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Universal Restart Strategy for Scalar (V/f) Controlled Induction Machines

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***Abstract*—This paper presents a universal flying restart strategy for scalar (V/f) controlled induction machines. The proposed method performs a frequency search to estimate the rotor speed, and applies the correct frequency and voltage to minimize the inrush current during the restart. This method uses the measured phase current and the motor nameplate parameters, thus making the approach ideal for scalar-controlled motor drives. In addition, the restart algorithm provides controllable restart dynamics, independent of the motor parameters. The main advantages of this method include: (1) simple and cost effective implementation, without the need for additional sensors and (2) controllable restart dynamics, independent of the motor parameters. Beyond the development of the algorithm, we consider implementation issues to provide a general guideline for the application of the developed algorithm.**

***Index Terms*— Universal Flying Restart Method, Induction Motor, V/f Scalar Control.**

I. Introduction

In many industrial settings, momentary power disruptions commonly occur, resulting in tripping of large electric machines, which then have to be brought to standstill before the machine can be restarted. This approach can result in frequent interruptions in an industrial process, adversely affecting productivity. A more practical implementation would bring back the machine to the commanded speed as soon as power is restored, not having to wait for the machine to reach standstill. In industry, this concept is called speed search, bump-less start, flying restart, speed synchronization, etc. We refer to this concept as flying restart.

The goal of this work is to develop a universal flying restart method that is capable of restarting an induction machine driving a high inertia load such as a fan or a pump, when supplied from a scalar-controlled drive. The scalar *V/f* control is a simple and robust machine control approach, used widely in applications with limited dynamic performance requirements, where cost and simple commissioning are the main requirements.

A robust flying restart algorithm requires machine speed estimation [1-16]. Reference [1] uniformly reduces the synchronous speed and monitors the stator current. The controller considers the synchronous and rotor frequencies matched based on a stator current threshold defined by the user. This approach requires proper threshold selection: a low current setting can result in regeneration due to low speed estimate; similarly, a high current setting may cause a high speed estimate, resulting in overcurrent. References [2, 3] make use of a current controller to maintain a constant phase current during the rotor speed search; this approach requires tuning of the controller gains, which are a function of the machine parameters such as the inductance and the resistance. Therefore, restart methods suggested in [2, 3] cannot directly be used in the scalar control mode, where the machine inductance and resistance are not known or measured.

The approach presented in [4] uses the DC current sensor, which may not be present in an induction motor drive implementation, as it adds extra cost to the drive. In addition, the method in [4] requires the use of a PI controller, which requires tuning. The approach described in [5] finds the phase angle between the stator current vector and the stator voltage vector. This method is sensitive to the ratio of stator resistance and inductance, and thus requires stator resistance compensation to ensure precise speed estimation. The approach presented in [6-8] uses an observer and phase-locked loop (PLL) to estimate the magnitude and the rotating angle of the back-emf. Therefore, these methods require the PI regulator gain tuning for the observer and the PLL.

An alternate approach uses high frequency signal injection to determine the machine speed and position [9-13]. In general, sensorless vector control makes use of high frequency injection methods to estimate the rotor speed and position, even at zero speed. However, these methods require a demodulation process and an observer or a state filter, which increases the complexity of the restart algorithm. Self-commissioning [14, 15] is another method to determine machine parameters, but this approach is never used in conjunction with scalar control as it would obviate the commissioning simplicity, considered one of the main benefits of scalar control.

