# Inteligent twin rotor drive system for electric and hybrid vehicles with random modulation techniques and with fixed switching frequency

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*Abstract* -**The paper present a survey of the wheel vehicles drived with electric and hybrid drive system. A theorethical analysis of the wheel hybrid vehicle drive system consisting of: a petrol motor cooperating with two induction motors, fed by transistor pulse feeder, or by transistor voltage inverter based on Inteligent Power Module (IPM), are presented in the paper. An alternating solution of the two induction motor drive system is application of twin rotor induction motor TRIM in a hybrid wheel vehicles. An original machine TRIM has a single stator and two rotors. Each core being a disc geometry, with stator sandwiched between two rotors. The rotors carry squirrel cage windings, and are mounted on individual, independent shaft, driving two wheels of an electric part of vehicles. The torque generated by each motor depends on the slip of each rotor and the dimensions of the cores, particularly the stator yoke depth which controls the magnitude of any differential flux in the two section of the machine. An analytical model of the machine is developed, based on a traveling wave model and taking into account the high harmonics, generated in the TRIM windings by saturation of magnetic circuits in the various parts of the TRIM cores. The mathematical model of the TRIM supplied with IPM inverter with random modulation technique is described in the paper. The techniques are based on adjusting the duration of the zero vectors or adjusting the three pulse positions in the switching period. The new method control of induction motor in hybrid vehicles are also compared with random switching frequency modulation and with fixed switching frequency modulation. Some variants of the adaptive control system: speed and current adaptive control system and also sliding adaptive control system are applied in the wheel hybrid vehicles. Adaptive controller are realised based on DSP controller. Modern controller realised of random modulation techniques are also based on DSP controller. The highly dynamic motor control system based on DSP controller should assured: energy-saving work system, optimal control of the benzin and electric motors, and realisation of the local and global diagnostics procedures and monitoring procedures of the wheel hybrid vehicles. Some results of the computer simulations performed for mathematical model of the hybrid drive system for specifical work states: start of the electric, electrical braking down to stand still, of the hybrid drive system are presented in the paper. Voltage, current and acoustic noise spectra are used for comparison and it's concluded that two of techniques are especially useful at lower fundamental frequencies. The proposed in the paper control method can substitue classic random modulation techniques with variable switching frequencies in application in electric and hybrid drive system. Some results of numerical calculation of the TRIM motor drive system was verified of the laboratory experiments performed for laboratory model of the hybrid wheel vehicles.**

## 1. Introduction

Clean air legislation is impelling advancements and promises for improvement in electric or hybrid machines performance, drive systems and control [4, 10]. Specially designed electric machines (induction or permanent magnet motor) have been usually employed in electric vehicles (EVs) or hybrid vehicles (HVs) applications, aiming optimization of efficiency, weight, volume and wider range control [4, 9, 10, 11]. Investigation of direct-drive high torque wheel-motor have been done in electric and hybrid vehicles and solar powered cars [4, 9, 10], indicating several advantages as elimination of transmission and gearing losses, beter powertrain transmission, fault tolerance improvements and fewer suspension struts requirements. Wheel motor can be used in city cars, electric and hybrid mini vehicles and in specials vehicles.

Electric and hybrid vehicles have attracted great interests as a powerful solution against environmental and energy problems. With improvement of motor and batteries, some pure electric vehicle with only secondary batteries have already achieved enough performance. Application of the fuel cell will be possibly in a major vehicle in the years: (2003-2008).

