SURVEY OF CONVENTIONAL &NEW GENERATION ADVANCED D.C.BRAKING SYSTEM OF 3-PHASE SQUIRREL CAGE INDUCTION MOTOR WITH VFD

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ABSTRACT

Any variable frequency drive requires an efficient and controlled braking system. Therefore, different braking techniques have been the subject area of researchers to enhance the performance as well as overall life of the drives. In this paper, a literature study is made of various existing braking methods, focused on induction motor (IM) drive performance. The braking methods are compared and summarized based on speed range, braking time and efficiency of 3-phase squirrel cage IM drive. Finally, an advancedD.C. braking technique is presented where braking torque in terms of varyingD.C.signal is injected into the stator windings using fully controlled Space Vector Pulse Width Modulation pulses (SVPWM). A method has been described for providing occasional fast, smooth and controlled braking torque from a non-regenerative VFD, without additional power circuits. Simulations are performed in MATLAB/Simulink, tested and validated on Digital signal processor (DSP) based drive. Test results are presented in this paper.

KEYWORDS

3-Phase Induction Motor, Braking, Conventional, AC Drive, VFD, MATLAB/Simulink, DSP.

1. INTRODUCTION

Three-phase induction motor drives are extensively used in different sectors of drives industry, but it is a challenge to stop them in short period of timeespecially for high inertia loads. To control an electric machine by electric drives, its braking system is very important because it helps to decrease the speed of the motor according to will and necessity. Braking is also a part of controlled stopping (as opposed to coasting), which helps to increase occupational safety while reducing wear on power transmission belts, sprockets, and gears.

Besides mechanical brakes, today's options include electronic brakes. Electronic D.C. braking provides reliable and fast load deceleration and stopping, requiring no maintenance and conserves energy as well with reduced maintenance costs. Many such applications where D.C. injection braking can be deployed are roller-table drives, grinding machines, centrifuges, circular saws, planers, roller and ball mills and so on to cut down stopping time. D.C. braking reduces undesirable oscillations and even vibratory motors can be stopped within few tens of seconds. Apart from all these, D.C. braking increases safety and productivity at thesame time.

Many conventional braking schemes are already practised by leading industrial drive manufacturers which could be broadly classified into two parts VFDand Non-VFD basedbraking.

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Non-VFD braking includes capacitor self-excitation braking, electronic brake module using rectifiers and thyristors for D.C. injection, single shortcircuit method(magnetic braking), simultaneous magnetic braking and D.C. injection refer reference[6], zero sequence braking, etc. VFD braking includes flux braking, dynamic braking (like D.C. injection braking, regenerative braking), double frequency braking, etc. The detailed descriptions of the braking schemes are provided in next section.

2. CONVENTIONAL BRAKING SCHEMES

Braking of inductionmotorscanbeclassifiedmainlyinthreecategories:

1) Regenerative braking
2) Plugging or reverse voltage braking
3) Dynamic braking

This paper will focus mainly on dynamic braking.

2.1. Dynamic braking can be further classified as

a)Self-excited braking using capacitors: Sometimes capacitors are kept permanent by connecting across the supply terminals of the motor. This is called self-excited braking of induction motors. This type of braking works mainly by the property of the capacitorsto store energy. Whenever the motor is disconnected from the supply, the motor starts to work as a self-excited induction generator and the power comes from thecapacitors connected across the terminals. The values of the capacitor are so chosen that they are sufficient to make the motor work as an induction generator after being disconnected from the supply. When the motor works as an induction generator the produced torque opposes the normal rotation of the motor and hence braking takes place.

b) Magnetic Braking: In this method, two or all three terminals of the stator windings are shorted for braking after power supply is cut. Magnetic braking is achieved when the residual magnetism of the already rotating rotor induces currents in the short circuit which opposes the motion of the rotor.

c) D.C. Injection braking: In non VFD D.C. Braking, a D.C. supply is connected between two stator terminals, with the third winding kept open or shorted with any of the other two windings.As it is known that speed of rotation of the air-gap field is directly proportional to the supply frequency, therefore, applying D.C. means air-gap field has effectively zero frequency, and the air-gap field will be stationary. The rotor always tries to run at the same speed as the field. So, if the field is stationary, and the rotor is still rotating, then a braking torque will be exerted which retards the rotor. The DC components in the input voltages and currents do not "pass through" the air gap of the induction motors and so have noimpact on the rotor circuit.

