Switching Transients of Low Cost Two Speed Drive for Single-Phase Induction Machine

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Abstract- Heating, ventilating, air conditioning & refrigeration (HVAC&R) systems represent one of the largest potential applications for Adjustable Speed Drives (ASD's). The focus of this work is to sudy the switching performance of a new alternative circuit topology. The drive is specifically aimed at applications that do not require continuous speed control and enables the machine to efficiently operate at two different speeds. The drive consists of front-end diode bridge followed by an inverter with four MOSFET or IGBT switches. A computer model is developed for the proposed adjustable speed induction motor. The simulation results of the currents, voltages, speed and torque are illustrated to show the dynamic performance and transient response of this adjustable speed induction motor during switching insants.

I. Introduction

The purpose of this study is the switching behavior of a new low-cost drive setup utilizing a single-phase induction machine with speed control capability suitable for relatively broad range of HVAC applications [3]. The drive operates basically at two different fixed speeds full or half speed. The drive consists of a front-end rectifier followed by a one-phase inverter with four MOSFET or IGBT switches. The drive is designed to operate either at full speed with a supply frequency of 60 Hz or at half speed with a supply frequency of 30 Hz. In the former case, the main winding of the motor is supplied with the sinusoidal voltage directly from the mains. In this case, the single phase PWM inverter generates a voltage waveform with suitable magnitude and phase shift in relation to the mains for the auxiliary winding [3].

During reduced speed operation both windings are fed from the 30Hz voltage source supplied by the inverter. The phase shift between the currents in the main and auxiliary windings is then achieved by the connection of an AC capacitor in series with the auxiliary winding. The main advantage of the proposed setup is that the power rating of the inverter can be lower in comparison to a classic adjustable-speed drive inverter for a single-phase induction machine. Matlab/Simulink software used to simulate the system model. In order to study switching behavior a suitable model of unsymmetrical single-phase induction motor (USPIM) driven by a single phase inverter has been developed.

II. Induction Machine Equations

A 2-Phase induction motor with identical rotor windings and nonsymmetrical stator windings is commonly considered as unsymmetrical 2-phase induction machine. The theory of operation of unsymmetrical 2-phase induction machine is applicable to a wide variety of single-phase induction machines [4]. In the analysis of this type of machine, it is generally assumed that:

1) Each stator winding is distributed to produce a sinusoidal mmf wave in space,
2) The rotor coils or bars are arranged so that, for any fixed time, the rotor mmf waves can be considered as space sinusoids having the same number of poles as the corresponding stator mmf wave,
3) The air gap is uniform,
4) The magnetic circuit is linear.

The equations which describe the transient and steady-state performance of an unsymmetrical 2-phase machine can be established by considering the elementary 2-pole machine shown in Figure 1.

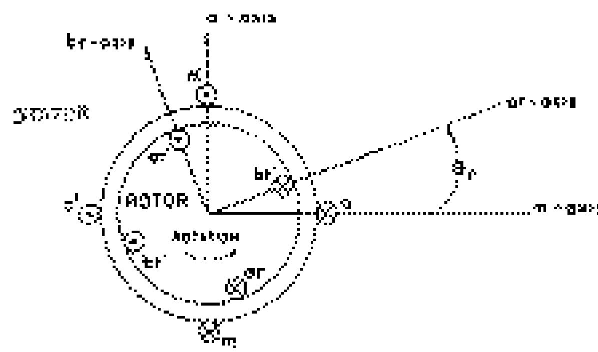

Figure 1. Unsymmetrical 2-Phase Induction Motor

In the case of a single-phase machine, the a-phase represents the main winding and the b-phase the auxiliary winding. The mechanical rotor position and speed are denoted θ_r, and ω_r, respectively. The positive direction for the shift angle θ_r turns in the opposite direction of rotation of the rotor. In Figure 1 the sign ( ) represents an imaginary winding coming out of the topology, and (**x**) represents an imaginary winding going into the topology. The *m* and *ar* -axes are displaced by θ_r degrees .

Since it is assumed that each winding is distributed in such a way that it will produce a sinusoidal mmf wave, it is convenient to portray each winding as an equivalent single coil, Figure 2. The equivalent stator winding and rotor winding in Figure 2 are the auxiliary (*a*) and main windings (*m*) respectively of a single-phase induction motor.

