REDUCED VOLTAGE COMBINED AC MOTOR AND DRIVE SYSTEM FOR SAFE ELECTRIC VEHICLE

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Abstract

This paper presents the design, analysis and implementation of a proposed combined three phase induction motor and its drive system to meet the demand of low-voltage electrical system for hybrid and electric cars, avoiding the high voltage human risks, expensive and complex requirements of the higher voltage insulation and power electronic devices. The development of electric vehicle technologies has been reviewed. A conventional 220V 3-ph induction motor has been rewound in order to get the required 48V 3-ph motor. A comparison between the old motor and the rewound motor has been theoretically and practically carried out including different characteristics. Design and simulation analysis of different control cards have been carried out using PSpice software while the overall drive system performance has been simulated using Simulink under Matlab package. The proposed setup has been practically implemented using commercial available components. Different practical waveforms have been obtained for different operation modes, showing the effectiveness of the proposed setup as a reduced voltage speed control drive system suitable for safe electric vehicle applications.

1 Introduction

Since the global oil reserves will be depleted and its prices are significantly increasing, in addition to the hazard and polluted emissions generated by the internal combustion engine, electric vehicles (EVs) have received great attention and the development technology of EV has taken on an accelerated pace during the last two decades [1]. With the exception of its battery, the electric vehicle is superior in many ways to gasoline powered cars. A major difference is the level of noise produced, battery EVs offer almost silent driving. Acceleration, speed, and handling for well-designed EVs are equivalent to, or better than, those of comparable internal-combustion-powered vehicles. It requires minimal maintenance, delivers high torque at low speeds, reliable and benefits from the advantage of electric drive to use regenerative braking instead of mechanical braking during deceleration and down slope driving [1]. Thus, EV can compete with internal combustion engine in terms of specific energy consumption, but still not in terms of power density. Recently, many commercial companies have produced hybrid and electric vehicles and are available in market sale, such as Toyota Prius, Honda Insight, Ford P2000, General Motors GM EV1, Nissa Altra and others. One factor that is hindering the advancement of these vehicles is the cost factor. Also new developments have to be made in battery technologies to make them more suitable and commercially available. More EV models, specifications and manufacturers achievements can be found in literature [1]-[12]. Traditionally, the DC motor has been used up to now in most electric vehicles since their torque-speed characteristics well suit traction requirements and speed control is simple. However DC motor has commutator hence it requires regular maintenance, small power-weight ratio with expensive production cost. Recently, commutatorless motors take the advantages over DC motors [1],[2],[5] and [6]. Induction motors (IM) are a widely accepted commutatorless motor type for EV propulsion because of their mature, high reliability and durability, together with low cost and maintenance. At present, induction motor drives offer one of the most reliable and mature technologies for use in EVs [6]. In order to avoid the high-voltage system risks, expensive and complex high-voltage insulation and also reduce dV/dt which may affect the motor life and system reliability, a low-voltage system to drive the EV is proposed in this paper. A complete low-voltage electric drive system based on rewinding of low cost conventional 3-hp 220V 3-ph induction motor and implementation of scalar chopper-inverter (constant V/F ration) drive is proposed. First the development in electric vehicle technologies are reviewed, second the characteristics and performance of the old and rewound machines are compared, then the design of system electronic cards and overall system performance are simulated; and finally the proposed set is practically implemented and tested.

2 Development of electric vehicle technologies

The developed trends of various electric vehicles with respect to different papers published on various topics can be categorized as depicted in figure 1 and summarized as:-