As evidenced by [1-15], many restart methods exist in the literature, and in practical drives. However, all of the proposed methods need some form of controller tuning, specific to the machine and drive application, and therefore are not well suited for use with scalar-controlled drives. This a major issue in the field, since an inexperienced technician may need technical support to make use of the state-of-the-art flyback restart algorithm. In [16], we have proposed a novel restart algorithm that does not require the measurement of machine parameters

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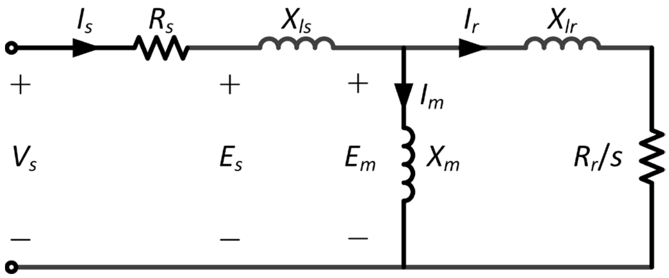
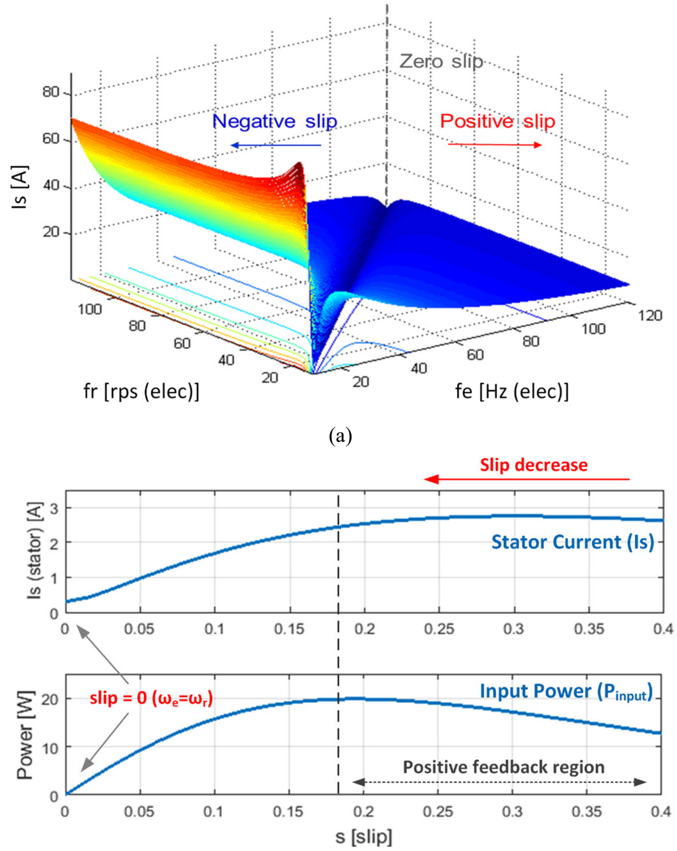


Fig. 2. The steady state equivalent circuit of induction motor.



(a)

(b)

Fig. 1. (a) Stator current corresponding to the stator frequency and the rotor speed; (b) input power corresponding to the slip.

or additional equipment such as DC current sensor, voltage sensor or speed sensor. In addition, the proposed restart method limits the stator current during the rotor speed estimation, does not need any additional tuning procedure, and it guarantees that the speed search time is independent of machine parameters. The resulting method is a universal restart algorithm for induction motors. In this work, we provide a more detailed review of the state-of-the-art, and the implementation of the proposed algorithm. Importantly, this work provides details on correctly determining universal restart algorithm gains, derived automatically from the parameters necessary to commission a scalar controlled drive.

II. Proposed Flying Restart Algorithm for Induction Machines

In developing the restart algorithm we have made the following assumptions: (1) during the outage, the drive loses power, but the controller has knowledge of the *V*/*f* ratio; (2) the controller recognizes the speed command prior to and after the fault; and (3) the controller monitors the input power (i.e. recognizes when power was lost and when power was restored). The following sub-sections describe the proposed restart method in detail.