For safety reasons, power circuits are usually incorporated into the motor’s thermal andoverload circuitry as D.C. injection generate a lot of heat.. Thus, when the motor is critically overheated, brakes won’t turn on. This D.C. Braking can be controlled by means of RMS magnitude modulation of chopped, rectified D.C. waveforms.

In VFD based D.C Injection, the amount of braking torque depends on the magnitude of the current which can be varied pulse by pulse. This allows the retardation to be varied over a wide time range. D.C. braking is initiated following a brake-enable delay of approx. 200ms. As soon as the set braking time-out is reached the PWM pulses are inhibited and the braking current decays.A typical torque-speed curve for braking a cage motor is shown in Figure 1, from which we see that the braking (negative) torque falls to zeroas the rotor comes to rest. Braking is a dissipative process, all the kinetic energy being turned into heat inside the motor. For standard D.C. braking method (VFD based) braking torque can be generated only up to 66% where asproposedadvanced DC braking is capable of generating braking torque up to 100%.

Characteristic of dynamic braking (fast ramp down) is the typical nonlinear stopping characteristic as shown in Figure 2. To increase the deceleration rate (decrease the stopping time), D.C. can be applied to the motor windings during the last 10% to 20% of the motor's speed. For example, a motor is turning at 1,500 rpm when the stop command is issued. Fast deceleration ramp reduces the speed to 150 rpm, and then injecting D.C. reduces the total stopping time by many seconds than if it were stoppedonly by dynamic braking alone.

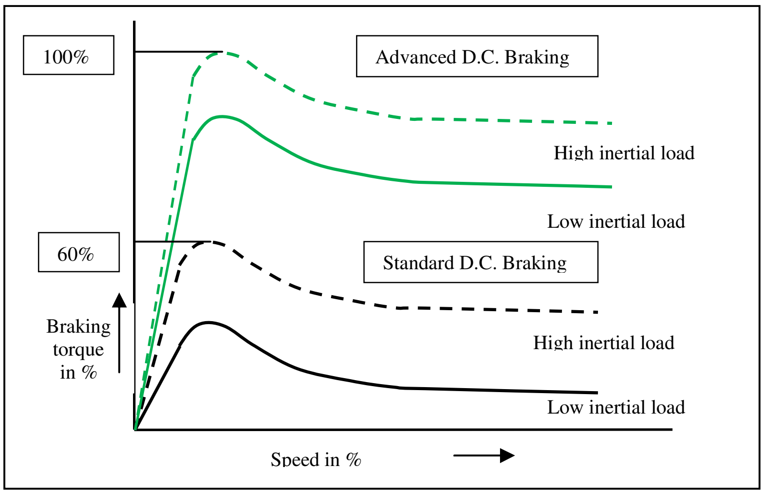


Figure 1.Torque Speed Curve of IM

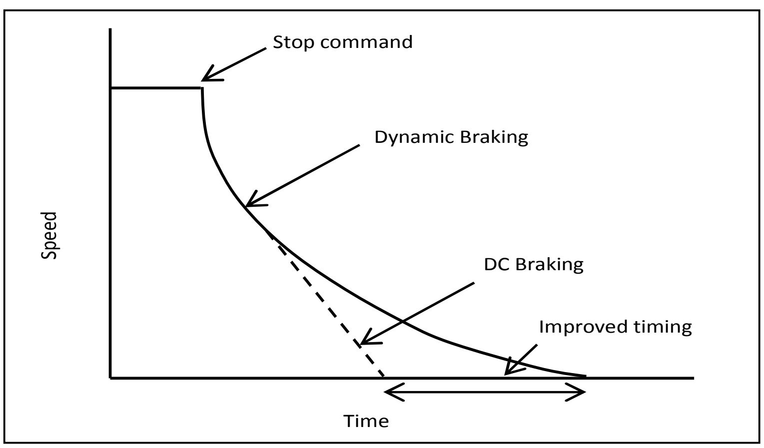


Figure 2. Stopping with dynamic braking and D.C. injection braking

d) Zero sequence braking: Here, the stator terminals are connected in series and either AC or D.C. voltage is supplied across two terminals. This produces a static magnetic field that opposes the rotor's motion.