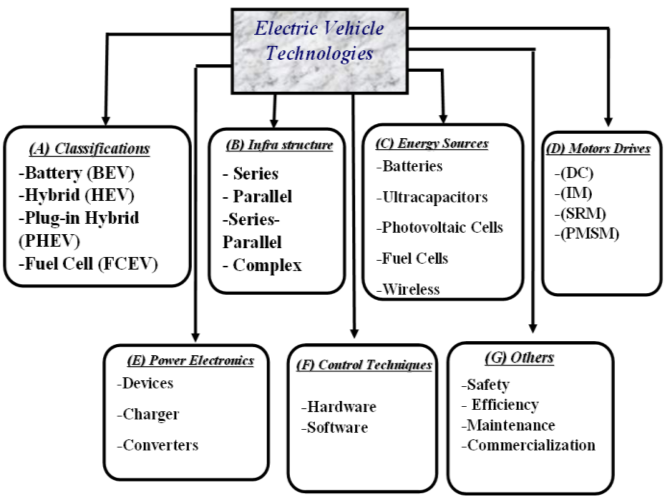


Fig.1: Developed trends of various electric vehicle technologies

***A. Classifications*:-** The critical issue of BEV is the battery. Therefore, BEV is mainly suitable for small EV for short range and low speed community transportation. HEV can meet consumers' need and has many added values, but cost is the major issue. FCEV has long term potential for future main stream vehicles; however the technology is still in development stage while cost and refueling are the major concerns [1] and [2].

***B. Infrastructure:* -** The key feature of the series hybrid is to couple the electric power from the ICE/generator and the battery together to supply the electric motor to propel the wheels, whereas the key feature of the parallel hybrid is to couple the mechanical power from the ICE and the electric motor to propel the wheels. The series-parallel hybrid is a direct combination of both. On top of the series-parallel hybrid operation, the complex hybrid can offer additional and versatile operating modes [1], [3] and [5].

C. Energy Sources:* - *The EV energy source has been identified to be the major obstacle of EV commercialization, with the following development criteria:- -High specific energy (kWh/kg) and energy density (kWh/L); -High specific power (kW/kg) and power density (kW/L); -Fast-charging and deep-discharging capabilities; -Long cycle and service lives; -Self-discharging rate and high-charging efficiency; -Safety and cost effectiveness; -Maintenance-free; and-Environmentally sound and recyclable. A single source of energy cannot meet the energy requirements for an electric vehicle. For the hybridization of two energy sources, one is selected for high specific energy while the other for high specific power [1], [3] and [4].

D. Motor Drives: - Induction motor (IM) and permanent magnet (PM) motor drives are highly dominant, whereas those on direct current (DC) motor drives are dropping while those on switched reluctance (SR) motor drives are still in a crawling stage. In terms of efficiency, the most efficient motor drives are the permanent magnet brushless motor. Next come the induction and the switched reluctance motor drives which have almost identical efficiency and the least efficient are the DC motors. In terms of the maturity of the technology for being used in propulsion system, induction motor and DC motor drives score the highest and these two technologies are slightly more mature than that of permanent magnet brushless and switched reluctance motors. In terms of reliability, the most reliable are the induction motor drives and switched reluctance drives, followed by permanent magnet brushless motor drives. When it comes to the power density, then permanent magnet brushless motors come out at the top followed by both induction and switched reluctance motors. The DC motor drives could have the lowest power density. In terms of cost factor, the best to be used are the IM followed by the DC and the SR motors. Surprisingly, permanent magnet brushless motors score the least in cost factors when compared with all the others [1], [2], [5] and [6].

E. Power Electronics: - At present, the IGBT is the most attractive because it possesses high input impedance and the high-speed switching characteristics of the MOSFET together with the good conductivity characteristic of the BJT. In the near future, the MCT would be a good candidate for EV propulsion because it combines high switching speed, high power handling capability, superior dynamic characteristics, and high reliability. In electric vehicles (EV), the state of charge (SOC) of a battery is an important quantity, as it is a measure of the amount of electrical energy stored in the battery. New trends on power electronics converter topologies, such as DC-DC choppers and DC-AC inverters, having significant impact on reliability and performance, and have been introduced for EV applications [1], [7], [8], [9] and [10].

***F. Control Techniques:*-** Since the drive systems of EV should be efficient and have to go through frequent start/stop along different operating speeds in different environments, microprocessor based controllers (such as microcontrollers and DSP) together with high performance control systems (such as adaptive and direct torque) have been involved in recent EV technologies [1], [11] and [12].