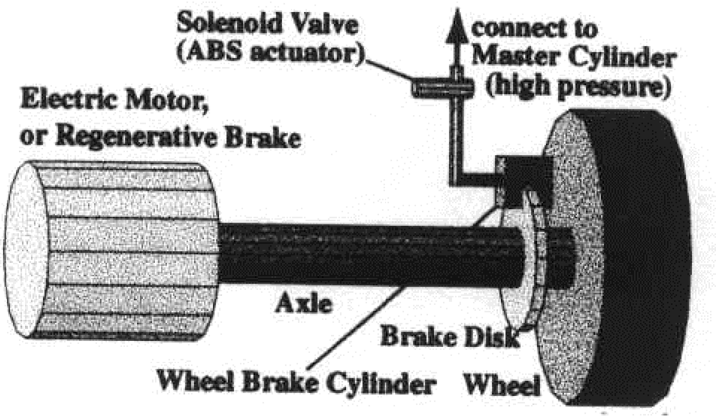


Fig.1 Drive system of the wheel vehicle

Modern drive system of road traction vehicles should ensure: enviromental safety, high reliability and economical speed control in specific duty circumstances. A significant improvement in economical and power indexes can be achieved by: application of new design drive motors (energy-sparing induction motor, permanent magnet motor, or hybrid drive system which contained petrol and electric motor), application of modern voltage converters controlled by microprocessor systems and optimum control of machines and electric vehicles. Wheels vehicle are usually fitted with petrol motor. However, due to the progress in power and information electronics, the robust induction motor drive and permanent magnet motor drives has become an attractive solution for this application since there is no need for commutators, switching devices, contactors and others parts subject to wear as necessary in DC series motor and petrol motor. Contactless changing of the direction is simply performed by electronic reverse of the phase-sequence. The highly dynamic motor control system based on field orientation guaranted optimal driving comfort through smooth tractive effort and electrical braking down to standstill. The paper present a survey on electric vehicle control system consisting of energy-saving induction motor, fed by transistor voltage converter based on Inteligent Power Module (IPM) and controlled by single chip microcontroller. The paper present also a survey on hybrid vehicle consisting of petrol motor and twin rotor, energy-saving, induction motors (TRIM), fed by transistor voltage converter based on IPM. The implementation of field oriented control, adaptive and sliding mode control are analysed in this paper. Although the dynamic performance of a FOC and DTC drive control is excellent, problems occur in the low speed region. The paper show how improved operation at low speed can be achieved using a sliding mode control scheme. Drive system of the hybrid wheel vehicle are presented in fig.1. The mathematical model of the TRIM supplied with IPM inverter with random modulation technique is described in the paper. The techniques are based on adjusting the duration of the zero vectors or adjusting the three pulse positions in the switching period.

The new method control of induction motor in hybrid vehicles are also compared with random switching frequency modulation and with fixed switching frequency modulation. Some variants of the adaptive control system: speed and current adaptive control system and also sliding adaptive control system are applied in the wheel hybrid vehicles. Adaptive controller are realised based on DSP controller. Modern controller realised of random modulation techniques are also based on DSP controller. The highly dynamic motor control system based on DSP controller should assured: energy-saving work system, optimal control of the benzin and electric motors, and realisation of the local and global diagnostics procedures and monitoring procedures of the wheel hybrid vehicles. Some results of the computer simulations performed for mathematical model of the hybrid drive system for specifical work states: start of the electric, electrical braking down to stand still, of the hybrid drive system are presented in the paper. Voltage, current and acoustic noise spectra are used for comparison and it's concluded that two of techniques are especially useful at lower fundamental frequencies. Control method proposed in the paper can substitue classic random modulation techniques with variable switching frequencies in application in electric and hybrid drive system. Some results of numerical calculation of the TRIM motor drive system was verified of the laboratory experiments performed for laboratory model of the hybrid wheel vehicles Some results of computer simulations performed for mathematical model of vehicles are presented in the paper.

## 2. Wheel axial induction motor

For electric vehicle applications, wheels motor drives represented a new attractive possible solution for their lightness and compactness. The wheels are directly driven by the electric motor and the gears are not necessary anymore. Because axial flux motors can find their advantageous applications in the low speed, high torque electrical drives. For axial flux motor applied in electric vehicle must be realised: high power/weight and torque/weight ratio, high efficiency and suitable shape to match the constrains space. In the axial flux motors family, the axial flux PM (permanent magnet) and axial flux induction motor are potential solution [8, 9, 11]. In the paper described axial flux induction motor **Trim** and permanent magnet motor [8, 11]. Axial flux induction motor (Trim) has one stator core with two polyphase windings and two rotors with two different shaft which may rotate independently. All the three magnetic cores (the stator and the two rotors) are in the form of discs with slots for the stator windings and the rotor cages. The machine can be classified as a twin rotor axial flux motor [8]. In this case, the motor can not be mounted inside the wheels but between them. The two rotors with independent shafts make the motor able to output different speeds for the two wheels. That results whenever the vehicle enters in a curve. In this situation the two rotors have different slips, that means that they links differents fluxes: the flux distribution tends to keep the motor torque balanced. Thus the motor can provide equal torque to the two driving wheels performing as the engine and the mechanical differential of conventional vehicles. Therefore only one inverter is needed to obtain the differential effect. Two identical polyphase windings are connected in series in such a way, that the stator current flows in the same direction in any back to back stator slot. There is one main flux which links the stator windings and the two rotor cages. No flux goes through the stator yoke except the leakage flux. The motor has a small stator yoke which reduces the iron core cost and the iron losses, but long ends windings which results in copper losses. This motor can be designed as single-phase or as three-phase.

Induction traction motor with twin rotor axial flux is a physical combination of two motors into one in such a way, that their magnetic circuits are no longer independent. Trim motor has a special torque characteristics, depending on the degree of interaction between the magnetic circuit of each