A. Rotor Speed Search Using Input Power

The basic concept proposed herein is to excite the machine with a constant-voltage, variable-frequency signal, starting from rated frequency and reducing towards zero. When the frequencies of the applied stator voltage and the rotor speed match, the machine slip will be zero, drawing near-zero input power. Therefore, the rotor speed can be determined by simply measuring the input power. We calculate the input power by measuring the resulting machine currents. Looking at the induction machine equivalent circuit in Fig. 1, the input impedance and resulting current can be represented as:

$$\begin{cases} Z_s = R_s + jX_{ls} + \left[jX_m // \left(\dfrac{R_r}{s} + jX_{lr} \right) \right]; \\ I_s = I_m + I_r \end{cases} \tag{1}$$

where s denotes the slip, X_{ls} & X_{lr} are the leakage reactance of the stator and the rotor respectively, X_m is the mutual reactance and ϕ is the input power factor. The stator current (i.e. the input current) is the sum of the magnetizing current and the rotor current. When the slip becomes zero (s=0), the rotor current will be zero due to the infinite rotor impedance, which also corresponds to the minimum stator current.
shows that the stator current reaches a minimum when the electrical and mechanical frequencies are the same.

The input power will also reach its minimum at zero slip, as demonstrated in Fig. 2(b). The input power consists of the motor losses, the change of the electromagnetic stored energy and the mechanical output:

$$p_{input} = p_{loss} + p_{stored} + p_{mech} \tag{2}$$

At zero slip, the input power will be close to zero, since the mechanical power (P_{mech}) will be equal to zero, and the power loss (P_{loss}) and change of the stored energy (P_{stored}) are relatively small. Therefore, to find the zero slip, and therefore the rotor speed, the proposed algorithm needs to find the minimum input power, p_{input}:

$$p_{input} = \frac{3}{2} V_s I_s \cos\phi \tag{3}$$

Here, V_s and I_s are the magnitude of the phase voltage and the phase current respectively. I_s can be obtained by measuring two phase currents of stator and $I_s cos\phi$ is calculated by transforming currents to the stator voltage reference frame [17]:

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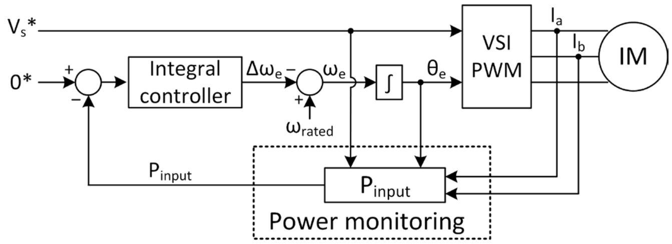

Fig. 4. Integrator controller method for rotor speed searching.

$$I_s \cos\phi = \frac{2}{3}\begin{bmatrix} i_{as}\cos\theta_e + i_{bs}\cos\left(\theta_e - \frac{2\pi}{3}\right) \\ -\left(i_{as}+i_{bs}\right)\cos\left(\theta_e + \frac{2\pi}{3}\right) \end{bmatrix} \tag{4}$$

where θ_e is the angle of the stator voltage vector in the stationary reference frame. The instantaneous input power is calculated using (3) and (4), where V_s is the magnitude of the stator voltage used during the rotor speed search.

As pointed out earlier, to identify the zero slip condition, and therefore the rotor speed, the proposed algorithm needs to find the zero input power. To achieve this, the proposed controller compares the measured input power in (3) to zero and changes the stator voltage frequency applied to the drive to minimize the error. The simplest controller that can drive a steady state error to zero is an integral controller. Fig. 3 shows the proposed approach. The stator frequency is initially set as the rated frequency, and the integral controller output is subtracted from the rated frequency. Thus, the stator frequency converges to the electric rotor speed.

The proposed integral controller approach, in Fig. 3, has a major drawback. Referring to the shape of the power curve shown in Fig. 2(b), as the slip reduces towards zero, the input power increases until it reaches a peak, before it starts reducing. As a result, there is a positive feedback in the system until the machine reaches the low slip region. Therefore, the convergence time and the stability of the controller is sensitive to the choice of the integrator gain, in that if the gain is chosen to be too small, the convergence time becomes very long. On the other hand, if the controller gain is very large, the controller may become unstable.