The detail of zero sequence braking is mentioned in reference [1] and [5]. Finally, all the methods are combined and each method is employed for braking for different time intervals, known as multistage braking. The speed range and time duration during which these methods are most effective, are analysed, by means of changing the capacitor values and injected D.C. current levels.

Capacitor self-excitation method of braking is found to be more effective at high speeds whereas zero sequence braking at medium and lower speeds and D.C. injection braking at low speeds.
It has been observed that the overall efficiency is improved and the braking response becomes fast in multistage braking as compared to individual methods done separately.

A series of experiments were performed in reference [3] to compare the performances of the conventional methods individually. Finally, it was observed that a combination of two or more methods will produce the most effective braking. The paper experimentally found out the range of speed and time duration that are most effective in fast brakingsystem. The minimum capacitance value has been determined by means of no-load test and block-rotor test.

The reference [7] describes multistage braking being achieved by capacitor self- excitation, magnetic braking and then D.C. injection braking at lower speed. Two parallel capacitors are used for capacitor self -excitation braking, with only one capacitor, speed drops up to 50% of final speed and then second capacitors comes into picture which further reduces the speed of motor. After completion of capacitor self-excitation magnetic braking is applied in which two legs are made short-circuited and at further lower speed D.C. is applied between two legs.

The Braking time is further reduced by combining magnetic braking with D.C. braking.In reference [2], the thermal behaviour of the induction motor is simulated by modelling the stator winding. The resistance/temperature model of stator is prepared by adopting D.C. injection methodology via soft-starters.

2.2 D.C. Braking Implementation by Different Drive Manufacturers

Various D.C. braking techniques are being followed in the industry by different leading drive manufacturers. In Figure 3, the waveforms related to typicalD.C. injection braking adopted in drives industries have been shown. From the graphs, it is clearly understood that when D.C. injection braking is initiated, current is unidirectional, i.e. D.C. and consequently speed starts decreasing. But before injecting direct current into the windings, some amount of time should be given as 'wait time' for the windings to get demagnetised.

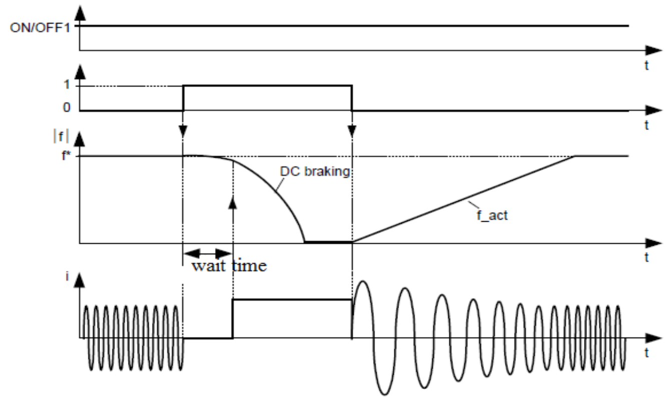


Figure 3.Typical D.C. braking adopted in drive industries

3. PROPOSED MODIFIED D.C. INJECTION BRAKING

VFDs have always included cost effective methods for providing fast, reliable braking. In this paper, an advanced technique of D.C. injection has been proposed that is flexible and easy to implement. The disadvantage of traditional D.C. injection is that maximum braking torque is limited (approximately 66%of full motor torque) and motor heating can be excessive. On the other hand dynamic braking uses a resistor bank to dissipate the heat. The motor being decelerated operate as a generator, which feeds energy into the drive's D.C. bus and braking resistor.In our proposed method, when braking is in progress, the frequency of voltage is controlled to maintain negative slip.This allows kinetic energy to be absorbed from the motor and load inertia. Voltage is applied to dissipate the absorbed energy in the motor as heat. Figure4 illustrates the balance of energy during braking.