***G. Others:*-** Others topics such as human safety issues, efficient operation, reliability, maintenance and cost have gained more attentions for future commercializing of the EVs and competition in marketing to replace the conventional gasoline cars [1] and [5].

3 The proposed setup

The proposed drive is designed to work under low voltage/high current. Figure 2 describes the proposed drive system architecture in a block diagram form. The power parts of the drive system are composed from a battery bank followed by a DC to DC chopper for controlling the voltage level; the chopper is then followed by an LC filter to purify the regulated DC voltage. After the LC filter, the power is fed to the DC to AC 3-ph inverter which in turn controls the frequency of the output 3-ph AC voltage supplied to the rewound low voltage high current induction motor.

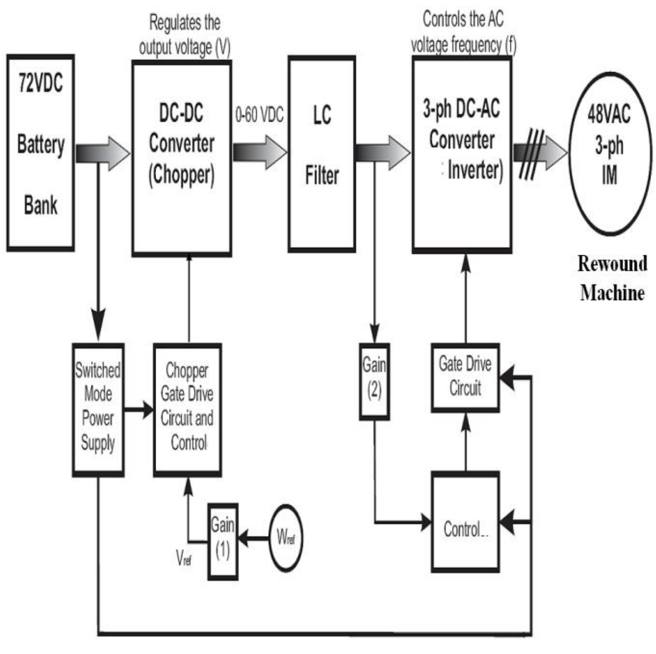


Fig.2: Block diagram of the entire proposed drive system

The control parts of the drive are then composed of a switched mode power supply to feed the different control cards with suitable isolated voltage levels from the battery bank, and two different gate drive circuits associated with their control cards for generating suitable gate drive signals for the chopper and the inverter. The inverter is operated with low frequency signals (0-60 Hz, with 180^0 conduction), which is found more suitable than the high frequency PWM technique for the required higher-current density operating conditions and the available commercial components.

4 Drive system design and simulation

The simulation of the power parts and overall system performance is carried out using Simulink under Matlab package Ver. R2007b, since it provides powerful toolbox for the simulation of power system components; while for the design and simulation analysis of the control cards, the PSpice software package Ver. 16.0 is then utilized as it has its own powerful library of different digital components required for the design of the gate signals generation.

A. Power System Simulation Using Matlab

The chopper is utilized to convert the fixed DC battery voltage into a regulated DC voltage feeding the 3-ph inverter. Series inductor and shunt capacitor are utilized in the output chopper circuit to stabilize and reduce voltage ripple in the chopper DC output voltage. As shown in figure 3a, the two identical parallel branches configuration at the negative terminals was chosen to reduce the transistors current and switching frequency by dividing the high input current into two different circuits, hence improve the overall losses and ripples in the output DC voltage. MOSFET transistors are used as switches inside the chopper while the LC filter values are chosen to be 82000uF for the capacitor and 250uH for the chock coils to insure minimum possible ripples for the high current operating conditions. The switching frequency is 200 Hz for each transistor and variation of gate signals duty cycle will directly change the value of the DC output voltage. The chopper output voltage, which is the voltage of the shunt capacitor, during ON and OFF periods of both circuits, can be written as:

$$V_{ch} = V_{ch1_{(on)}} + V_{ch1_{(off)}} + V_{ch2_{(on)}} + V_{ch2_{(off)}} \quad (1)$$

$$V_{ch1_{(on)}} = \frac{1}{C_{ch}} \int_0^{T_{1on}} i_{1on} dt = E_B - L_{1ch} \frac{di_{1on}}{dt} \quad (2)$$