To avoid the issues associated with positive feedback, we enable the integral control only after the machine reaches the low slip region. Fig. 4 shows the results of a machine excited by a constant-magnitude stator voltage, and uniformly reducing synchronous frequency (i.e. stator frequency). From Fig. 4, it is apparent that after the input power perturbation, Δp_{input}, reaches zero, the input power has a negative feedback characteristic: as the difference between the stator frequency and the rotor frequency reduces, so does the input power. The negative feedback extends into the negative slip region: as the difference between the stator and rotor frequency becomes more negative, so does the input power.

Thus, the proposed method suggests that the integral controller only be used after the input power perturbation, Δp_{input}, reaches zero. Before the input power perturbation reaches zero, the stator frequency is reduced with a constant slope. With this approach, the instability issue of the integral controller is resolved.

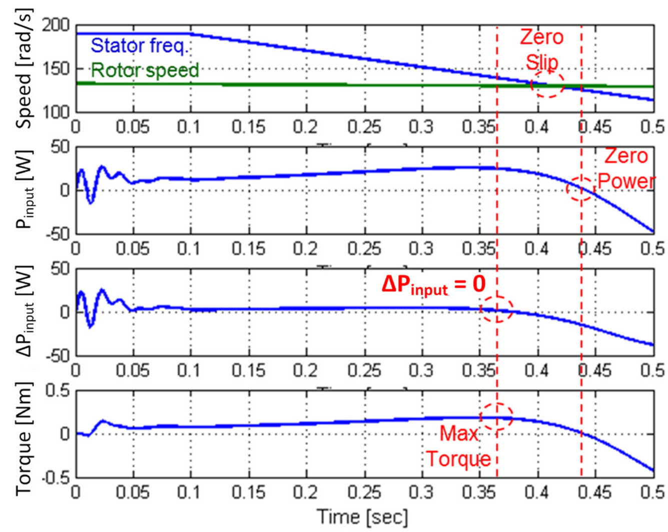

Fig. 3. Torque and input power at the zero input power perturbation.

We propose using a first-order high-pass filter [17] to determine when the input power derivative reaches zero:

$$\Delta p_{input} = \frac{s}{s + 1/\tau_h} p_{input} \tag{5}$$

where τ_h is the time constant of the high pass filter. The cutoff frequency of a high pass filter is set as 3Hz.

B. Determining Universal Restart Algorithm Gains

Based on the discussion above, the proposed approach is to excite the machine with a constant-voltage, variable-frequency signal, starting from rated frequency and reducing towards zero at a constant rate R, while monitoring the input power perturbation, Δp_{input}. When Δp_{input} reaches zero, we enable the integral controller with a gain I. Therefore, for this algorithm to be truly universal, the parameters R and I need to be defined.

First, we define the stator frequency sweep rate, R. Since the main application of the proposed universal restart strategy is to work with *V/f* controllers, which typically have slow dynamics, we adopt the same ramp rate specified for the *V/f* controller. The ramp rate, R, of the *V/f* controller is typically set by the user, and will be determined based on the application requirements, system inertia and machine size. Assuming that the *V/f* control operates as expected, the frequency search algorithm would not excite the machine poles in such a way to destabilize the system, much like accelerating from zero speed to rated speed using the ramp rate R will result in stable machine operation, without causing over-current.