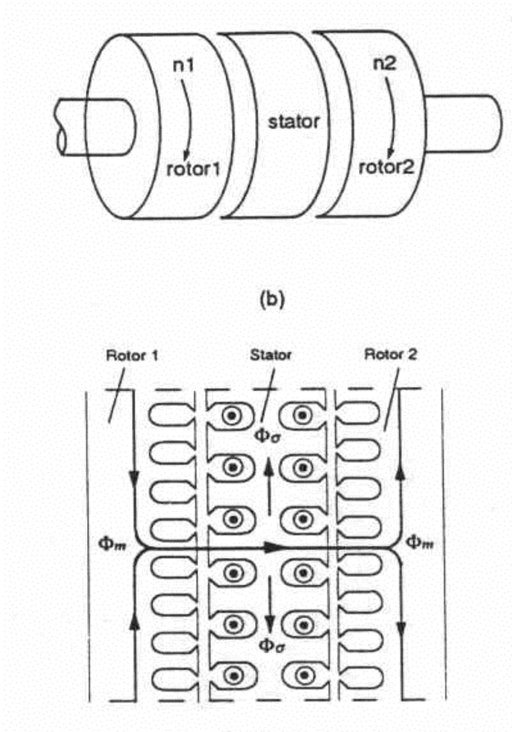


Fig.2 Twin rotor induction motor

side of the rotor [8, 11]. The major component of the Trim motor are represented in fig.2a and 2b, with winding ommited. The rotor are on different shafts and may rotate independently. All three magnetics cores are in the form of discs, with slots for the the windings cut accros the face. In the fig.2a and 2b show details of the cores. The holes for the slots are punched out of a continuos strip which is wound onto aa circular former to build up the cores. The space be-tween the slots is adjusted continuosly during the process. Two identical polyphase windings are mounted on the stator and connected in series in such a way that stator current flows in the same direction down any two back-to-back slots. The rotor carry cast squirrel cage windings. In the simple terms, the machine operates as follows. When the vehicle is steered straight ahead, both driving wheels run at the same speed, and therefore at the same slip. Conditions in the the machine are symmetrical and both rotors produce equal armature reaction. Thus all flux, exacpt leakage, linking the stator windings, also links each rotor winding. No flux passes around the yoke of the stator. Both rotor produce the same torque. When the vehicles enter a curve, the inner wheel reduced speed and increases slip whereas the outer wheel increases speed and reduced slip. Therefore the armature reaction from the slower rotor exceeds that from the faster rotor. The same total flux linkage is maintained at the stator winding and the net is that the flux linking the low speed rotor is reduced while that linking the high speed rotor is increased. The redistribution of the flux tends to keep the rotor torques balanced. The difference in the fluxes passes around the stator yoke. As the radius of the curve followed by the vehicle is reduced, this process continues and flux in the stator yoke builds up to the point of saturation. Up to this point, the machine behaves like two machines in series. After this point, saturation limits the flux which can pass around the stator core, and therefore limits the amount by which the rotor flux linkages can differ. These rotor fluxes are then more or less fixed, and the machine starts to take on the characteristics of two machines in parallel con-nenction. The same total flux linkage is maintained at the stator winding and the net is that the flux linking the low speed rotor is reduced while that linking the high speed rotor is increased. The redistribution of the flux tends to keep the rotor torques balanced. The difference in the fluxes passes around the stator yoke. As the radius of the curve followed by the vehicle is reduced, this process continues and flux in the stator yoke builds up to the point of saturation. Up to this point, the machine behaves like two machines in series. After this point, saturation limits the flux which can pass around the stator core, and therefore limits the amount by which the rotor flux linkages can differ. These rotor fluxes are then more or less fixed, and the machine starts to take on the characteristics of two machines in parallel connenction. This machine is designed to make use of the magnetic saturation of electric steels. Additionally, as a results of the disc geometry, saturation will naturally occur in areas of the machine other than the stator yoke. The rotor yokes may saturate, especially at the outer radius, and the teeth of the rotor and stator will saturate, especially at the inner radius. A polyphase windings sets up a main MMF wave which rotates at the synchronuos speed and brings into being a main flux wave which also rotates at the synchronuos speed. If a machine is going into saturation in a particular region, the wave will be distorted and will tend to be flat topped in that region, so that the resultant flux waveform will contain space harmonics which must rotate at the synchronuos speed.. If the windings is nonideal, these harmonics fluxes produce harmonics voltages and currents. Supply voltage of the transistor voltage inverter also contain a full spectrum of high harmonics in voltages and in currents.

Most of wheel motor have been constructed as axial flux based, but there are some of the motors have also radial flux construction. Thoses motors have been high field intensisty across stator windings construction due to a better magnetic path and utilization of standard rectangular magnets, which are easier to handle. The outer rotor may be designed to have permanent magnet NdFeB Vacodym magnets with high remanence (1,1 T) and coercity (1275 kA/m.) on the inside surface and concentrated windings on the stator. In the motor applied in electric vehicle drive systems must be concerned problems: rise temperature to avoid demagnetization effects, exposition to road shocks, spils, dust and particles, and force demands on the wheel and tire, but mechanical construction of the motor is out of the scope this paper. High number of poles reduced the torque ripple and yields a smaller magnetic yoke, decreasing volume and weight. Also, the permanent magnet area physically limits the maximum number of poles.

## 3. Transistor supply for electric and hybrid motor

Electric vehicle are driven by petrol motor or by electric motor. IGBT transistors or Inteligent Power Modules (IPM) voltage inverters or three-phase pulse width modulation AC chopper can be used for drive supply system. Fig.3 presents voltage inverter circuit with IPM and 16-bit microcontroller. IPM structure contains IGBT transistor circuit with diodes, transistor gate driver supply, overload, short circuit, thermal and under voltage protection circuits and pulse braking circuit. 16-bit microcontrollers with 32-bit aritmetic, HSO, HSI and PTS circuits can be used for IPM control. Control circuit can ensure: wide frequency range close to sinusoidal voltage and currents, complex motor control algorithms (vector control, direct control and sliding mode control), failure state detection, analog signal (voltage, current, rotational and linear speed) measurement, position, speed and acceleration feedback) [9, 10]. The high inverter switching frequency guaranted low noise and a good current waveform (small losses due to current harmonics). For loading the inverter DC link, a battery current-limiting loading resistor is used. Some sensor elements give information about actual state of system. Two transfo-shunts yield actual phase current control and overcurrent protection. A digital encoder (250 pulses per revolution are sufficient) can be applied for speed measurement. A control electronic consist of: 16-bit microcontroller Siemens production, digital signal processing system-single ADSP 2101 or TMS 320C25 processor board performing some control task and communicating with I/O units.. For control strategy based on field oriented induction motor control, flux calculation based on two flux models are combined. In the lower speed range, an indirect current models is used, in the higher speed range, a voltage model calculates the flux and the current model is used for motor model adaption. The inverter switching frequency is 6 to 9 kHz, depending on the operation point. Main part of the control unit is the signal processing system (DSP), for highly dynamic traction control via field orientation and for user specific control tasks (I/O control, driver information, start-up sequence, reference torque generator, battery management, emergency operationand others). These software tools are programmed and presented in a graphical monitors Some diagnostics and monitoring procedures are describrd in [9, 10]. The Input/Output unit (SSP) provides the analog and digital hardware interface. The driver unit (TRP) generates the gate drive signals for the power IGBTs. The serial RS 485 link is used for real time optimization of the drive behaviour. All analog and digital inputs and outputs can be monitored on a laptop PC in real-time or changed, respectively.