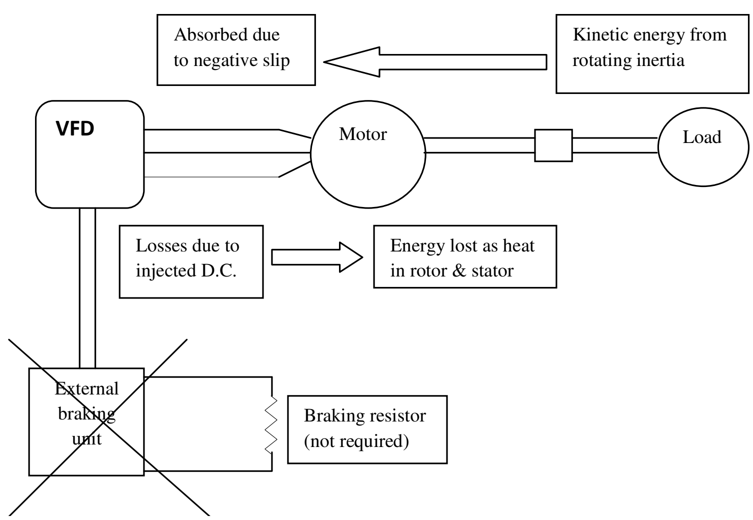


Figure 4. Balance of energy during D.C. braking

Proposed advanced D.C. Braking is a cost-effective sopping method whichproduces drastic reduction in braking time while eliminating the extra expense of external braking resistors and additional braking chopper power circuits by offering higher braking torque per ampere in non-regenerative A.C. drives. The modified D.C. braking discussed in this paper for high inertia loads can provide braking torque in excess of 100% full load motor torque. Control scheme, controls the deceleration to make the motor operate as very inefficient induction generator by modifying the V/F pattern so that load energy is observed in the rotor bars, stator windings and stator core of the motor. Current level is controlled to avoid excessive motor heating. Deceleration time is directly related to the actual load torque and inertia.

Simulationsare performed on MATLAB/Simulink platform (R2014a).Here D.C. voltage, in form of pulses is injected in two phases and magnetic braking is performed by shorting two phases externally. Three phases and single phase switches are used to switch the braking methods using specified time. Series of experiments were performed and graphs were plotted to analyse the results.To apply D.C. braking, duty cycle of PWM pulses were varied based on current required denoted in equation (1) and (2).

$$\frac{\frac{T_{on}}{T} * V_{DC}}{2R_s} = I_{req} (1)$$

$$\frac{T_{on}}{T} = \frac{2R_s * I_{req}}{V_{DC}} (2)$$

$I_{req}$is the required D.C. current to be injected. $T_{ON}$is the ON time of the injected pulses. $R_s$is the stator resistance, V_{DC} is the D.C. bus voltage, $1/T$ is switching frequency. For simulation 3 phase, 415V, 50Hz, 5.5kW squirrel cage IM was used.

3.1. MATLAB Simulation Results

To apply D.C. braking we have two methods, one is to apply D.C. after supply is cut-off and base-block time is attained. And in second methodmotor speed is decelerated according to deceleration ramp in 'ramp to stop' and when speed reaches pre-determined value D.C. braking is applied. The amplitude of D.C. Braking current affects the strength of the braking torque attempting to lock the motor shaft. Increasing the level of current increases the amount of heat generated in stator windings.

