware results were presented under no load condition for step change in speed. Simulation results were presented under same and different ratings of induction motors [47]-[48]. The system was stable in either case of same ratings and different ratings. Adaptive observer was used [44]-[48] to estimate the speed and rotor fluxes of both induction motors.

In [38]-[46], q-axis stator current changes with load torque and d-axis stator current was maintained constant. But in [49]-[50], the d-axis stator current changed with load torque to make the system stable under unbalanced load conditions. The average and differential torque of the motors under unbalanced load conditions were controlled by using adjustable PI controllers. Adaptive observer was used to estimate the speed and rotor fluxes of both induction motors.

Low cost matrix converter with slip-frequency vector control was discussed in [51]-[53]. Two degrees of freedom control was used for automatic speed regulator to design both reference value tracking and disturbance rejection characteristic. Under unbalanced load conditions, the absolute value of the difference between the motor speed and the speed command were the same. Two more P controllers were included in the speed control loop to improve the performance in addition to the PI controllers present in both speed control loop. Simulation results were provided to validate the proposed method. Speed sensor was used to measure the speed and sensorless vector control technique was not employed. Space vector modulation technique was employed to control the inverter and reduce the total harmonic distortion [51] whereas Pulse Amplitude Modulation (PAM) technique was used in [52]-[53].

Masao Yano et al [54] presented a control technique in which the d-axis was aligned with the mean flux vector of both motors. The magnitude of the flux vector was controlled at a constant value. Simulation and hardware results of constant torque operation were presented. Speed sensors were used to measure the rotor speed of both motors.

A simple smart switching was used in [55] to control the voltage necessities of each motor in a parallel connected induction motor drive fed by a single inverter. Virtual speed controller was connected in between the inverter and each motor. To control the speed of induction motors, conventional V/f control technique was used. Speed sensor was employed to measure the speed and sensorless vector control technique was not used. Simulation and experimental results for a two 1.1 kW induction machines with single V/Hz scheme and fed by a single inverter were presented.

To improve the efficiency of parallel connected induction motor drive fed by a single inverter, optimal voltage and frequency were calculated by nonlinear programming method [56]-[57]. Load torque of each motor was estimated by disturbance observer from the estimated instantaneous torque and the detected motor speed. The instantaneous torque was estimated by current simulator and flux simulator. The speed difference between the two induction motors is 3% or less.

The parallel connected induction motors were treated as single motor by means of parameter averaging. Rotor flux oriented control scheme with parameter averaging and space vector averaging was

discussed in [58] for parallel connected induction motor drive system. In parameter averaging, two motors were treated as one motor but in space vector averaging, each motor had their own internal space vectors. Different PI controllers such as speed, torque and flux compensators were used to give voltage references  $V_{ds}$  and  $V_{qs}$ . Experimental set up was developed for two 110kW traction motor drives.

Multiphase, multi motor vector controlled drive system fed by a single inverter was discussed by Levi et al [59]. Multiphase induction motors such as six phases (double star) and nine phases (triple star) are preferred in electric locomotives because of fault tolerant features. Stator windings of the machine are connected in series, with an appropriate phase transposition, and the supply is a single current controlled VSI. Parallel connected multiphase multi motor drive system controlled by a single multiphase inverter was discussed in [60]. The performances were compared with series connected multi phase multi motor drive system. Indirect rotor field oriented control scheme for a multi phase multi motor drive was implemented in real time.

To understand the concepts clearly, simulation results are presented. The ratings and parameters of the induction motor are given in table 1. The reason behind the use of low power rating for simulation work is to use the same rating for miniature hardware set up. Fig. 5 and Fig. 6 show the actual and estimated speed waveforms for motor 1 and motor 2 under unbalanced load conditions. Natural observer was used to estimate the torque and speed. The induction motors initially have at no load and motor 1 is given 5 Nm load at  $t = 1.5s$ . Both motors run at a constant speed of 1000 rpm. The zoom in view of the estimated speed waveforms under unbalanced load conditions are shown in Fig. 7. It observed that the speed of machine 1 loaded by 5 Nm decreases by 12 rpm and the speed of the machine 2 under no load increases by 15 rpm. The system is stable because average and differential current flowing through the induction motors are considered. A balanced load of 5 Nm is applied to both induction motors at  $t=3s$  and both motors follow the command speed. It is observed that the estimated speed deviated from the command speed only when the conditions of the two motor are different. Fig. 8 and Fig. 9 show the estimated and actual torque responses respectively for motor 1 and motor 2 under unbalanced load conditions.

