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Electric Multi-Motor Drives with Improved Induction Machine for Agricultural Wide-Span Implement Carrier (WSIC)

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Abstract.

Agricultural wide-span implement carriers (WSIC) are machines specially adapted to the controlled-traffic farming field management system. The agricultural WSIC requires many main and auxiliary drives that can be controlled separately. Electric drives are highly efficient, cleaner and more environmentally friendly for actuation compared to other power sources such as hydraulics especially with the recent improvement in power to weight ratio. This paper reviews the relative merits of electric motor and drives systems currently in use in electric vehicle systems and evaluates the possibility of employing induction machines for agricultural WSIC (tractors and implements). The electric components for the implement part include two induction electric motors, a Permanent Magnet (PM) electric motor, and an electric stepper motor with a closed loop speed, and torque control. The electric components for the tractors include a generator and its controllers, a rectifier, inverters, and an appropriate power interface. To enhance the performance of the employed induction machine, a MATLAB simulation and a typical experimental test have been carried out to compare an off-the-shelf Squirrel Cage Induction (SCI) machine with another one of the same type but employing an auxiliary winding. The new SCI machine will be called "modified" in the rest of the paper. The results show significant improvement in the performance of the modified machine with a power factor of almost 0.99, a decrease in losses of 27% and a noticeable reduction of in-rush current.

Keywords. *Wide-Span Implement Carrier, Electric induction machine, Automatic control, Cranberry production*

Introduction

Hydraulic power systems have led to increased productivity of agricultural tractor-implement systems by allowing greater design flexibility and control, but have also increased the complexity of these systems. Hydraulic power can be used to operate multiple actuators and to power hydraulic motors. With the advent of the Controller Area Network (CAN) bus controls and power beyond, implements are increasingly using smart valves and providing new options for implement controls and configurations. Matching tractor and implement systems reduces energy waste. In the same way, improved electrical power systems can allow for expanded design options for controlling implements and for directing power to remote parts of implements, where there may not be space to route hydraulic lines (Stoss et al., 2013; Jürgen, 2012). The other potential benefits would be a cleaner and more environmentally friendly solution for actuation.

Several manufacturers and research institutions have been working on electrification or hybridization of agricultural machinery and implements recently (Karner, 2012). The choice of motors and controls are wide and almost any tractor control requirement can be met by selection of suitable motor, gear drive and control configurations (Prankl et al., 2011; Ajit et al, 2006). Example of application of electric drives on implements include threshing cylinder of combine harvesters (Herlitzius, 2009); fertilizer spreader (Hahn, 2008; Sobotzik, 2010); vertical cutter bar in a combine harvester (Sharobeem, 2008); forage harvester (Gallmeier, 2009); traction applications (Stoss, 2013; Li et al., 2013), and an electrically powered WSIC (Williams et al., 1991).

The simplicity and flexibility provided by induction machines in providing electromechanical energy conversion make it an alternative choice for agricultural machinery. Induction machines in general have many advantages: simple, cheap, reliable, brushless (squirrel cage rotor), no synchronizing equipment, absence of DC power supply for excitation, good over-speed capability, inherent protection against short-circuit, easy to control, not producing sparks like DC motors, and they require very little maintenance (Habash et al., 2012). The induction machine, however, is not without its drawbacks including the need for a high starting current, reactive power for operation, and poor voltage regulation under varying speeds. Thus its power factor is inherently poor, and it is worse especially at starting and when running with light loads or when operating with power electronics converters. At starting, the input power to an induction motor is mainly reactive. It can draw up to 6 times of its rated current at about 0.2 power factor and it requires some time to come to its rated speed; where the power factor improves significantly to above 0.6 depending on the load. This high starting current at a poor power factor usually affects the loads and limits the application range of the machine; accordingly, new techniques should be developed to enhance its performance. Deere & Company introduced the first agricultural tractor with high voltage engine auxiliaries in 2007 (the 7430/7530 EPremium). On these tractors, a 20 kW AC induction generator was mounted directly to the engine flywheel.