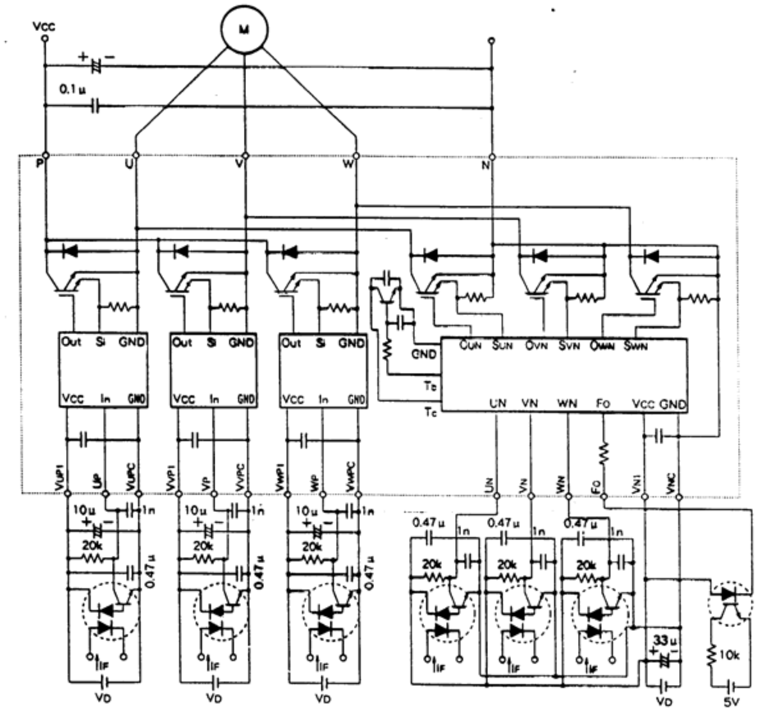

Fig.3 Transistor voltage inverter composed with Inteligent Power Module

## 4. Vehicle drive control system

The paper present three control method of induction motor drive system: field oriented method), adaptive control method and sliding mode control method [3, 4, 5, 6, 7]. In adaptive control method of induction drive system are performed a mathematical analysis of wheel vehicle drive system drived trim induction motor and two single induction motors. System of differential equations described a dynamic state of the induction motor with one rotor are presented by (1):

$$\frac{d\psi_{s\alpha}}{dt} = -\alpha\psi_{s\alpha} + \alpha K_r \psi_{s\alpha}^{(s)} + u_{s\alpha}$$

$$\frac{d\psi_{s\beta}}{dt} = -\alpha\psi_{s\beta} + \alpha K_r \psi_{ss\beta}^{(s)} + u_{s\beta}$$

$$\frac{d\psi_{r\alpha}^{(s)}}{dt} = \beta K_S\ \psi_{s\alpha} - \beta\psi_{r\alpha}^{(s)} - \Omega\psi_{r\beta}^{(s)} + u_{s\alpha}$$

$$\frac{d\psi_{r\beta}^{(s)}}{dt} = \beta K_S\ \psi_{s\beta} - \beta\psi_{r\beta}^{(s)} + \Omega\psi_{r\alpha}^{(s)} + u_{s\beta} \qquad (1)$$

$$\frac{d\Omega}{dt} = \frac{3p^2 K_r}{2\sigma L_s J}\left[\psi_{s\beta}\psi_{r\alpha}^{(s)} - \psi_{s\alpha}\psi_{r\beta}^{(s)}\right] - \frac{p}{J}T_M$$

$$T_e = \frac{3p L_M}{2\left(L_S L_R - L_M^2\right)}\left[\psi_{s\beta}\psi_{r\alpha}^{(s)} - \psi_{s\alpha}\psi_{r\beta}^{(s)}\right]$$

where:

$$K_S = \frac{L_M}{L_S},\quad K_R = \frac{L_M}{L_R},\quad \sigma = 1 - \frac{L_M^2}{L_S L_R},\quad \alpha = \frac{R_S}{\sigma L_S},\quad \beta = \frac{R_R}{\sigma L_R},$$