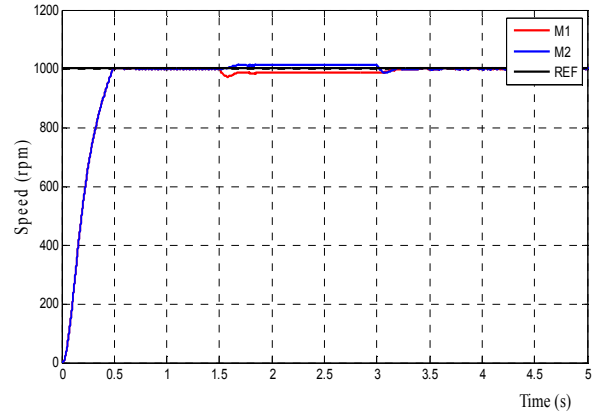


Fig. 5 Actual speed of M<sub>1</sub> and M<sub>2</sub>

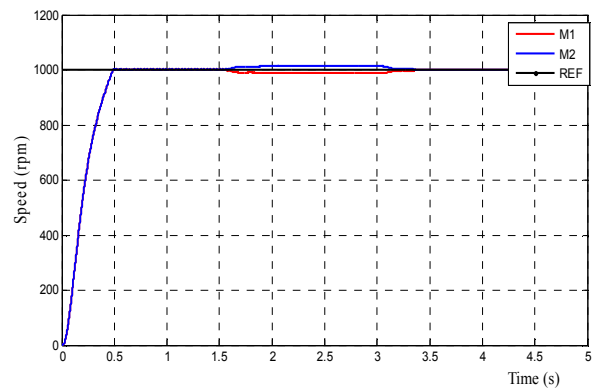


Fig. 6 Estimated speed of M<sub>1</sub> and M<sub>2</sub>

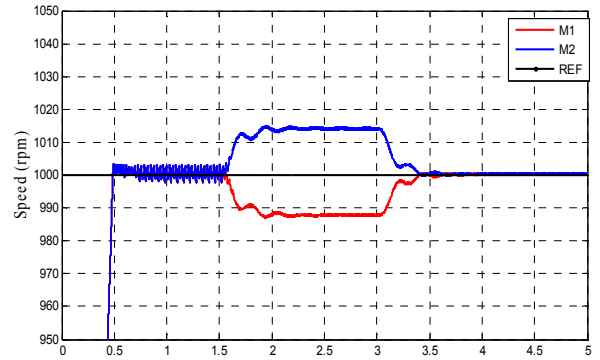


Fig. 7 Estimated speed of M<sub>1</sub> and M<sub>2</sub>

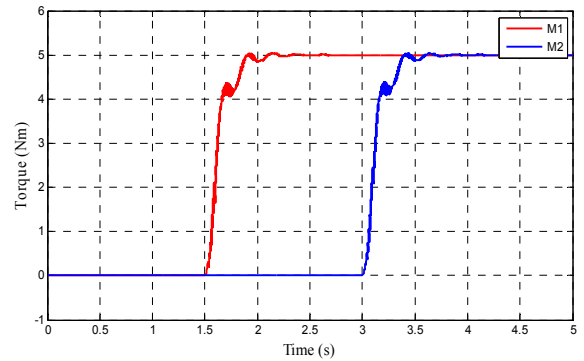


Fig. 8 Estimated torque of M<sub>1</sub> and M<sub>2</sub>

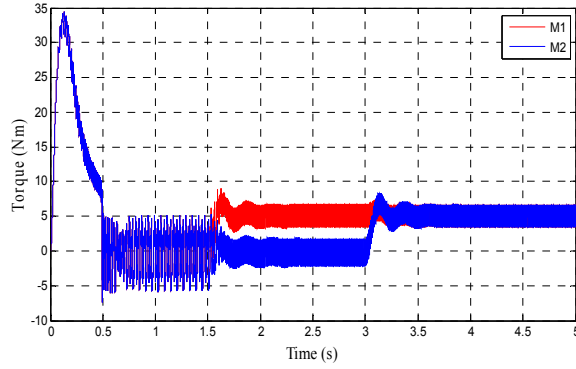


Fig. 9 Actual torque response of M<sub>1</sub> and M<sub>2</sub>

TABLE 1  
RATING AND PARAMETERS OF INDUCTION MOTOR

Motor Rating	
Output	0.75 HP
Poles	4
Speed	1420 rpm
Voltage	400 V
Current	1.8 A
R <sub>s</sub>	14.775 ohm
R <sub>r</sub>	4.767 ohm
L <sub>s</sub>	0.8075 H
L <sub>r</sub>	0.8075 H
L <sub>m</sub>	0.7485 H