Figure 2. Equivalent Stator and Rotor Windings

The stator windings are unsymmetrical; the windings have an unequal resistance and an unequal number of turns. The resistance and the effective number of turns of the (m) winding are denoted as r_{1m} and N_m, respectively. In the case of the (a) winding, r_{1a} and N_a denote that the windings are in quadrature and are identical; that is, the windings have an identical number of effective turns N_2, and identical resistance r_{22} [1].

Stator Voltages

$$v_m = p\lambda_m + i_m r_{1m} \quad (1)$$

$$v_a = p\lambda_a + i_a r_{1a} \quad (2)$$

Rotor Voltages

$$v_{ar} = p\lambda_{ar} + i_{ar} r_{22} \quad (3)$$

(4)

where λ is the total flux linkages of a particular winding and p is the operator $\frac{d}{dt}$.

In the case of a symmetrical machine, time-varying coefficients appear in the voltage equations. Because of the variation of the mutual inductances with respect to displacement θ_r, these coefficients can be eliminated by transforming the voltages and currents of both the stator and the rotor to a common reference frame. In the case of an unsymmetrical 2-phase induction machine, it is convenient to select a reference frame fixed in the stator. The derivation of the transformed equations to this new reference frame, the *d-q* transformation, can be found in [1].

Development of Induction Machine Equivalent Circuits

In the development of the induction machine equivalent circuits, it is customary to refer all quantities to the stator windings. If the machine is symmetrical, the quantities can be referred to either stator winding by the same turns ratio. In the case of the unsymmetrical 2-phase machine, however, the stator windings do not have the same number of effective turns. Although in some instances it may be desirable to refer all quantities to one of the stator windings, in this development, the q quantities will be considered as the m winding and the d quantities will be considered as the a winding. All the q quantities are then referred to the m winding (N_m effective turns) and all d quantities referred to the a winding (N_a effective turns). The voltage-equations can then be expressed as the new reference frame voltage equations:

(5)

$$v_{qr}' = 0 = p\lambda_{qr}' - \frac{N_m}{N_a}\lambda_{dr}' p\theta_r + r_{2m} i_{qr}'$$

$$v_{dr}' = 0 = p\lambda_{dr}' + \frac{N_a}{N_m}\lambda_{qr}' p\theta_r + r_{2a} i_{dr}' \quad (6)$$

where

$$\lambda_{qs} = L_{1m} i_{qs} + L_{Mm}\left(i_{qs} + i_{qr}'\right) \quad (7)$$

$$\lambda_{ds} = L_{1a} i_{ds} + L_{Ma}\left(i_{ds} + i_{dr}'\right) \quad (8)$$

$$\lambda'_{qr} = L_{2m} i_{qr}' + L_{Mm}\left(i_{qs} + i_{qr}'\right) \quad (9)$$

$$\lambda_{dr}' = L_{2a} i_{dr}' + L_{Ma}\left(i_{ds} + i_{dr}'\right) \quad (10)$$

in which

$$L_{Mm} = \frac{N_m}{N_2} M_{m2} \quad (11)$$

$$L_{Ma} = \frac{N_a}{N_2} M_{a2} \quad (12)$$

where L_{1m} is the leakage inductance of the m winding and L_{1a} is the leakage inductance of the a winding. The quantities M_{m2} and M_{a2} are the main winding/rotor winding and auxiliary winding/rotor winding mutual inductances respectively.

The equivalent circuit of the unsymmetrical induction motor in the new transformed frame is given in Figure 3.

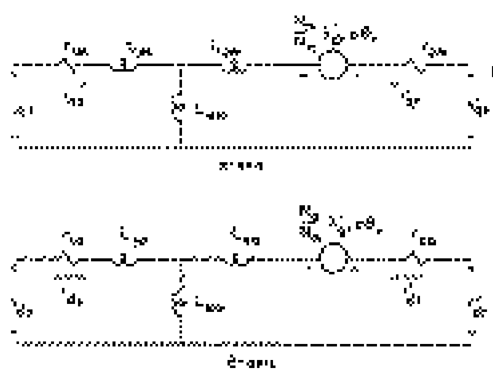

Figure 3. d-q Equivalent Circuit of Unsymmetrical 2-Phase Induction Machine

Computer Representation of an Unsymmetrical 2-Phase Induction Machine

The computer equations that can be used to simulate the unsymmetrical machine are given by:

(13)

(14)

(15)

(16)

where:

(17)

(18)

.

where ω_e is the base electrical angular velocity corresponding to rated frequency. If (5) through (10) are solved for the flux then , are obtained as:

(19)

(20)

(21)

(22)

where:

(24)

(25)

in which:

(26)

(27)

In these equations, ω_r is the rotor speed in electrical radians per second

Although the currents can also be eliminated from the torque expression, it is generally desirable to observe the four currents. Therefore, it is convenient to obtain the instantaneous torque by using

(28)

where P is the number of poles.