Next, we define the integral controller gain. Once the input power perturbation is reaches zero, the input power, $P_{in,max}$, will be at its maximum. At this point, the controller will determine the integrator gain as $I=R\ /\ 10P_{in,max}$. This choice of the integrator gain ensures that the rate of change of frequency at the slip corresponding to $P_{in,max}$ is 10 times smaller than R. After this point, as the power input decays, resulting in the integrator error reducing. Therefore, the change in the synchronous

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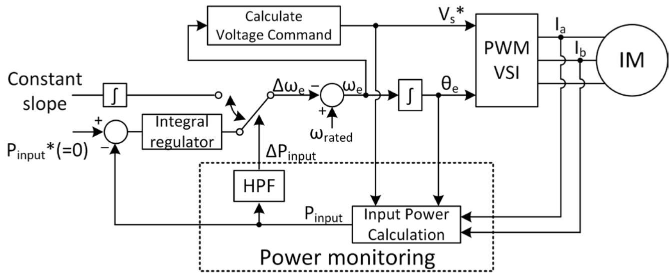

Fig. 6. Complete scheme for searching the rotor speed.

frequency will reduce as the rotor and stator speeds approach each other. This choice of the integrator gain ensures an overdamped response, thus minimizing stator speed oscillations during the search process. Since the $P_{in,max}$ occurs at a low slip for NEMA Class A machines, the use of this approach will not extend the search algorithm substantially.

It is also interesting to note that the zero slip and zero power points do not perfectly match. At zero slip, the input power primarily feeds the friction losses and core. However, the small error in the rotor frequency estimation will not affect the algorithm performance, due to the damping property of induction machines.

C. Implementation of Proposed Restart Method

A novel restart algorithm using the input power and the input power perturbation is proposed, which resolves the instability issue and the searching time issue of the integrator controller to identify the rotor speed. The procedure for searching the rotor speed is explained as following steps. Fig. 5 shows the proposed scheme for searching the rotor speed using the input power and the input power perturbation.

- Step 1 – The frequency of stator voltage is set as the rated frequency. The applied stator voltage is increased gradually from zero. The voltage increase is stopped when the stator current reaches 10% of the rated current, to ensure that the power is easily measured, while still limiting the losses and peak currents during the restart process.
- Step 2 – Stator frequency is reduced at a constant rate, *R,* while maintaining voltage magnitude determined in step 1.
- Step 3 – Input power perturbation is monitored (using a high pass filter) until the zero crossing point of the input power perturbation, $P_{in,max}$, is found.
- Step 4 – When the input power perturbation is zero, the stator frequency is adjusted by using the integral controller instead of using the constant slope. The controller gain is determined as $I=R\,/\,10P_{in,max}$.
- Step 5 – After the input power reaches the zero point corresponding to almost zero slip, the integral controller will make the stator frequency settle at the rotor speed. The settling time is required because an integral controller generally has the oscillation around the searched rotor speed.
- Step 6 – After fixing the stator frequency, increase the stator voltage up to the rated *v/f* ratio.
- Step 7 – If the stator voltage is increased up to the rated *V/f* ratio, increase both the stator frequency and the stator voltage together keeping the *V/f* ratio, to bring the machine back to the reference speed.

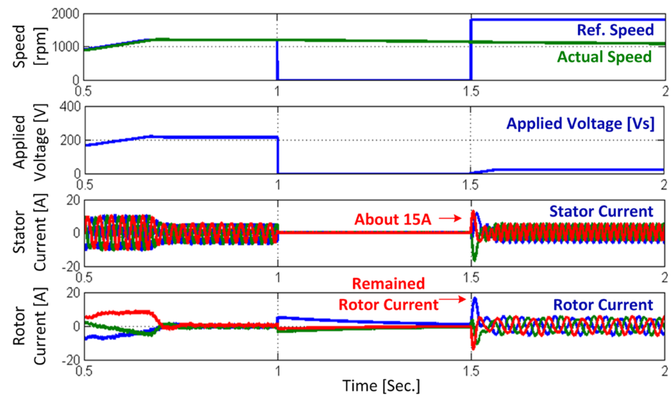

Fig. 5. Inrush current due to the residue magnetizing voltage.

III. Dealing with Residual Stator Voltage

Sometimes, the inverter power will be restored in shortly after the loss of power. When the speed searching is started, the induction motor can be still energized because the rotor current is not attenuated to zero. If the inverter switching is started in this condition, it can cause the stator inrush current. The magnitude of inrush current will depend on the motor parameters and the power interruption time. In this section we investigate this inrush current due to the residual magnetizing voltage.