All the literatures pointed out in earlier discussions [6] – [12], [17]-[20], [34]-[39] and [44]-[46] hysteresis current controller was used in the inner current loop. Torque ripple and current distortion are high in hysteresis current controller. To reduce the torque ripple and current distortion, SVPWM controller may be preferred. But the steady state response was faster in hysteresis current controller than SVPWM controller.

A harmonic study to characterize the impact on harmonics and overall efficiency of single inverter connected to two motors at varying loads was discussed in [61]. It was proved that the efficiency of dual motor drive increases as the load increases. V/f scalar control method was employed and sensorless vector control was not applied.

## V. ANTI-SLIP AND RE-ADHESION PHENOMENA IN TRACTION DRIVES

The drive system of electric motor coach in electric trains where two induction motors connected in parallel must have a robust anti-slip re-adhesion control system in order to avoid slip phenomena which are uncomfortable for the passengers. Slip phenomena occurs when the driving torque of

electric motor coach is bigger than the maximum adhesion force. First order disturbance observer and a new torque command function were discussed [17]-[18], [62] to realize the desired anti-slip re-adhesion control. The condition equation for the maximum adhesion force was  $d\mu/dt=0$ , where  $\mu$  is the adhesion force coefficient. PI control is difficult in case of large variation of adhesion force coefficient to keep the desired locus of operating point. A new open loop torque command function  $C(t)$  was proposed to carry out the adhesion control near to the optimal driving point.

The graphical modelling of different components in traction systems were described by A. Bouscayrol et al. [63]. Weighted control of traction drives was discussed and it is experimentally proved that the performance of weighted control was better than master slave control for anti-slip phenomena.

## VI. CONCLUSION

In this review paper, the speed-sensorless vector control of parallel connected induction motor drive is reviewed. Different power semi conductor devices employed in traction drives are presented. Various types of speed controllers and control techniques used to make the system stable under unbalanced load conditions are reviewed. Multiphase multi motors used in traction applications are also discussed.

## REFERENCES

- [1] Blaschke F., *The principle of field orientation as applied to the new transvector closed-loop control system for rotating machines*. In: Siemens Review (1972), vol 39, 1972, pp. 217-220.
- [2] Bimal K. Bose, *Modern Power Electronics and AC Drives*, Upper Saddle River, NJ: pp.348-350, Prentice-Hall, 2001.
- [3] Gratzfeld P. and Skudelny H. C., "Dynamic performance of two parallel-connected induction machines for traction drives," In: Proceedings of IEEE IAS Conf. Rec., 1984 Annual Meeting, pp. 287-295.
- [4] Matsuse K., Kouno Y., Kawai H. and Oikawa J., "Characteristics of speed sensor-less vector controlled dual induction motor drive connected in parallel fed by a single Inverter", In: IEEE Trans. Industry Applications (2004), vol. 40, Jan./Feb. 2004, pp. 153-161.
- [5] Matsuse K., Kouno Y., Kawai H. and Yokomizo S., "A Speed-sensor-less vector control method of parallel-connected dual induction motor fed by a single inverter," In: IEEE Trans. Industry Applications (2002), vol. 38, Nov. /Dec. 2002, pp. 1566-1571.
- [6] Berman B., "All solid state method for implementing a traction drive control", In: IEEE Trans. Industry