The following equation is used to obtain the capacitor –run voltage,

(32)

III. ADJUSTABLE SPEED DRIVE

Figure 4 shows the proposed reduced cost adjustable speed drive with the unsymmetrical single-phase induction motor. The figure consists of a full bridge inverter fed PWM with four MOSFET or IGBT switches. A large capacitor is used to filter out voltage ripple. The PWM has a control signal $v_{control}$ (constant or slowly varying in time) that is compared with triangular waveform, to generate the switching signals [2].

This adjustable speed motor is designed to operate either at full speed with a supply frequency of 60 Hz or at half speed with a supply frequency of 30 Hz. In the former case, the main winding of the motor is supplied with the sinusoidal voltage directly from the AC source. In this case, the single-phase PWM inverter generates a voltage waveform with suitable magnitude and phase shift in relation to the mains for the auxiliary winding. During reduced speed operation both windings are fed from the inverter. The phase shift between the currents in the main and auxiliary windings is then achieved by the connection of an AC capacitor in series with the auxiliary winding.

The main advantage of the proposed setup is that the power rating of the inverter can be lower in comparison to a classic adjustable-speed drive inverter for a single-phase induction machine. The inverter supplies only the auxiliary winding during full-speed operation and both windings in half-speed operation. This can result in smaller size of the drive and, therefore, in lower manufacturing costs of the drive as well. Another important feature of this drive is the fact that it could continue to operate in the event of a failure of the semiconductor portion of the inverter. The motor would be, in such a case, supplied directly from the mains with the AC capacitor connected in series with the auxiliary winding.

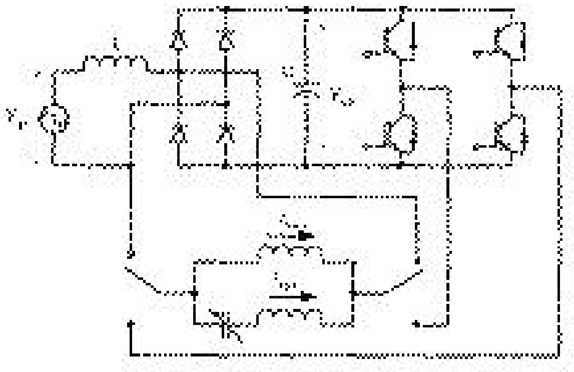

Figure 4. Induction Motor Drive Topology

The controller shown in Figure 5 controls the level of the full-bridge output voltage. The function of the controller is to minimize the drop in speed of the USPIM when switching from a AC source input to a PWM scheme. The equations for this controller are derived as follows:

The sinusoidal input voltage is defined as:

(29)

where: $\sqrt{}$.

The source inductance is defined as L where:

$L = \frac{1}{5} L_s$ where L_s is the stator inductance:

Hence,s the rectifier dc current i_1 will be:

$i_1 = \frac{1}{L} (V_{ac} - V_{dc})dt$, when $V_{ac} > V_{dc}$ or $i_1 > 0$. (30)

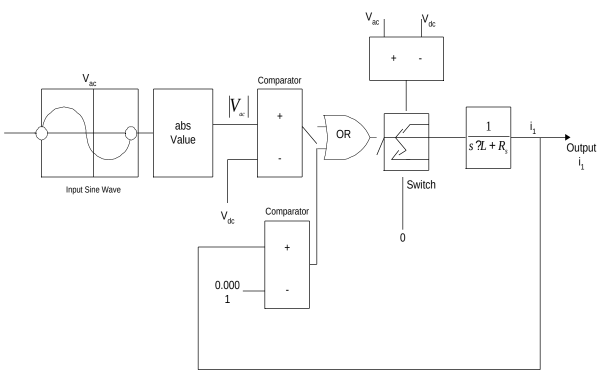

Figure 5. Controller Simulating Rectified Voltage V_{dc}

When the rectifier bridge is operational the voltage across the capacitor V_{dc}, is calculated as follows:

— (31)

where C is the link filter capacitance and is the inverter current created by the PWM.