System of differential equations described a dynamic state of the induction motor with one rotor are presented by (2):

$$u_s = R_s i_s + L_{\sigma s}\frac{di_s}{dt} + \ L_s\frac{di_s}{dt} + M_{s,r1}\frac{di_{r1}}{dt} + M_{s,r2}\frac{di_{r2}}{dt}$$

$$u_{r1} = R_{r1s} i_{r1} + L_{\sigma r1}\frac{di_{r1}}{dt} + L_{r1}\frac{di_{r1}}{dt} + M_{r1,s}\frac{di_s}{dt} + M_{r1,r2}\frac{di_{r2}}{dt}$$

$$u_{r2} = R_{r2s} i_{r2} + L_{\sigma r2}\frac{di_{r2}}{dt} + L_{r2}\frac{di_{r2}}{dt} + M_{r2,s}\frac{di_s}{dt} + M_{r1,r2}\frac{di_{r1}}{dt}$$

$$M_{M1} = i_s^T\frac{\partial}{\partial\phi_{M1}}\left[M_{s,r1}\right]\cdot i_{r1} \qquad (2)$$

$$M_{M2} = i_s^T\frac{\partial}{\partial\phi_{M2}}\left[M_{s,r2}\right]\cdot i_{r2}$$

$$M_{M1} - M_{ob1} = J_{M1}\frac{d\omega_{M1}}{dt} + D_1\omega_{M1}$$

$$M_{M2} - M_{o21} = J_{M2}\frac{d\omega_{M2}}{dt} + D_2\omega_{M2}$$

State observer  defined for fixed coordinate αβ in induction motor vector control without ratational speed sensor, for magnetic flux connected with rotor windimg may be presented in the form of equation (3):

$$\frac{d}{dt}\hat{\underline{x}} = \begin{bmatrix} -\left(\frac{1}{\sigma T_S}+\frac{1-\sigma}{\sigma T_R}\right)\underline{I} & \frac{L_M}{\sigma T_S T_R}\left(\frac{1}{T_R}\underline{I}-\hat{\omega}\underline{J}\right) \\ \frac{L_M}{T_R}\underline{I} & -\frac{1}{T_R}\underline{I}+\hat{\omega}\underline{J} \end{bmatrix}\hat{\underline{x}} + \begin{bmatrix} \frac{1}{\sigma L_S}\underline{I} \\ 0 \end{bmatrix}\underline{u}_s + \begin{bmatrix} K\underline{I} \\ 0 \end{bmatrix}\left[i_s - i_r\right]$$

where:

$$\hat{\underline{x}} = \begin{bmatrix} \hat{i}_{s\alpha}, \hat{i}_{s\beta} & \hat{\psi}_{s\alpha} & \hat{\psi}_{s\beta} \end{bmatrix}^T, \quad \underline{u}_s = \begin{bmatrix} u_{s\alpha} & u_{s\beta} \end{bmatrix}^T; \quad \underline{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; \quad \underline{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

where estimative angle $\hat{\rho}$ of the magnetic field vector location connected with rotor windings for transformation system of variables αβ is equal: $\bar{\rho} = arctg\frac{\hat{\psi}_{r\alpha}}{\hat{\psi}_{r\beta}}$ (3)

On the ground of analysis global stability of drive system with state observer applied of the research Lapunow function method  calculate a variability section of correction feedback K≤0. [3, 4, 5]. Adaptive algorithm of motor speed $\hat{\omega}$ with adaptive period $T_a$ can be done in discrete forms by equation system (4):

$$\begin{aligned} \omega^*_{n+1} &= \omega^*_n + K_i T_a \varepsilon_n \\ \hat{\omega}_{n+1} &= \omega^*_{n+1} + K_P \varepsilon_n \end{aligned} \tag{4}$$

where  $K_i$  and $K_P > 0$.

Adaptive error can be calculate with relation (5):

$$\varepsilon = \left(\hat{i}_{s\beta} - i_{s\beta}\right)\hat{\psi}_{r\alpha} - \left(\hat{i}_{s\alpha} - i_{s\alpha}\right)\hat{\psi}_{r\beta} \tag{5}$$

In the sliding mode controller of electric vehicle all problems in the low speed region are caused by use of inactive or zero vectors of the inverter. Therefore a possible solution woulb be to avoid using these zero vectors, but this leads to a high inverter switching frequency. However, if the inactive voltage vectors are only removed in transient conditions, it is possible to achieve torque and flux control, even in the low speed region while lowering the switching frequency in steady-state. For the transient conditions the switching scheme is based on sliding mode control. The equivalent control is defined as the input which zeroes derivatives of sliding mode. For stator flux and torque control are selected as:

$$S_x = \left\|\bar{\Psi}_s\right\| - \bar{\Psi}_{sw}, \quad S_{y'} = T_e - T_{obc} \tag{6}$$

To find the equivalent control $V_{seq}$ the derivatives of (6) are taken:

$$\hat{S}_x = \left\| \Psi_s - \bar{\Psi}_{sw} \right\|, \ \hat{S}_{y'} = \hat{T}_e - \hat{T}_{obc} \tag{7}$$

Supposing that the set values for torque and stator flux are constant, these equation are simplified:

$$\hat{S}_x = \left\| \hat{\bar{\Psi}}_s \right\| \quad \hat{S}_{y'} = \hat{T}_e \tag{8}$$

With the machine equation rewritten in a reference frame fixed to stator flux these equation become:

$$\begin{gathered} \Psi_{s,z} = V_{s,z} + f_1(x) = \hat{\hat{S}}_x \\ \hat{S}_{y'} = \frac{3}{2} N_p \left( \Psi_{s,z} I_{sy} + \Psi_{s,z} \hat{I}_{sy} \right) \end{gathered} \tag{9}$$

with $f_1(x)$ and $f_2(x)$ nonlinear function of the motor state x. [3, 4, 5, 6].