After the loss of inverter power, the stator current is attenuated to zero in very short time due to the freewheeling through the anti-parallel diodes and the DC-link capacitor of the inverter. Thus, the residual magnetizing voltage is only generated by the rotor current. The rotor current seen from the stator side will be defined as:

$$i_r = I_r \cos\left(\omega_r t + \theta_0\right) \tag{6}$$

The frequency of rotor current seen from the stator side will be approximately similar to the electric rotor speed (ω_r). θ_0 is the arbitrary initial rotor current angle when applying the stator voltage. The residual magnetizing voltage (E_m) in Fig. 1 can be expressed again as:

$$E_m = L_m \frac{di_r}{dt} = -\omega_r L_m I_r \sin\left(\omega_r t + \theta_0\right) \tag{7}$$

After the inverter power is restored in shortly, the zero stator voltage will be applied for the rotor speed searching. The stator inrush current can be calculated with the following equation.

$$0 = R_s i_s + L_{ls} \frac{di_s}{dt} + E_m \tag{8}$$

The equation of (8) can be solved using the Laplace transform as:

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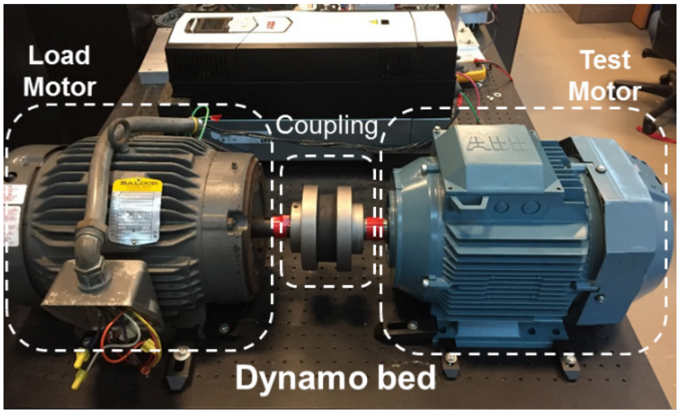


Fig. 7. Dynamo set configuration.

TABLE I. TEST MOTOR PARAMETERS

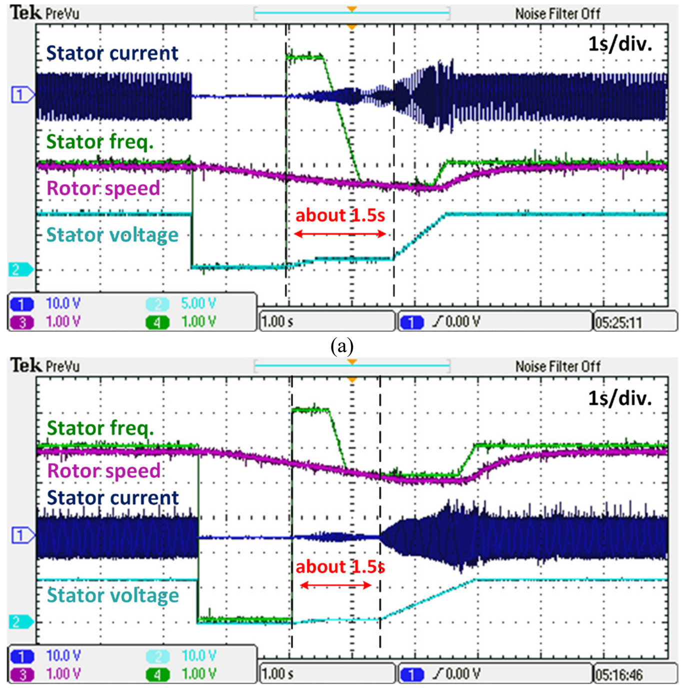
Parameter	Unit	Symbol	Values
Rated Power	[kW]	P_{out}	7.5
Rated Speed	[rpm]	N_r	1745
Rated Torque	[Nm]	T_e	47
Rated Voltage (line-line)	[V]	V_s	220/440
Phase Current (rms)	[A]	i_s	30.8/15.4
Pole	-	n	4
Stator Resistance	[Ω]	R_s	0.61
Rotor Resistance	[Ω]	R_r	0.54
Mutual Leakage Inductance	[mH]	L_m	151.90
Stator Leakage Inductance	[mH]	L_{ls}	3.97
Rotor Leakage Inductance	[mH]	L_{lr}	5.82
Inertia	[Nm/rad·s^{-2}]	J	0.05
Inverter DC Link Voltage	[V]	V_{dc}	500
PWM Switching Freq.	[kHz]	f_{sw}	5
Current Sampling Time	[µs]	t_s	200