IV. Simulation Results

The following figures are simulation results for the proposed adjustable speed drive as the input source changes from an AC voltage input to a PWM voltage input. The simulation parameters based on the _ hp motor are described by the following measured parameters [3].

Table 1
_ hp Machine Parameters

Main Winding (m-winding)	**Auxiliary winding (a-winding)**	**AC Capacitor**
r_{1m} = 8.69 Ω	r_{1a} = 7.14 Ω	R_1 = 0.67 Ω
L_{Mm}=366 µh	L_{Mm} = 137.982	C_1 = 4.833µf
L_{1m}=32.8 mh	L_{1a} = 31.0174	**Link Capacitor**
N_a/N_m = 1.36	r_{2a} = 5.74 Ω	C=500µf

Three transient condition have been investigated in this study: 1) the changeover from the 60 Hz supply to 30 Hz after accelerating from zero speed on the 60 Hz supply, 2) the changeover which occurs when the drive switches from the 30 Hz PWM supply to 60 Hz in order to accelerated to full speed., 3) the transient which occurs when a command is given to reduce the speed from full speed (60 Hz source) to half speed.

The transient conditions which occur when the motor is suddenly switched from the 60 Hz supply to a 30 Hz PWM frequency is illustrated in Figs. 6 to 9. It can be noted that the transients under this condition are minimal indicating that this condition is not a serious problem

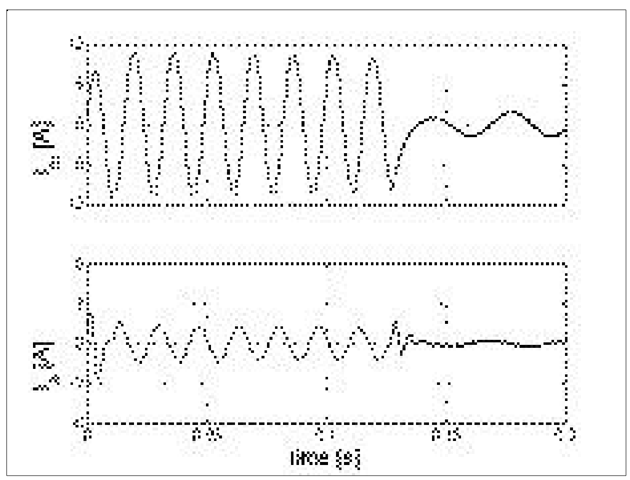

Figure 6. Currents i_m and i_a for _ hp Machine for Switchover from 60 Hz Supply to 30 Hz PWM Inverter Supply.

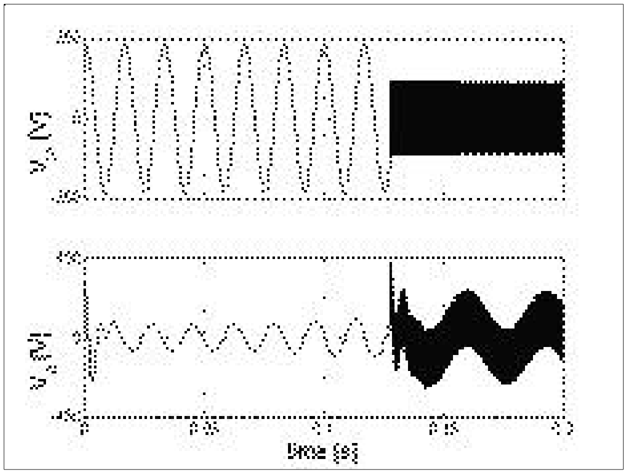

Figure 7. Main and Auxiliary Winding Voltages for _ hp Machine with Switchover from Line to Inverter Supply