In the field oriented method digital signal processor (ADSP or TMS320C25) performing all task of control electronic and drive system. A slow task (20ms) carries out interface and communication functions (break and gas pedal, driver interface), a medium task (0,7ms) calculates the motor control algorithms, yielding stator-oriented reference current components according to the field-oriented control structure. A fast (45μs) current control task calculates directly inverter switching command [3, 5, 9]. At low speed of motor, a rotor frequency feed-forward control is used, at higher speed including field-weakening range the slip control is coupled with a voltage model for flux detection. This EMF based flux information is used to adapt the temperature-dependente rotor resistance to its actual value [3, 5, 6, 7]. If the machine is operated below about 35% of base speed (20km/h vehicle speed), no EMF information is utilized for control. Hence, rotor resistance adaptation is inactive and the last value is stored and used until next high-speed operation. In this speed range, the rotor flux reference value is defined constant (rated magnetization). The torque command is generated by a driver via gas and brake pedal signals (considering limitation, rise time by superimposed drive control). The mentioned current components define the reference space phasor of the stator current in a field oriented (x,y) reference frame. Hence, the space phasor has to be transformed into stator- oriented (α,β) coordinates. The transformation angle is in angular position of the rotor flux space phasor $\rho_R$. The main problem of field -orientation control method is to find accurate field information. In the low speed range, the reference flux angle $\chi_{\psi,ref}$ calculated by integration of the reference rotor flux angular velocity $\omega_{\psi,ref}$, is used for transformation. It's speed is obtained from reference values of $i_{Sy}$ and rotor flux magnitude $\rho_R$ and measured rotor angular velocity $\omega_m$. Since no auxiliary information for adaptation of the rotor resistance is available in the low-speed region, the rotor resistance is kept constant until next high-speed operating point. Returning back from high speed to low speed, the rotor resistance is fixed at the lst adapted value. However, since the duration of low speed operation is relatively short (vehicle speed below 20km/h), the change of rotor resistance during this operation can usually be neglected. This control method are described in [3, 5, 9].

## 5. Random modulation technique with fixed switching frequency for Trim indukcion motor

Adjustable speed drives have reached a state, where they have became armature component in many professional application, particularly in the wheel vehicles. The main reasons are their capabilities of energy savings, improved automation performance, and also the cost is steadily decreasing. Sensorless control, power converter design and pulse width modulation PWM is important for the wheel vehicles drive performance in respect to current harmonics, torque ripple, and also acoustic noise, emitted from: induction motor and supply system [1, 2]. Different approaches are used in PWM including switching with lower frequency [1, 2], switching with high frequency (greater than 17kHz) [1, 2, 9], or using a **r**andom **s**witching **f**requency - **RSF** [1, 2, 9].

The method **RSF** is very efficacious, because the average switching frequency can be kept low as can the acoustic annoyance [2, 4]. One approach uses the space vector modulation technique extended with a variable switching frequency operation, which effectively reduces the acoustic annoyance, but problems arrise in the control system because then a variable sampling frequency in the controller are needed if the modulator and the controller shall operate in synchronism [2]. Another method shifts randomly between lagging and leading edge modulation [1], which effectively gives a random modulation but problems appear in the sampling of the currents without using any anti-aliasing filter. The original new method RSF presented in the paper operating at a fixed switching frequency, but the pulses are randomly positioned within the switching period. In that method is randomly changes the duration of zerovectors: 111 and 000 [1, 2]. RSF method are applicable to power converter, which supplying of the traction motors in wheel veclicles, without any neutral connection. All random PWM techniques have common property that the switching frequency is constant. As stated above this may ease the implememntation of digital controllers, which often are synchronized to the switchings of the inverter, which in turn is controlled by the PWM unit. Having excludeed the switching frequency as the parameter to randomize, it seems that the pulse position is the only quantity which can be randomized, while still keeping the average voltage produced by the inverter fully controllable within each switching interval. The fundamental idea behind random pulse position techniques is that the mean voltage measured across one switching inrterval is independent of the position of the pulse. This degree-of-freedom may be utilized in various ways: from a theoretical point of view, the only constraint is that a pulse must not extend beyond the boudaries of the switching interval in question. That constraint may be met in a number of different ways, but the literature dealing with random pulse position has focussed almost exclusively on one simple variant, namely the so-called lead-lag random pulse position technique originating from [6]. Sketches of the investigated method are show in fig.4 including the method of [6]. The symbols: $q_a$, $q_b$, $q_c$, indicates the PWM switching function for the hree phases, and T is the switchting period.