$$i_s(t) = -\frac{E_m}{R_s}\left(1 - e^{-\frac{R_s}{L_{ls}}t}\right) \tag{9}$$

In here, the inrush current is generated in the very short time, and it is mostly determined by the stator leakage inductance as:

$$\frac{\Delta i_s(t)}{\Delta t} = -\frac{E_m}{L_{ls}} \tag{10}$$

In general, the leakage inductance value of the induction motor is very small. Sometimes, the huge inrush current can be occurred depending on the motor parameters. Therefore, the restart method will need the inrush current protection logic. When the overcurrent is measured at the beginning of speed searching, the inverter will automatically stop and have some waiting time. It will take about several rotor time constant (L_r/R_r) for the rotor flux to be almost zero after the stator current becomes zero. Typically, 10kW to 100kW induction motors take several hundreds of milliseconds or even few seconds for the rotor flux to disappear, respectively [2, 18]. Fig. 6 shows the simulation result that a stator inrush current is generated by the remained rotor current at the restart instant. When the speed searching is started, the stator voltage frequency is set the rated frequency (60Hz) and the voltage magnitude is increased gradually from 0V.



(b)

Fig. 8. The experimental results using constant slope and integral control for rotor speed searching (a) 900 rpm (b) 1,500 rpm; CH1: the stator current (1A/1V), CH2: the magnitude of the stator voltage (10V/1V), CH3: the actual rotor speed (300rpm/1V), CH4: the stator voltage frequency (10Hz/1V).

IV. EXPERIMENTAL RESULTS

A set of experiments validate the performance of the proposed restart method. As shown in Fig. 7, the dynamo test bed consists of an induction motor acting as test motor and another induction motor acting as the load. The parameters for test motor are listed TABLE I. The V/f control and the proposed restart method are implemented using the OPAL-RT. For the proposed restart control, only two phase-current sensors of the inverter are used. The load motor connects to a commercial voltage source inverter (VSI), which is capable of measuring its produced torque and the speed of the coupled machines. Fig. 8 shows the test results of the complete restart algorithm. First, the motor is rotating at the reference speed. Then, the inverter stops feeding induction motor for 1.5 seconds. During this time, the motor speed reduces as a function of system load and inertia. After 1.5 seconds, the speed search algorithm starts. The stator voltage frequency is set to the rated frequency (60Hz) and the voltage magnitude increases gradually from zero while monitoring the stator current. Next, the stator voltage frequency reduces at a constant rate (R=60Hz/sec) until the power perturbation reaches zero, at which point the integral controller operates. During the transition, the input power, $P_{in,max}$, was measured to be 50W, and the controller gain I was then calculated using $I= R\ /\ 10P_{in,max}$ to be 0.12. Once the stator voltage frequency approaches the rotor speed, the rotor speed is determined, and the magnitude of the stator voltage increases gradually to meet the rated V/f ratio. The stator voltage