- Applications (1972), vol.1A-8, no.2, March/April 1972, pp.195-202.
- [7] Berman B., "Battery powered regenerative SCR drive," ", In: IEEE Trans. Industry Applications (1972), vol.1A-8, no.2, March/April 1972, pp. 190-194.
  - [8] Wasako C. R., "AC drives in traction applications", In: IEEE Trans. Industry. Applications (1986), vol.1A-22, no.5, Sept/Oct.1986, pp. 842-846.
  - [9] Salihi J. T., "An inverter for Traction Applications", In: IEEE Trans. Industry Applications (1972), vol.1A-8, no.5, Sept/Oct.1972, pp. 644-650.
  - [10] Saadate S., Doeuff R.L. and Periot R., "Design of a high voltage GTO chopper for traction drive", In: IEEE Trans. Industrial. Electronics (1991), vol.38, no.1, Feb. 1991, pp. 51-56.
  - [11] Ueda A., Ibamoto M., Narita H., Hori T., Tsuboi T. and Yamada Y., "GTO inverter for AC traction drives", In: IEEE Trans. Industry Applications (1983), vol. 1A, no.3, May/June 1983, pp.343-348.
  - [12] Thomas M. Jahns and Vladimir Blasko, "Recent advances in power electronics technology for industrial and traction machine drives", In: Proceedings of IEEE, vol.89, no.6, June 2001, pp. 963-975.
  - [13] Bartos S., Jehlika V., Skramlik J., Valouch V., Vecerka T., Bures J., Kalcik K. and Venhoda E., "Converters based on IGBTs in light traction drives", In : Proceedings of IEEE IECON'02, 2002, pp. 1273-1276.
  - [14] [http://www2.automation.siemens.com/Id/html\\_00/produkte/bahnen/bahnen.html](http://www2.automation.siemens.com/Id/html_00/produkte/bahnen/bahnen.html)
  - [15] John L. Oldenkamp and Steven C. Peak, "Selection and design of an inverter-driven induction motor for a traction drive system", In: IEEE Trans. Industry Applications (1985), vol. 1A-21, no.1, Jan/Feb 1985, pp. 259-265.
  - [16] Thomas M. Jahns and Vladimir Blasko, "Recent advances in power electronics technology for industrial and traction machine drive", In: Proceedings of IEEE, vol. 89, No. 6, June 2001.
  - [17] Ohishi K., Ogawa Y., Miyashita I. and Yasukawa S., "Anti-slip re-adhesion control of electric motor coach based on force control using disturbance observer", IEEE industry applications conference, pp.1001-1007, 2000.
  - [18] Kadowaki S., Ohishi K., Miyashita I. and Yasukawa S., "Re-adhesion control of electric motor coach based on disturbance observer and sensorless vector control", In: Proceedings of IEEE power conversion conference, 2002, pp. 1020-1025.
  - [19] Kubota H., Matsuse K. and Nakano T., "New adaptive flux observer of induction motor for wide speed range motor drives", in Conf.Rec.IEEE IECON'90, 1990, pp.921-926.
  - [20] Kubota H., Matsuse K. and Nakano T., " DSP-based speed adaptive flux observer of induction motor", In: IEEE Trans. Industry Applications (1993), vol. 29, no. 2, March/April 1993, pp.344-348.
  - [21] Kubota H. and Matsuse K., "Speed sensorless field-oriented control of induction motor with rotor resistance adaptation," In: IEEE Trans. Industry Applications (1994), vol. 30, Sept. /Oct. 1994, pp. 1219-1224.
  - [22] Young-Real Kim, Seung-Ki Sul and Min-Ho Park, "Speed sensorless vector control of induction motor using Extended Kalman Filter", In: IEEE Ttrans.Industry Applications (1994), vol. 30, no. 5, Sept. / Oct. 1994, pp.1225-1233.
  - [23] Luigi Salvatore, Silvio Stasi, and Lea Tarchioni, "A new EKF-based algorithm for flux estimation in induction machines", In: IEEE Trans. Industrial Electronics (1993), vol.40, no.5, Oct.1993, pp.496-504.
  - [24] Young-Real Kim, Seung-Ki Sul and Min-Ho Park, "Speed sensorless vector control of induction motor using Extended Kalman Filter", In: IEEE Trans.Industry Applications (1994), vol. 30, no. 5, Sept. / Oct. 1994, pp.1225-1233.
  - [25] Shi K. L., Chan T. F., Wong Y. K. and Ho S. L., "Speed estimation of an induction motor drive using an optimized Extended Kalman Filter", In: IEEE Trans. Industrial Electronics (2002), vol. 49, Feb. 2002, pp. 124-133.
  - [26] Murat Barut, Seta Bogosyan and Metin Gokasan, "Speed-sensorless estimation for induction motors using Extended Kalman Filters", In: IEEE Trans. Industrial Electronics (2007), vol. 54, no.1, Feb. 2007, pp. 272-280.
  - [27] Murat Barut, Seta Bogosyan and Metin Gokasan, "Experimental evaluation of braided EKF for sensorless control of induction motors", In:IEEE Trans. Industrial Electronics (2008), vol. 55, no.2, Feb. 2008, pp. 620-632.
  - [28] Mineo Tsuji, Yousuke Umesaki, Ryo Nakayama, and Katsuhiro Izumi, "A Simplified MRAS based sensorless vector control method of induction motor", In: Proceedings of IEEE, 2002, pp.1090-1095.
  - [29] Mohamed Rashed, Fraser Stronach and Peter Vas, "A Stable MRAS-based sensorless vector control induction motor drive at low speeds", In: Proceedings of IEEE, 2003, pp. 1181-1188.
  - [30] Cardenas R., Pena R., Asher G., Clare J. and Cartes J., "MRAS observer for doubly fed induction machines", In: IEEE Trans.Energy Conversion (2004). vol.19, no.2, June 2004, pp. 467-468.
  - [31] Cirrincione M., Pucci M., Cirrincione G. and Capolino G. A., "A new TLS-based MRAS speed estimation with adaptive integration for high-performance induction machine drives", In: IEEE Trans. Industry Applications (2004), vol. 40, no.4, July/Aug. 2004, pp.1116-1137.
  - [32] Cirrincione M. and Pucci M., "An MRAS-based sensorless high-performance induction motor drive