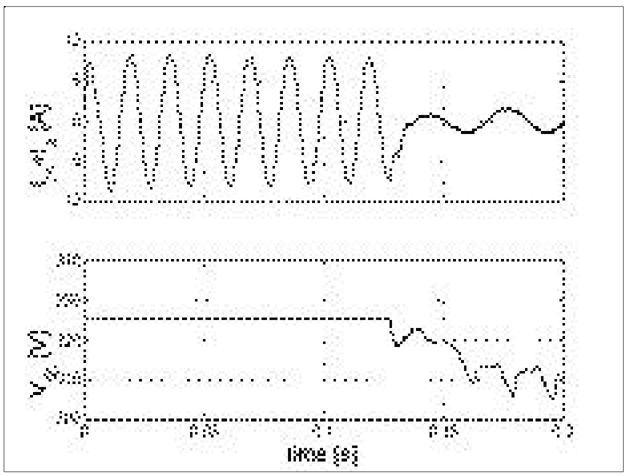

Figure 8. Total Motor Current and DC Link Voltage Transient with Switchover from Line to Inverter Supply at Half Speed

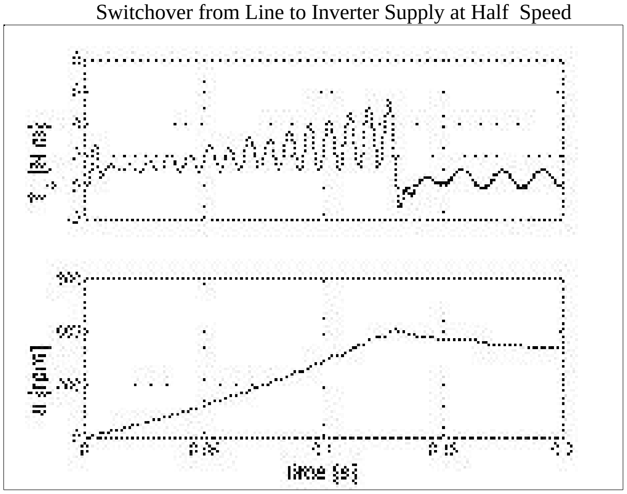

Figure 9. Torque and Speed Transients for Changeover from Line to Inverter Supply at Half Speed

Figures 10 to 14 illustrate the transients which occur when a request is made for full speed operation when the drive is operating with a 30 Hz inverter supply. In this case the switchover is from a 30 Hz PWM inverter to a 60 Hz sine wave. In this a more serious transient is noted and the current peak suddenly triples. However, since this current flows in the ac supply rather than the PWM inverter it is again not of concern.

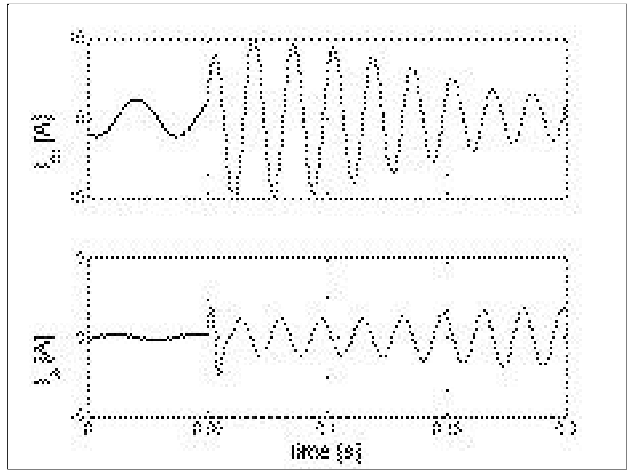

Figure 10. Currents i_m and i_a for _ hp Machine for Switchover from 30 Hz PWM Supply to 60 Hz AC Supply

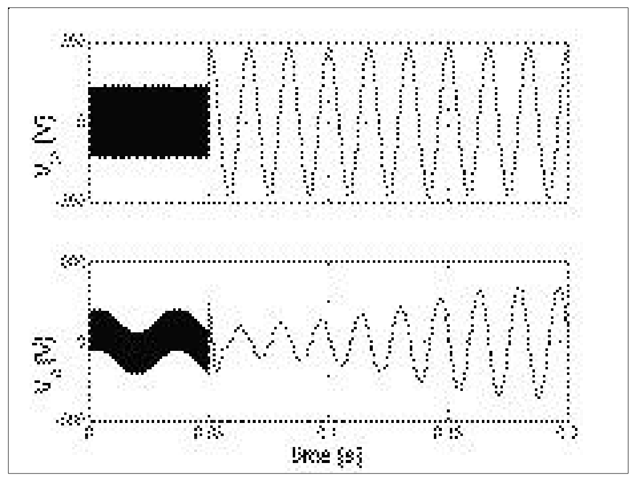

Figure 11. Main and Auxiliary Winding Voltages for _ hp Machine with Switchover from inverter to AC Supply at Half Speed