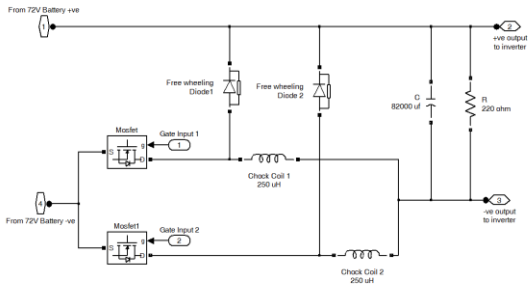
$$V_{ch1_{(off)}} = \frac{1}{C_{ch}} \int_{T_{1on}}^{T_{ch}} i_{1off} dt = 0 - L_{1ch} \frac{di_{1off}}{dt} \quad (3)$$

$$V_{ch2_{(on)}} = \frac{1}{C_{ch}} \int_0^{T_{2on}} i_{2on} dt = E_B - L_{2ch} \frac{di_{2on}}{dt} \quad (4)$$

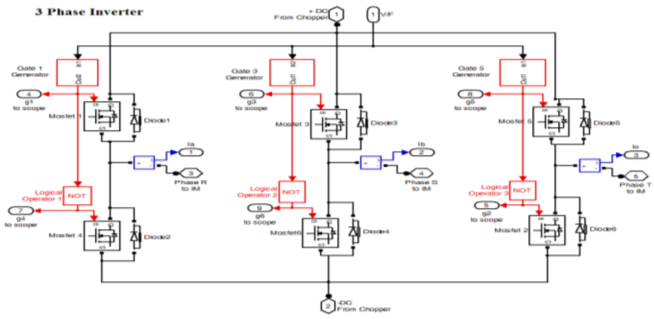
$$V_{ch2_{(off)}} = \frac{1}{C_{ch}} \int_{T_{2on}}^{T_{ch}} i_{2off} dt = 0 - L_{2ch} \frac{di_{2off}}{dt} \quad (5)$$

Where ***(T_{ch})*** is total period, ***($T_{(on)}$)***is ON time, ***($T_{(off)}$)***is OFF time, ***(E_B)*** is battery voltage, (***C_{ch})*** is filter capacitor and ***(L_{ch})*** is filter inductance. The inverter proposed in this thesis is utilized for converting the regulated DC voltage from the chopper to 3-ph AC signals with variable frequency. Unlike the PWM inverters, the inverter will control only the frequency. Hence, the amplitude of the AC signal will be dependent on the DC voltage level regulated by the chopper. This technique was chosen to improve the system reliability due to the high current conditions under which the drive will operate which is not easy to be achieved with PWM high frequency technique, particularly with the available switching devices in the local market. The three phase inverter connection diagram is shown in figure 3b, followed by example of simulation results of the control signals and output line voltages at different input DC voltages in figure 3c. It should be noted that the ratio V/F is set according to the rating of the driven machine. This can be achieved through the proposed setup shown in figure 1 by proper adjustment of the Gain (1) and Gain (2) of the control parts of the drive system. The inverter line to line RMS output voltage could be written as:-