- with a predictive adaptive model', In: IEEE Trans. Industrial Electronics (2005), vol. 52, no.2, April 2005, pp. 532-551.
- [33] Sidney R. Bowes, Ata Sevinc and Derrick Holliday, "New natural observer applied to speed sensorless DC servo and induction motors", In: IEEE Trans. Industry Applications (2004), vol. 51, no.5, Oct. 2004, pp. 1025-1032.
- [34] Gunabalan R. and V. Subbiah V., "Speed-sensorless vector control of parallel connected induction motor drive fed by a single inverter using natural observer", In: World Academy of Science, Engineering and Technology (2010), vol.68, 2010, pp.554-559.
- [35] Guzinski J., Diguët M., Krzeminski Z., Lewicki A. and Abu-Rub H., "Application of speed and load torque observers in high-speed train drive for diagnostic purposes", In: IEEE Trans. Industrial Electronics (2009), vol. 56, no. 1, Jan. 2009, pp.248-256.
- [36] Guzinski J., Abu-Rub H., Diguët M., Krzeminski Z. and Lewicki A., "Speed and load torque observer application in high speed train electric drive", In: IEEE Trans. Industrial Electronics, vol. 57, no. 2, pp.565-574, Feb. 2010.
- [37] [www.iricen.indianrailways.gov.in](http://www.iricen.indianrailways.gov.in)
- [38] Yamada T., Matsuse K. and Sasagawa K., "Sensorless control of direct field oriented induction motor operating at high efficiency using adaptive rotor flux observer", In: Proceedings of IEEE IECON'96, , 1996, pp.1149-1154.
- [39] Matsumoto Y., Osawa C., Mizukami T. and Ozaki S., "A stator flux based vector control method for parallel connected multiple induction motors fed by a single inverter", In: Proceedings of IEEE, APEC'98, 1998, pp. 575-580.
- [40] Matsumoto Y., Ozaki S. and Kawamura A., "A novel vector control of single inverter multiple induction motors drives for shinkansen traction system", In: Proceedings of IEEE APEC'01, 2001, pp.608-614.
- [41] Taniguchi M., Yoshinaga T. and Matsuse K., "A speed-sensorless vector control of parallel connected multiple induction motor drives with adaptive rotor flux observers", In: Proceedings of IEEE PESC'06, 2006.
- [42] Kono K., Fushimi T. and Matsuse K., "Speed sensorless vector control of parallel connected induction motors", In: Proceedings of IEEE power electronics & motion control conference, 2000, pp. 278-283.
- [43] Kelecý P.M. and Lorenz R. D., "Control methodology for single inverter parallel connected dual induction motor drives for electric vehicles", In: Proceedings of IEEE PESC'94, 1994, pp. 987-991.
- [44] Kouno Y., Kawai H., Yokomizo S. and Matsuse K., "A speed sensorless vector control method of parallel connected dual induction motor fed by a single inverter", In: Proceedings of IEEE conference, 2001, pp. 1218-1223.
- [45] Kawai H., Kouno Y. and Matsuse K., "Characteristics of speed sensorless vector control of parallel connected dual induction motor fed by a single inverter", In: Proceedings of IEEE power conversion conference, 2002, pp. 522-527.
- [46] Kawai H., Kouno Y. and Matsuse K., "Characteristics of speed sensorless vector control of parallel connected dual induction motor fed by a single inverter", In: Proceedings of IEEE power conversion conference, 2002, pp. 832-836.
- [47] Inoue T., Azegami K., Matsuse K., Ito S. and Nakajima Y., "Dynamic performance of sensorless vector controlled multiple induction motor drive connected in parallel fed by single inverter", In: Proceedings of IEEE IAS meeting, Oct.2011.
- [48] Inoue T., Azegami K., Matsuse K., Ito S. and Nakajima Y., "Characteristics of sensorless vector controlled multiple induction motor drive connected in parallel fed by a single inverter", In : Proceedings of IEEE power engineering conference, 2011.
- [49] Ruxi W., Yue W., Qiang D., Yanhui H. and Zhaoan W., "Study of control methodology for single inverter parallel connected dual induction motors based on the dynamic model", In: Proceedings of IEEE PESC'06, 2006.
- [50] Wei S., Ruxi W., Yue W., He Y., Wang Z. and Liu J., "Study of Speed Sensorless Control Methodology for Single Inverter Parallel Connected Dual Induction Motors Based on the Dynamic Model", In: Proceedings of IEEE IPEDMC'06, 2006.
- [51] Yoshinaga T., Terunuma T. and Matsuse K., "Basic characteristic of parallel connected dual induction motor drives with matrix converter", In: Proceedings of 34<sup>th</sup> Annual conference of IEEE Ind. Electronics, 2008, pp.584-589.
- [52] Osawa A., Yamazaki M. and Matsuse K., "Vector control method of parallel connected induction motor drives fed by a matrix converter", In: Proceedings of IEEE IAS meeting, Oct. 2011.
- [53] Osawa A., Yamazaki M. and Matsuse K., "Vector control method and driving characteristics of parallel connected induction motor drives fed by a matrix converter", In: Proceedings of IEEE power engineering conference, 2011.
- [54] Masao Yano, Satoru Kuramoti and Hiroyuki Matsuda, "Vector control method of parallel connected induction motors", Electrical engineering report, pp. 34-39, NR-12, Nov.2001.
- [55] Perez-Pinal F.J., Nunez C. and Alvarez R., "A novel speed control approach in parallel connected induction motor by using a single inverter and electronic virtual line shafting", In: Proceedings of IEEE PESC'05, 2005, pp. 1339-1345.
- [56] Ando I., Sato M., Sazawa M and Ohishi K., "High efficient parallel connected induction motor speed