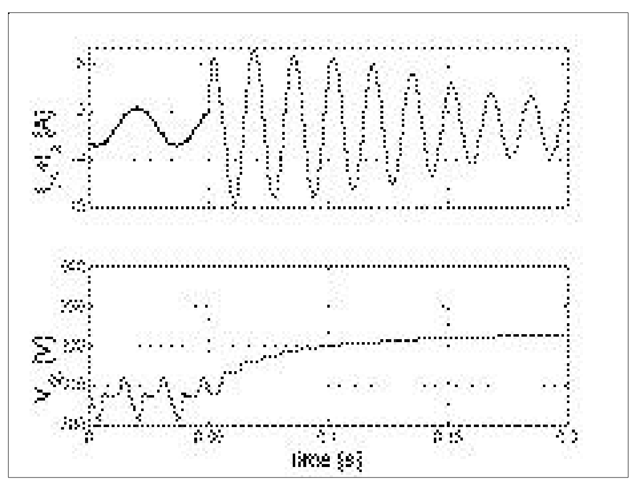

Figure 12. Total Motor Current and DC Link Voltage Transient with Switchover from Inverter to Utility Supply at Half Speed

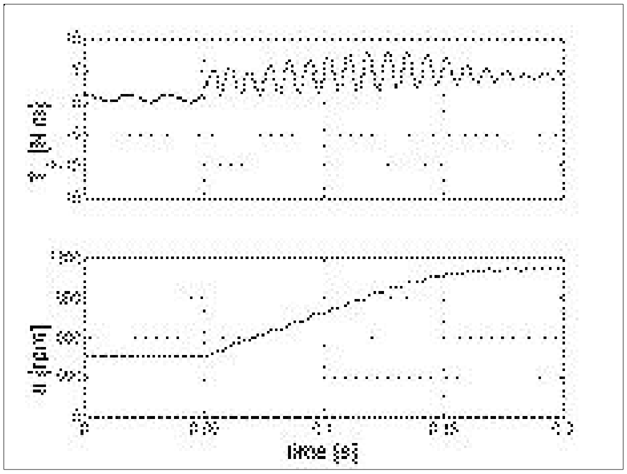

Figure 13. Torque and Speed Transients for Changeover from PWM Inverter to Line Supply at Half Speed

In Figures 14 to 17 the case in which the drive operates at 60 Hz and a command to reduce the speed to 30 Hz is issued. In this case the initial speed is full rather than half speed.

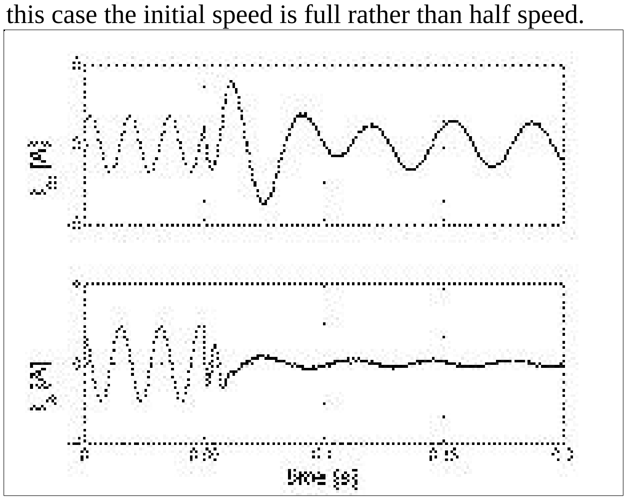

Figure 14. Currents i_m and i_a for _ hp Machine for Switchover from 60 Hz Supply to 30 Hz PWM Inverter Supply at Full Speed