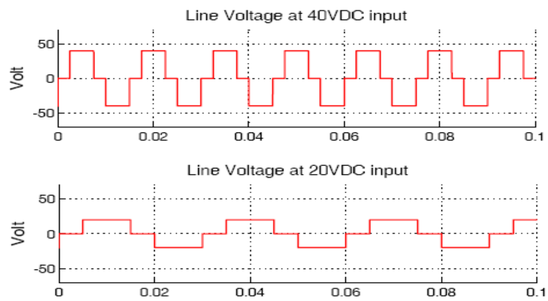
$$V_{inv} = 0.8165 V_{ch} \quad (6)$$



a) Chopper circuit

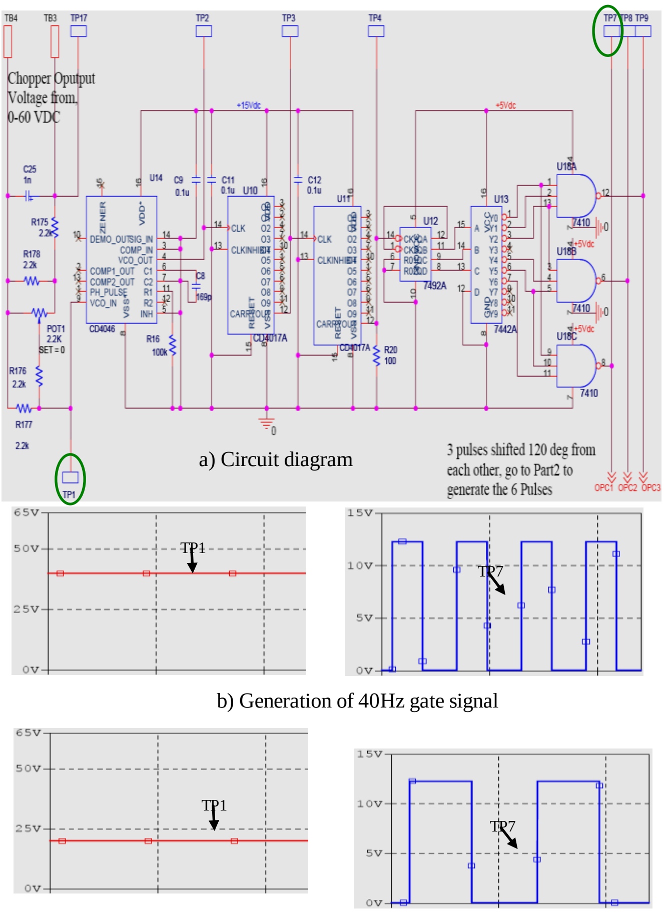


b) Inverter circuit



c) Inverter AC output voltage at different chopper DC input voltage

Fig. 3: Simulation of power circuits using Simulink under Matlab



b) Generation of 40Hz gate signal

c) Generation of 20Hz gate signal

Fig.4: Part of inverter gate drive circuit to control the frequency (as an example of PSpice simulated circuits)

B. Simulation of Gate Drive Circuits Using Pspice

All gate drive circuits are designed to have a source of isolation and amplification in order to provide the suitable voltage and current levels for the power switching devices. The drive circuits are powered from the switched mode power supply which has been designed for the given application requirements.

One control circuit is designed to provide the DC chopper with the required 10V, 200Hz PWM gate signals, while the duty cycle is adapted through an externally connected joystick controlled manually by the driver.

Two control circuits are designed to operate the inverter. The first circuit (Gate Generation Circuit) required to generate the 6 signals and the second circuit (Driving Circuit) required to isolate and adapt the signals for driving the inverter power transistors. Unlike the chopper signals, the inverter signals duty cycle is fixed while the frequency is varying with the DC voltage level. Figure 4 illustrates part of the inverter circuits simulated by PSpice software as an example of the overall designed circuits.

From the previous simulation analysis it can be seen that the proposed set has shown a good performance and can then be validated for practical implementation which will be discussed through the following section.

5 Motor rewinding for reduced voltage operation

The objective of the work in this thesis is to introduce a complete motor-drive system with reduced voltage for safe electric vehicles. Since the objected 48V 3ph IM is not available in the local commercial market, the proposed solution is to get an available low cost 3ph IM with standard voltage 220V (machine-A, see table 1) then rewinding it to fulfill the requirement (machine-B). This will be cheaper and very helpful to understand and validate such motor in the study. The main opinion is to reduce the 220 voltage of machine-A to 48V while keeping the original motor power and characteristics unchanged as possible, hence:

$$Q_A = 3V_A I_A = Q_B = 3V_B I_B \quad (7)$$

Given: $V_A = 220V$ and $V_B = 48V$ (8)

Then: $I_B = \frac{220}{48} I_A$ (9)

Since: $a_A = \frac{\delta}{I_A}$, while $a_B = \frac{\delta}{I_B}$, then $a_B = \frac{220}{48} a_A$ (10)

Where ***(Q)*** is total power, ***(V)*** is phase voltage, ***(I)*** is phase current, ***(a)*** is cross section area and ***(δ)*** is current density.