The paper is structured into four main sections. The first section deals with the selection of electric drives for agricultural WSIC including harvester beaters and displacement of the mobile carriage, header height, and rotation of implement. The second section discusses a proposed control strategy suitable for agricultural WSIC. The third section involves a theoretical and experimental investigation to enhance the performance of a squirrel cage induction (SCI) machine for operating the agriculture WSIC. Discussion and research outcomes are included in the fourth section of the paper.

Selection of Electric Drives for Agricultural WSIC

The particular WSIC considered for this study was developed for cranberry production by Laguë et al. (1997). It is a versatile machine able to support and operate the equipment required to complete the pruning, fertilizing, weeding, and fruit harvesting field operations. The main components of the WSIC are a 61-m long bridge and two low profile tractors that provide support to the bridge at each end and ensure the mobility of the machine. A mobile carriage is mounted under the bridge to support and operate different field implements. The WSIC has two operating modes: stationary and mobile. In the stationary mode, the field operations are completed along the span of the bridge while both tractors are at rest. The mobile mode involves completion of the field operations in a direction perpendicular to the bridge. The full descriptions of the WSIC were reported by et al. Laguë et al. (1997).

The required power for the WSIC is 12.26 kW (Laguë et al, 1997) which can be supplied by a power take-off

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(PTO) generator. E Premium 7430/7530 series of John Deere can be alternatively used to provide up to 20 kW of required electric power. This power can be transferred from combustion engine to the generator which is either mechanically linked to the crankshaft directly or powered through a transmission. The four main power consumers for the implement part of the WSIC are an electric motor for adjusting the harvester height, an electric motor for adjusting the implement rotation by 180 degrees, and two other electric motors for rotation of the harvester beaters and carriage displacement along the WSIC truss (Figure 1).

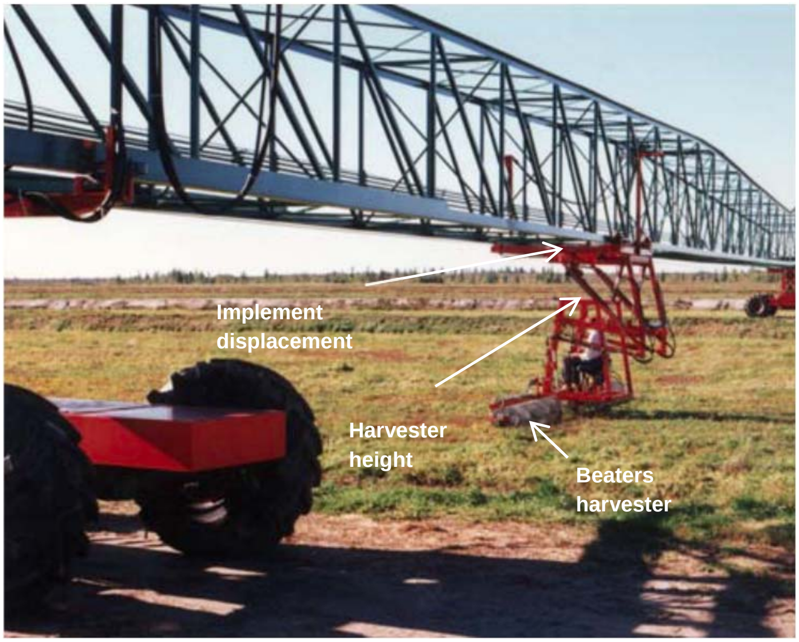

Figure 1. WSIC system for cranberry production (Laguë et al., 1997)

Harvester beaters and Displacement of the mobile carriage

Electric drives could be characterized using a variety of factors i.e. torque density, inverter size, extended speed range-ability, energy efficiency, safety and reliability, thermal cooling, and cost (Rahman and Ehsani., 1996). Zeraoulia et al, (2006) reviewed a comparative study on the performances of the four main electric propulsion systems for a parallel Hybrid Electric Vehicle (HEV). Potential candidates were DC, induction, Permanent Magnet (PM) synchronous, and switched reluctance. They found that the cage induction motor fulfilled better the major requirements of the HEV electric as a solution.