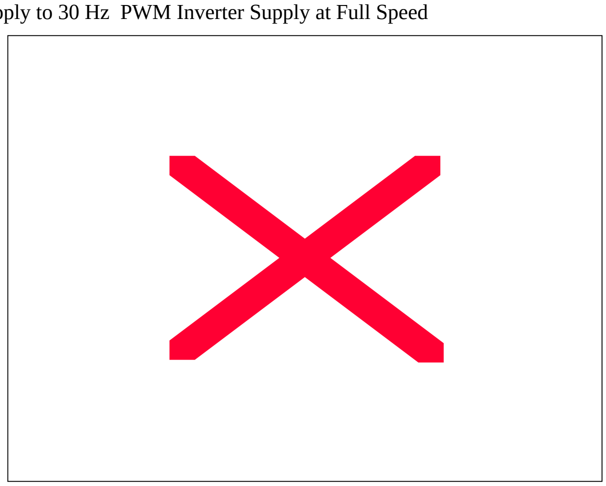

Figure 15. Main and Auxiliary Winding Voltages for _ hp Machine with Switchover from Line to Inverter Supply at Full Speed

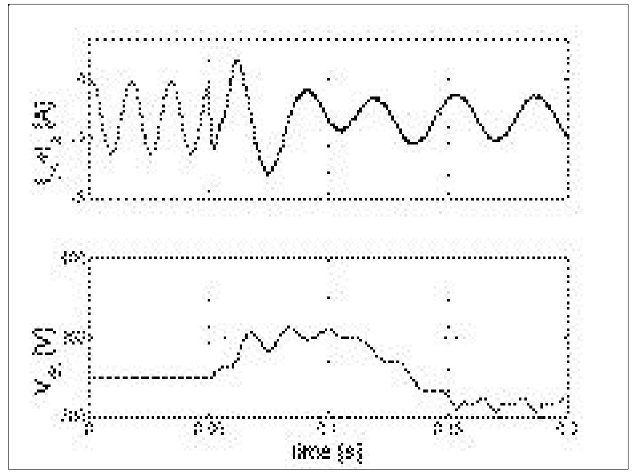

Figure 16. Total Motor Current and DC Link Voltage Transient with Switchover from Line to 30 Hz Inverter Supply at Full Speed

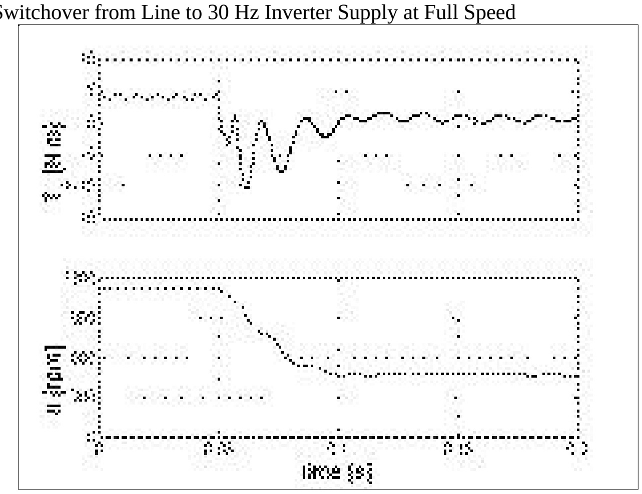

Figure 17. Torque and Speed Transients for Changeover from Line to Inverter Supply at Full Speed

It can be noted that the current transient is considerably more severe for this case than for the switchover at 30 Hz (Figs. 7-10). A peak inverter current of roughly 150% of the peak steady state load current is encountered. It is interesting to note that this peak transient did not vary appreciably with closing under various phase angle relationships of the AC source and PWM voltages. Hence, it was established that only a modest current margin (200%) is needed to ensure safe operation of the drive under all scheduled switching events. Also it can be noted that since the drive begins to regenerate under this considion, the dc link voltage rises above the value set by the line side diode bridge. However, it is apparent that this transient is very modest and should not impact the voltage rating of the inverter switches.

V. Conclusions

The purpose of this study is to evaluate the transient performance of a new low cost dive setup unitizing a single-phase induction motor with speed control capability suitable for relatively broad range of HVAC applications in which discrete speeds are utilized. In particular, the proposed method is designed to operate either at full speed with a supply frequency of 60Hz or at half speed with a supply frequency of 30Hz. A computer model has been developed to study the proposed adjustable speed induction motor drive. Simulation traces of the currents, voltages, speed, and torque illustrate that the switching transients of this new discrete speed drive are not severe and will not significantly impact the voltage and current rating of the inverter switches.

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