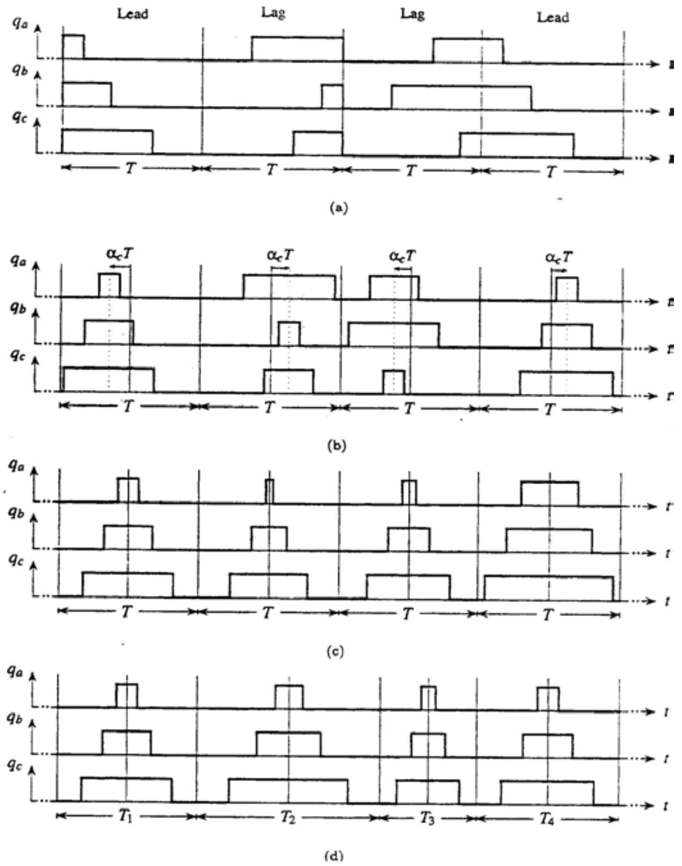


Fig.4 Different fixed switching frequency modulation scheme

Method **RLL** (Random Lead–Lag Modulation- fig.4a): the pulse position is either commencing at the beginning of the switching interval, or is tailing edge is aligned with the end of the interval. The choice between leading and lagging modulation is controlled by a random number generator. Method **RCD** (Random Displacement of the Pulse Center-fig.4b): show a method where the pulses are mutually center-aligned as in space vector modulation SVM, but the common pulse center is displaced by the amount $\varpi_c T$ from the middle of the period. The parameter $\varpi_c$ is varied randomly within a hand limited by the maximum duty cycle. Method **RZD** ( Random Distribution of the Zero Voltage Vector-fig.4c): in three phase, three wire system the duration of the zero voltage vector does not alter the phase voltages. This fact is utilized in the random distribution of the zero voltage vector, where the proportion between the time duration for two zero vector states and 000 is randomized in a switching cycles. All pulses are center-aligned as in standart SVM. Method **RSF** (Random Switching Frequences-fig.4d): in this method the switching period is randomly varied ($T_1$, $T_2$,,$T_3$,...) within a limited interval. The method RLL, RCD and RZD are all operating with fixed switching frequency. Two different limitation in respect to randomization exist in RCD and RZD. In the RCD the maximum duty cycle of: $q_a$, $q_b$, $q_c$ gives the maximum possible displacement of the pulses. This mean that at high modulation indices the available displacement interval will be reduced.. In all cases, the modulators produce active vectors of duration identical to the SVM, exactly the same average voltage vector $\bar{u}_r$ is generated by the inverter irrespective of randomization method. In order to implement the random modulation strategies it is necessary with flexible PWM unit. Fig.4 shows how the two new modulation strategies can be implemented. The reference for the modulator is the average voltage vector defined by is magnitude U and its position q. This is used uin standard space vector modulation. The output is three duty–ratios ($D_a$, $D_b$, $D_c$). Those are used to calculate the maximum possible displacement $\alpha_{max}$ by comparison of their magnitudes. The actual displacement is calculeted by randomizing of $\alpha_{max}$ and depending on whether RCD or RZD is used two compare levels ($P_1$, $P_2$) in timer are calculated and used for $q_a$. Correspondingly are P3-P6 also calculated for the two other phases. If RCD is used, then αequal $\alpha_c T$, and if RZD is used, α is equal to the duration of the zero-vector (000) $t_0$. Lead – lag modulation is implemented by using only one compare level $P_1$ for each phase.

## 6. Computer simulation and test results

On the basis of mathematical model of wheel vehicles with electric and hybrid drive system was performed a computer simulation with applied Matlab- Simulink procedures. A scheme of mathematicalmodel of Trim induction motor are presented on fig.5. Results of computer simulationnwas verified in laboratory. Provisional scheme of laboratory performence presented in fig.6. The control is implemented in a combined DSP (ADSP-21 062) and microcontroller (SAB C167) system. The DSP handles all calculations in real-time using floating–point arithmetic, including the task of generating random number s to the random PWM. The microcontroller generates the switching functions to the inverter by means of built-in Captiure-Compare timers that have a resolution of 400 ns. A Bruel- Kjaer Pulse Multi Analyzer system is used as Dynamic Signal Analyzer. The noise hand with for the analyzer is 12 Hz. A microphone measures the acoustic noise from the induction motor is placed in distance of 20 cm from the motor. Voltage and current are sensed using Tektronix probes and amplifiers.