Multi-motor drives for crane application were investigated by Mitrovic et al, (2009). They found that induction motor drives with control concept, based on application of PLCs and industrial communication network could represent the standard solution which can be used in complex applications. Dordea et al, (2012) used an induction motor with a large number of poles to create various speed and torque. It can be concluded that induction motors that are rugged, reliable and economic could accommodate the torque control (current control) and they could be an ideal option for application on the harvester beaters, displacement of the mobile carriage and also automatic guidance systems of agricultural WSIC.

Header height

A linear motor is functionally the same as a rotary electric motor with the rotor and stator circular magnetic field components laid out in a straight line. Electric linear drives are used in a variety of applications across numerous industries, including agriculture machinery, high-voltage switch gears, train and bus doors, and medical machinery. Selection of an appropriate linear drive for header height depends on a variety of factors i.e. force (push, pull, vertical, and/or horizontal), the desired life time, and environmental factors (temperature variations, moisture, vibration, or end-product shock). Linear drives can be classified as single-sided or double sided, can have either of flat, cylindrical or transverse air gaps; can be of synchronous, induction or reluctance types (Salman, 2012). Permanent magnet offers solution to various industrial applications particularly when high dynamic performance is required. H2W Technologies Inc. introduced a high acceleration, permanent magnet with a closed loop positioning system for high force positioning applications of gantries and a linear induction motor for applications where accurate positioning is not required.

Rotation of the implement (180 degrees)

A stepper motor is particularly well suited to applications that require accurate positioning and repeatability with a fast response to starting, stopping, reversing and speed control. Another key feature of the stepper motor is its ability to hold the load steady once the required position is achieved. Stepper motors are controlled electronically and do not require costly feedback devices (Wang et al, 2012). Servo motors are capable of delivering more power than stepper motors, but do require much more complex drive circuitry and positional feedback for accurate positioning. Servo motors are also much more expensive than stepper motors and often require gear boxes, especially for lower speed operation. The requirement for a gearbox and position encoder make servo motor designs more mechanically complex and increase the maintenance requirements for the system. Selecting the best stepper motor for rotation of the implement depends on a few key design criteria including cost, positional accuracy requirements, torque requirements, drive power availability, and acceleration requirements (Burris, 2014). Based on above criteria, the stepping motor model 42K322S-CB8 from Anaheim Automation Inc. was chosen which can provide positional accuracy of the implement (180 degree), torque, and acceleration requirements of the implement.

Control strategies

Studies on productivity improvement in agriculture made possible through the automation of agricultural machines have been progressing rapidly in recent years. Automatic control of header height has been employed in combine harvesters as a means to reduce harvest losses, operator fatigue and the risks of equipment damage (Lopes et al., 2002). Forward speed is also a main variable that controls the feeding rate of combine harvester for high efficiency. The importance of the easiest controller implementation in order to achieve minimum overshooting and high position accuracy leads to the use of a proportional-integral-derivative (PID) controller (Koroneos et al., 2011).

PID controller

PID controllers are widely used in different industries for control of different plants and have a reasonable performance. It is widely used in the induction motor drive applications due to its simplicity in structure, superior robustness, and familiarity to most field operators. The key factor in designing PID controller for the induction motor drive is to settle the gains so that the controller works well in various conditions. Among many advantages, the PID controller can keep the speed of induction motor continuously at a desired set point value in the presence of disturbance or set point change. Chen et al. (2012) developed a control strategy based on optimum threshing power consumption model that was integrated into a speed control system for combine harvester automation. The forward speed was adjusted by an electric-hydraulic unit based on designed PID controller to achieve an optimum range of threshing power consumption. From obtained results, the controller could improve the efficiency of tested machine during field operation. An electrohydraulic automatic control of header height and the rotation of harvester of agricultural WSIC were designed using the closed loop PID control system (Mohsenimanesh et al, 2013). The simulation results showed good performance for positioning of cylinders with a very small error relative to the set point and also for hydraulic motor speed response with different predefined resistance load applied on the hydraulic motor. However, hydraulic systems have some drawbacks in comparison to electric which are mentioned earlier especially for directing power to remote parts of implements i.e. header height and the rotation of harvester of agricultural WSIC.