- control with unbalanced load condition using one inverter*", In: Proceedings of IEEE, IECON'03, 2003, pp. 162-167.
- [57] Ando I., Sazawa M. and Ohishi K., "*High efficient speed control of parallel connected induction motors with unbalanced load condition using one inverter*", In: Proceedings of IEEE, 2004, pp.1361-1366.
- [58] Wang J., Wang Y., Wang Z., Yang J., Pei Y. and Dong Q., "*Comparative study of vector control schemes for parallel connected induction motors*", In: Proceedings of power electronics specialist conference, IEEE , 2005, pp. 1264-1270.
- [59] Levi E., Jones M., Vukosavic S. N. and Toliyat H. A., "*A novel concept of a multiphase, multimotor vector controlled drive system supplied from a single voltage source inverter*", In: IEEE Trans. Power Electronics (2004), vol.19, no.2, March 2004, pp. 320-335.
- [60] Martin Jones, Vukosavic S. N. and Emil Levi, "*Parallel connected multiphase multi drive systems with single inverter supply*", In: IEEE Trans. Industrial Electronics (2009), vol. 56, no.6, June 2009, pp. 2047-2057.
- [61] Mitsui C., Tu S., Taufik and Anwari M., "*Efficiency study of adjustable speed drive with dual motor connecton*", In: Proceedings of IPEC '07, 2007, pp. 555-558.
- [62] S. Kadowaki, K. Ohishi, T. Hata, N. Iida, M. Takagi, T. Sano S. Yasukawa, "*Antislip readhesion control based on speed-sensorless vector control and disturbance observer for electric commuter train—series 205-5000 of the east Japan railway company*", In: IEEE Trans. Ind. Electron.(2007), vol. 54, no. 4, Aug.2007, pp. 201-208.
- [63] A. Bouscayrol, M.P. David, P. Delarue, R.P. Eguiluz, P.E. Vidal and X. Kestelyn, "*Weighted control of traction drives with parallel connected AC machines*", In: IEEE Trans. Ind.Electron (2006), vol. 53, no.6, Dec. 2006, pp. 1799-1806.