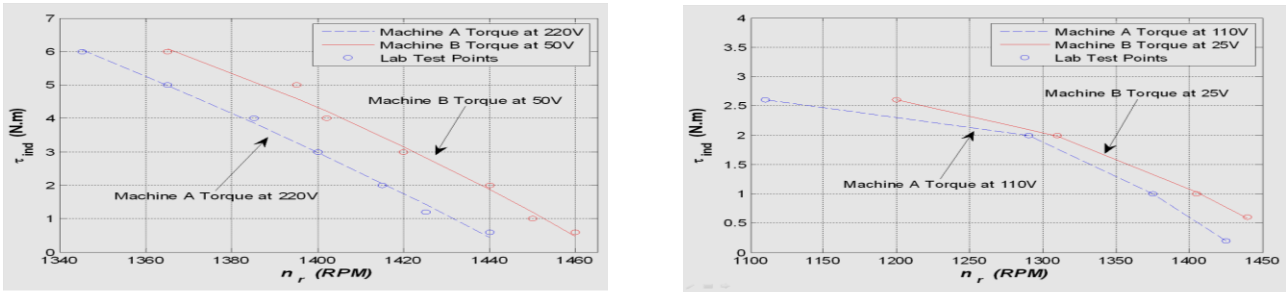
It should be noted that the machine-A coils were composed from two wires in parallel forming two parallel circuits having two cross section areas, (a_{A1}= 0.385mm^2) and (a_{A2}= 0.332mm^2). Therefore, machine-B will also have two parallel circuits with two cross section areas, (a_{B1}= 1.765mm^2 and a_{B2}=1.522mm^2). As these exact cross section areas are not available in the market, we replace them with a cross section area with radius of (1.54 mm^2) for both wires. To keep the total ampere turns of both machines constant,

$3T_A I_A = 3T_B I_B$, then $T_B = \frac{48}{220} T_A$ (11)

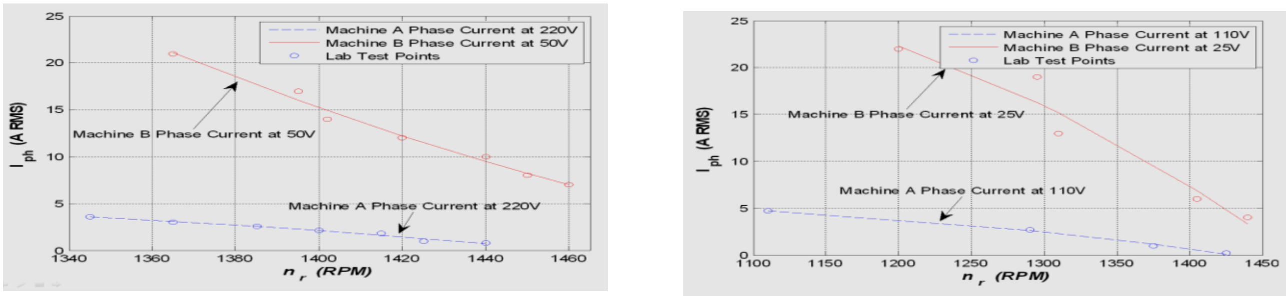
Since the number of turns per phase per each coil T_A =35, therefore T_B =7.63 ≈ 8 turns, and total number of conductors (Z_B) =8*2*2*6*3=576.