Agricultural WSIC electrification systems

The electrification systems consist of components for both tractors and implement (Figure 2). The first two electric components on the implement side (right) includes an induction electric motor with a closed loop torque control for rotation of the harvester beaters and an induction electric motor with a closed loop speed control for the mobile carriage movement (forward speed).

The other two components on the implement side include a PM electric motor with a closed loop positioning system for adjusting the harvester height, an electric stepper motor for rotation of the implement by 180 degrees. The electric components on the tractors side include a generator and its controllers, rectifier, inverters, and an appropriate power interface.

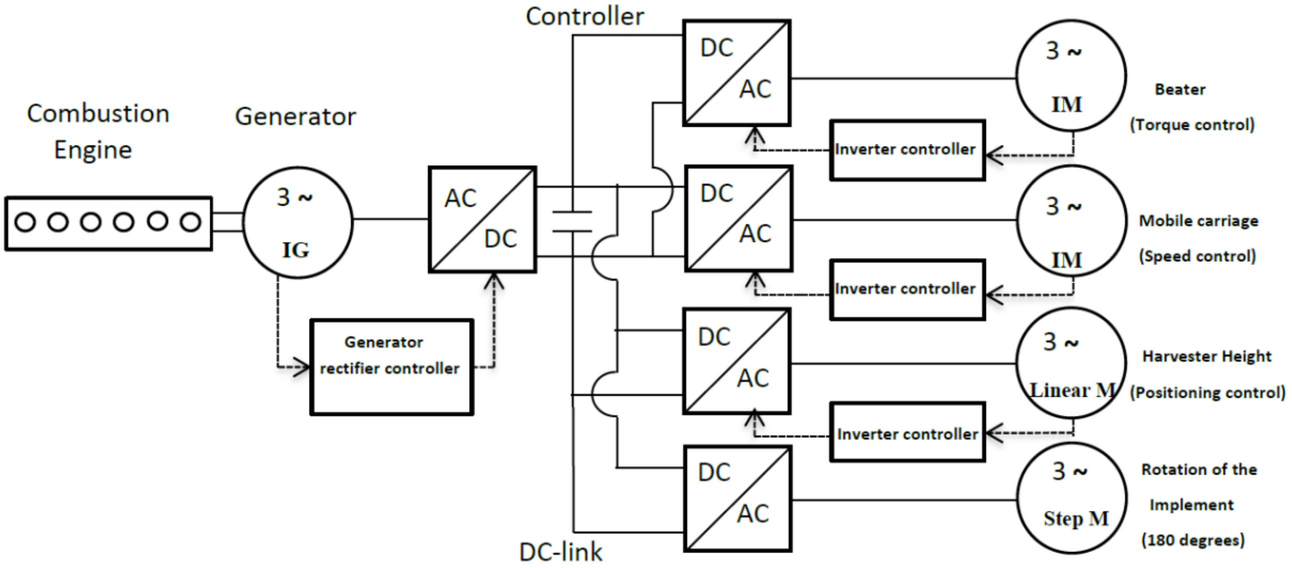

Figure 2. Schematic of an electric drive system (right) and generator (left) for the agricultural WSIC

Performance Enhancement of Induction Machine

Habash et al., (2012) reinforced with theoretical and experimental evaluation the effectiveness of employing an induction machine to enhance the performance of a small wind energy converter (SWEC). The above enhanced machine can be implemented for agricultural WSIC as well. To verify the performance of the induction machine, a model has been proposed, simulated, built, and experimentally tested over a range of operating conditions. The results demonstrate a significant increase in output power with an induction generator that employs an auxiliary winding, which is only magnetically coupled to the stator main winding. It is also shown that the operating performance of the induction machine with the novel proposed technique is significantly enhanced in terms of suppressed signal distortion and harmonics, severity of resistive losses and overheating, power factor, and preventing high inrush current at starting.