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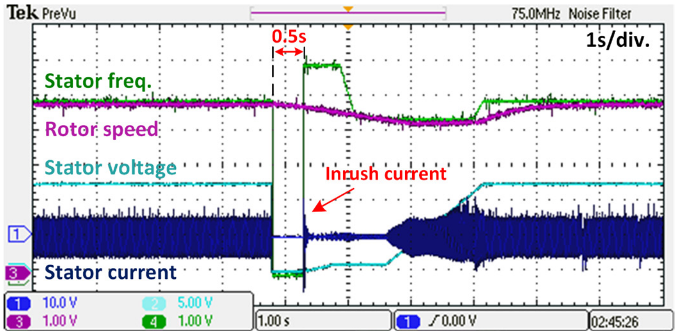
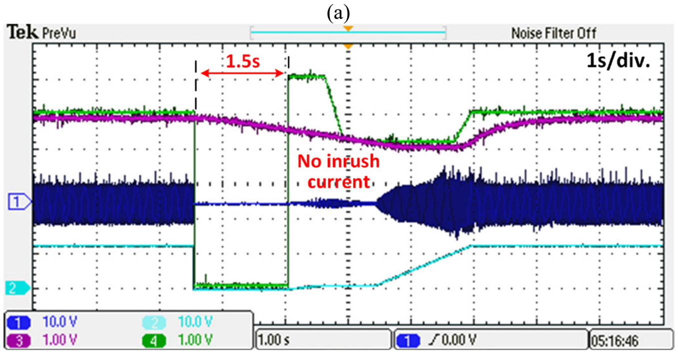


(a)



(b)

Fig. 9. The experimental test results for the residual stator voltage (a) 0.5 seconds (b) 1.5 seconds; CH1: the stator current (1A/1V), CH2: the stator voltage (10V/1V), CH3: the actual rotor speed (300rpm/1V), CH4: the stator voltage frequency (10Hz/1V).

frequency will go back to the former reference speed while maintaining the *V*/*f* ratio. Test results verify that the proposed approach does not result in any inrush current. In addition, the estimated speed (green line) matches the actual speed (purple line), soon after the integral controller is enabled. As the machine speed decays due to the machine loading, the algorithm correctly estimates the changing speed until the *V*/*f* control restarts.

Figure 9 shows the effect of the residual stator voltage. The inverter feeding the induction motor is stopped by intentionally for 0.5 seconds and 1.5 seconds. In Fig. 10(a), there is the inrush current due to the residual stator voltage. As mentioned before, when the overcurrent is measured at the beginning of the speed searching, the inverter will automatically stop and spend the additional waiting time. It will be determined by the inverter rating or the motor rating power. In general, the nameplate gives the rating power of the machines. The delay of several hundred of milliseconds is used for 10kW and the delay of few seconds is used for 100 kW induction machines. Fig. 10(b) shows the test result when the inverter is stopped for 1.5 seconds. There is no inrush current because it is passed enough time for rotor current to be zero.

V. Conclusion

This paper described a universal flying restart algorithm for induction motors. Experiments were conducted to validate the performance of the proposed method. The goal of proposed restart method was to develop the universal algorithm for induction motors. First, the proposed method uses only motor parameters available from the nameplate. In general, the nameplate includes the machine rating information such as the power, the current, the speed and the voltage. Second, this method does not require any tuning and the rotor speed searching time will be almost constant for any machine. In addition, the proposed restart method is designed to be less sensitive to the motor parameters and other conditions (such as rotor speed, input power and so on) as monitoring the input power perturbation as well as the input power. Finally, this restart method does not require the additional hardware such the speed sensors, phase voltage sensors, DC-link current sensor which are not installed in commercial inverters.

In addition, this paper investigates the inrush current due to the residual magnetizing voltage, and suggests the logic when the overcurrent is measured at the beginning of the flying restart algorithm.

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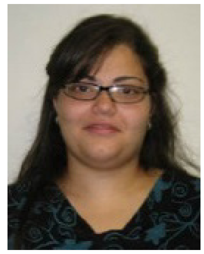

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