3 hp	Motor Length: 19 cm
4 poles	No. of stator slots: 36
50 Hz	No. of coils per phase: 6
1460 RPM	No. of slots per pole per phase (*q*): 3
380 V Star / 220 V Delta	No. of turns per coil (T_B): 35
5 A at Star / 9 A at Delta	Total No. of stator conductors (Z_a): 2520
Outer Diameter: 15.5 cm	No. of parallel circuits : 2
Bore (*D*): 9.4 cm	Conductor diameter: 0.7 mm & 0.65
Rotor Diameter: 9.2 cm	Coil Pitch: 7/9/11 “Concentrated”

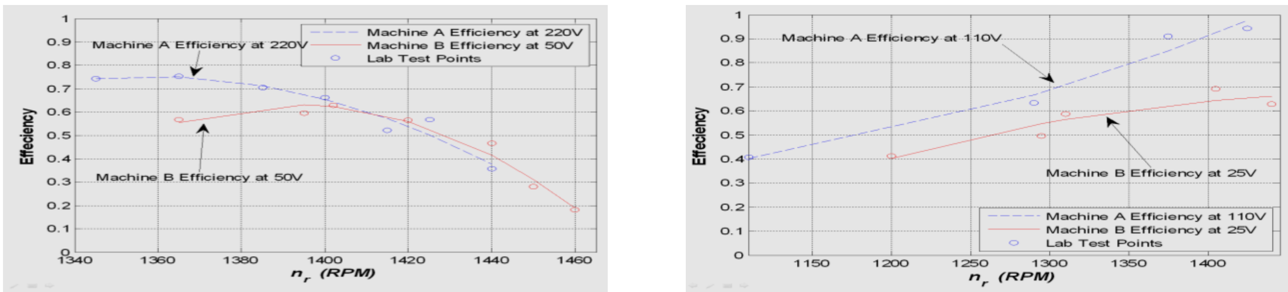
Table 1: Specifications of the original machine-A



a) Torque-Speed Characteristics



b) Current-Speed Characteristics



c) Efficiency-Speed Characteristics

Fig.5: Machine-A (original) versus machine- B (rewound) characteristics at different supply voltages, (Laboratory results plotted by the Polyfit function at different supply voltages).

The characteristics of both machines have been experimentally tested and results are illustrated through figure 5. From the performance comparison between both machines, it can be noted that the torque-speed characteristics of machine-A and machine-B are almost identical; however the current in machine-B is 5 times the current in machine-A, since the voltage has been reduced by almost the same factor to keep constant power; as a result, the efficiency in machine-B is a bit lower than efficiency in machine-A. Values of winding resistance and inductance should be reconsidered for better efficiency and machine performance optimization. The practical tests have validated the low cost rewound machine to work as Reduced-Voltage 3-ph induction motor for the proposed electric vehicle drive application.

6 System implementation

The overall proposed setup shown in figure 2 has been experimentally implemented to drive the reduced voltage rewound induction motor at different operating speeds. A lead acid battery bank of 72V, 6A/H is used for testing the setup.

The chopper and inverter power circuits (shown in figures 3a and 3b) have been implemented using three parallel power MOSFET (3xIRFP250) per each leg to provide the required high current density operation conditions of the proposed reduced voltage system. A switched mode power supply, based on small DC to AC inverter through a center-tapped primary and multi-tapped secondary transformer, and then through AC to DC rectifiers, has been designed and implemented to provide different isolating DC power supplies with different voltage levels required by the different gate drive circuits of the chopper and inverter. A photograph of the experimental implemented setup is shown in figure 6a, while figures 6b and 6c depict the experimental waveforms obtained by storage scope for different operating speeds (from 0rpm to 1450rpm then to 950rpm and back to 1450rpm). From these results, it can be seen that the variation of motor speed is achieved by regulating the DC voltage fed to the inverter through the chopper and the LC filter, while the inverter converts such regulated DC to corresponding 3-ph 180 conduction AC voltage with a frequency depending on the value of such DC voltage, hence providing a constant V/F ration. It should be noted that the reversing of motor rotation direction has been easily implemented using external reversing switch, as a command signal, through the interchange of the inverter gate signals, but with limited regenerative breaking operation due to the chopper circuit. Utilization of power modules and digital controller could reduce the overall system size.