A passive technique is proposed to overcome most of the drawbacks noted above. The proposed technique makes use of an auxiliary winding connected in wye configuration (with capacitors) as shown in Figure 3.

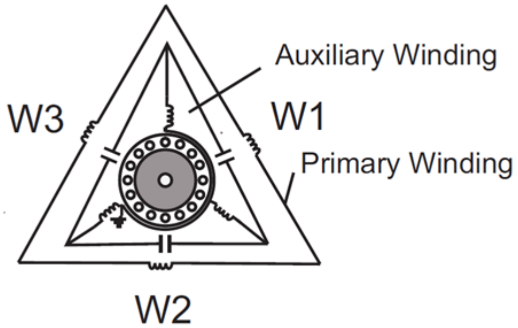

Figure 3. A three-phase generator with auxiliary winding

It is only magnetically coupled to the main winding. Therefore, the performance can be increased without any additional active mass. This method uses combined (two three-phase) windings on the stator similar to the scheme used in delta-star connected three-phase transformer (neglecting the rotor effect). The main stator winding is the primary connected in delta to the source and the auxiliary winding is the secondary in wye. It means that the third harmonics component would be short circuited by the delta side with the result that there will be no third harmonic voltage across the lines. In addition, the above two sets of windings have the same poles, so they share the same operating frequency. Basing on delta-wye transformation of the auxiliary windings and on transformer approach of the induction machine, the electric model per phase of the proposed strategy is shown in Figure 4.

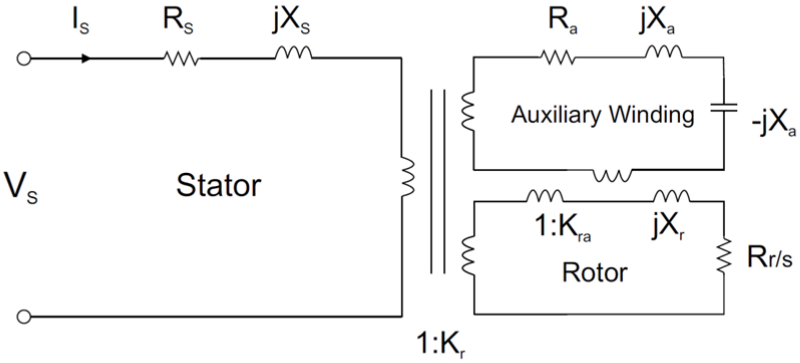

Figure 4. Model per phase of the proposed strategy

Since both the windings occupy the same slots and are therefore mutually coupled by their leakage flux, they can be modelled by two branches each having separate leakage reactance and resistance with a common mutual inductance. The effect of capacitor in auxiliary winding is represented by X_{ceq} for a 920 hp, 460V, 6 poles, and 60 Hz induction motor. Figure 5 shows the variation of imaginary part of the impedance (Z) with respect to X_{ceq} for different values of slip and also demonstrates that a unity power factor can be obtained at different values of the slip. It can be observed that for a particular slip, a unity power factor can be obtained at two different values of X_{ceq}. The larger value of $_{\mathrm{Xceq}}$ (smaller capacitance) corresponds to a small value of current and a smaller value of X_{ceq} (larger capacitance) corresponds to a higher current. It may also be concluded from Figure 5 that to obtain a unity power factor at higher load requires smaller value of X_{ceq} than that required for lighter load.