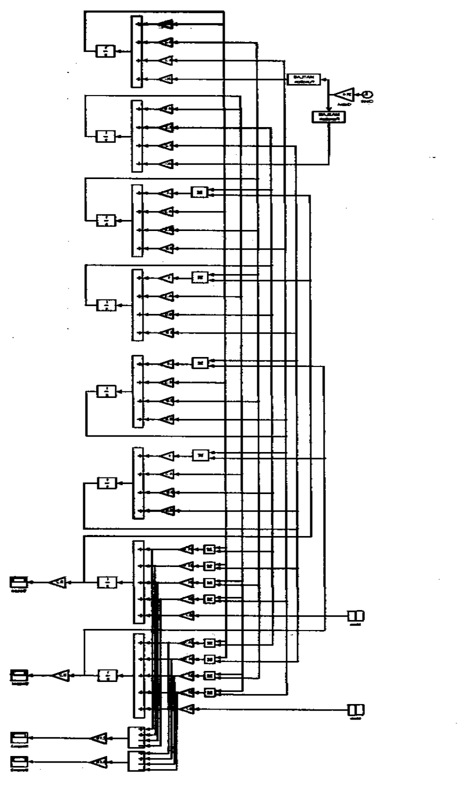

Fig.5 Matlab-Simulink calculation scheme of the Trim induction motor

Experiment are done for the three random modulation techniques with fixed switching frequency. Inluded are also results for classic random switching frequency technique with the minimum switching frequency $f_{min}$=4kHz, maximum switching frequency $f_{max}$= 6kHz and for fixed frequency operation at 5kHz..

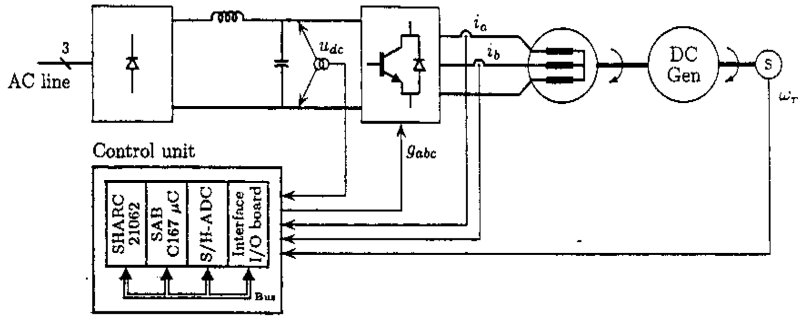


Fig. 6 Scheme of the laboratory scheme of supply system

Comparing the voltage spectra distinct harmonic voltage components appear in the case of fixed switching and random lead-lag, while the power spectra is much more smooth for the other three method. The most smooth power spectra is zero-vector distribution and from a subjective point of view the acoustical noise from induction motor is the least annoying. At higher fundamental frequency more pronouced harmonics are presented in all measured spectra excert for the random switching frequency technique. When random switching frerquency is used the control loops have to be modified. In the RLL strategy a correct current sampling is very dificult to achieve beacause of the assymetric modulation. Space vector modulation at low modulation index with fixed switching frequency assures at low current ripple. Using RS, RZD or RCD will increase the peak to- peak ripple, but not as the poor-performing RLL technique. The acpustic noise are more pleasant or rather less annoying for RCD, RZD and RD both at low and high modulation index. Some results of noise analysis are presented in fig.7.

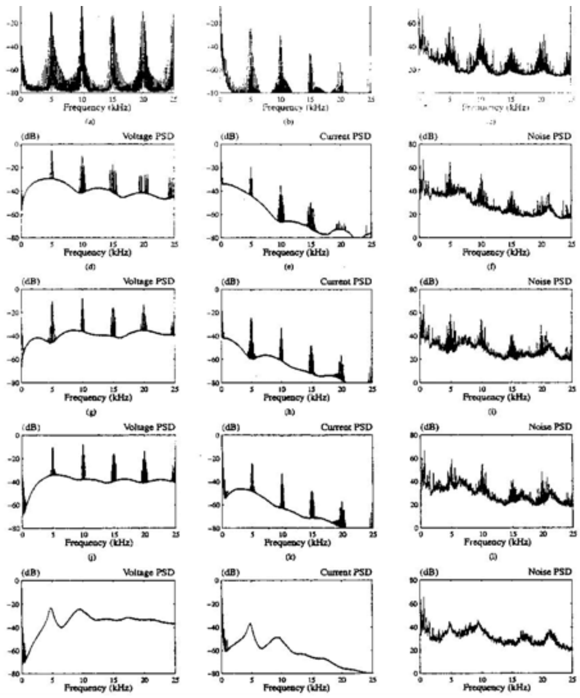

Fig.7 Results of laboratory experiments Trim induction motor

## 7. Conclusion

New energy-saving inverter fed motor for electric vehicle drive systems make possible energy sparing traction drive system design. Microprocessor-based hierarchical control systems ensure automatic drive motor control, contactless power supply system operation and implementation of complex control algorithms (minimising voltage and current higher harmonics), power dissipation, ensuring suboptimum control for normal and emergency operation and drive system diagnostics. Universal solution (with some necessary modification) can be applied not only in vehicle drive system. From the power capability and the principal dimensions, the axial flux PM and induction motors can be mounted into the wheels to realize the driving strategy. A new calculation family of random methods for three-phase power converter, operating at fixed switching frequency is proposed. Two different method for randomize the pulse width or pulse position have been shown to have the same performance with respect to acoustic noise abortment as random switching frequency at low fundamental while the random switching frequency method has the best performance at higher fundamental frequencies.

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