7 Conclusions

Different developed trends related to electric vehicle technologies have been reviewed. A conventional low cost 3-ph induction motor available in commercial market has been rewound in order to be operated at high-current low-voltage conditions while maintaining the torque speed characteristics unchanged as possible. A complete scalar V/F drive, based on DC to DC chopper and 3-ph DC to AC inverter has been introduced and investigated through this paper. The system has been designed and analyzed by simulation software programs to validate the proposed setup for practical implementation. The setup has been experimentally implemented and tested for different mode of operations, showing the effectiveness of the combined motor drive system to be operated under reduced-voltage high-current conditions, providing simple and low cost system with safe voltage level suitable for safe electric vehicle drive.

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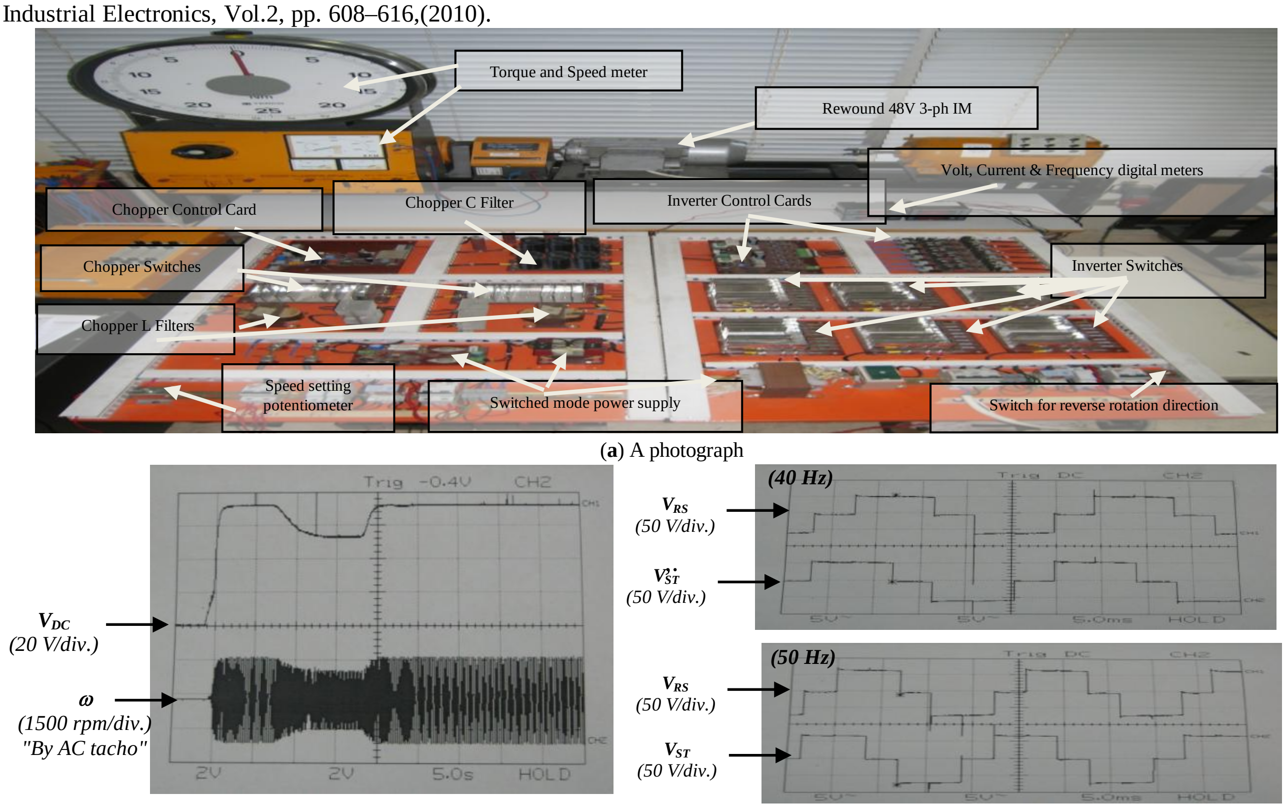

(**a**) A photograph

(**b**) Variation of speed with the variation of DC chopper voltage

(**c**) Variation of motor line-voltages with different reference speeds

Fig.6: The implemented setup