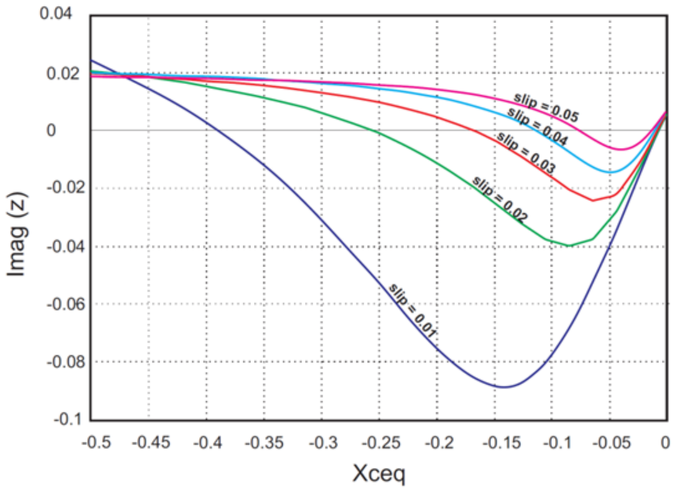

Figure. 5 Imaginary component of the impedance Z as a function of Xceq for various values of the slip

A typical experimental test was conducted to compare a standard SCIG (120 V, 1800 rpm) with the proposed one (standard SCIG with a passive auxiliary winding: Modified) (Figure 6). A DC motor is connected to the shaft of the two induction machines as a drive. By varying the load from 10% up to 125% of the full load, different values of input power, power factor, reactive power, and apparent power are respectively obtained. The experimental results recorded during the experimental tests are given in Table 1.

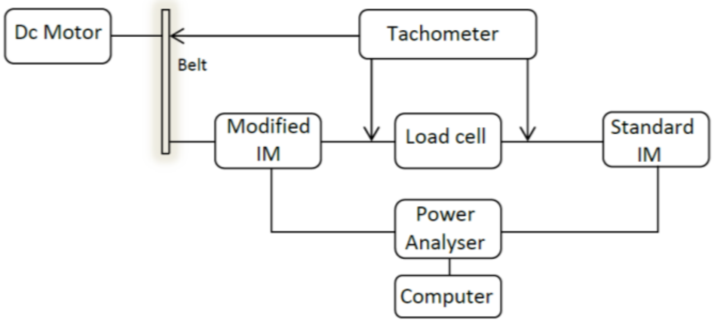

Figure 6. Measurement set up for testing the SCI machine performance

Table 1. Experimental Test Results of a Standard and Modified SCI machine

Quantity (unit)	Standard	Modified
Voltage (V)	117	117
Current (A)	2.69	0.43
Power (W)	43.2	43.7
Power factor	-0.13	-0.87
Reactive power (VAR)	-311	-24.1

Discussion and Concluding Remarks

The simplicity and flexibility exhibited by the induction machine in providing electromechanical energy conversion make it an alternative choice for agricultural machinery. In this paper, the performance of an off-the-shelf three-phase induction machine can be enhanced and implemented for various agricultural applications. To facilitate the design of such machine, simulation and experimental procedures are presented to predict the steady-state performance of a three-phase induction generator with its stator windings connected under various loading conditions at any power factor. A passive auxiliary winding connected in wye configuration and magnetically coupled to the main winding of the induction machine has been successfully designed and implemented. The excited induction machine uses capacitance and inductance to match the natural occurring impedance in the inductive elements of a machine–allowing the machine to sustain its own magnetic energy internally, virtually independent of the power source. Also, the machine reduces load current up to 30%. Because the utility does not need to supply the magnetization current in the modified induction machine, the full load current is reduced. By reducing peak demand current up to 25%, the net inrush current is reduced.

We may therefore summarize as follows:

1. The appropriate electrical components of agricultural WSIC were identified for both tractors and implement.
2. The performance of three-phase induction machine can be enhanced for possible implementation in various agricultural applications and in particular as a generator in a tractor energy converter to produce electricity to feed the implement power supply.

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