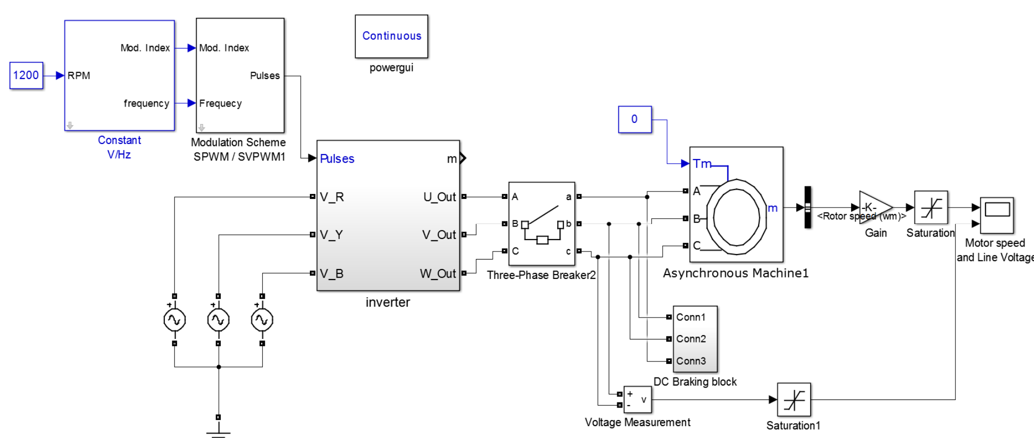


Figure5. MATLAB circuit of D.C. Injection braking combined magnetic braking

Referring Figure 5, The control strategy used for simulation is constant V/Hz method in which RPM is taken as input and converted in frequency as, $freq = RPM * p/120$, where p is number of poles. The frequency is taken as reference and corresponding modulation index is selected by constant V/Hz curve. Pulses are generated by SVPWM and applied to converter. Converter generates three phase ac signals and these signals are fed to motor via circuit breaker. Loads ranging from 0 to full are selected by switch. Second circuit breaker is used for applying D.C. Braking. Line voltage, stator current, speed and motor torque were observed in scope. Induction motor was stopped at $t = 5sec$, magnetic braking applied at $t = 5.5sec$ up to $t = 7sec$ and D.C. Braking applied after $t = 5.7sec$ as shown in figure 6.

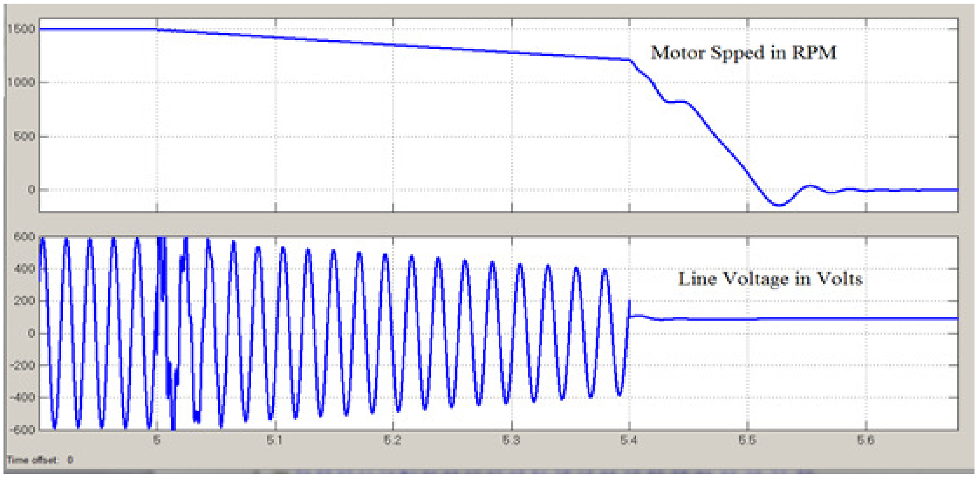


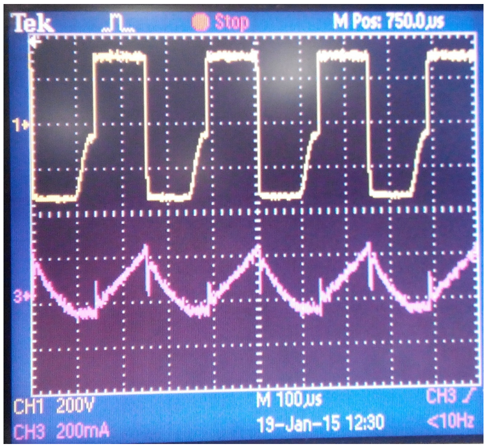
Figure 6.Speed- time curve and Line to Line voltage of IM during combined D.C. braking and magnetic braking.

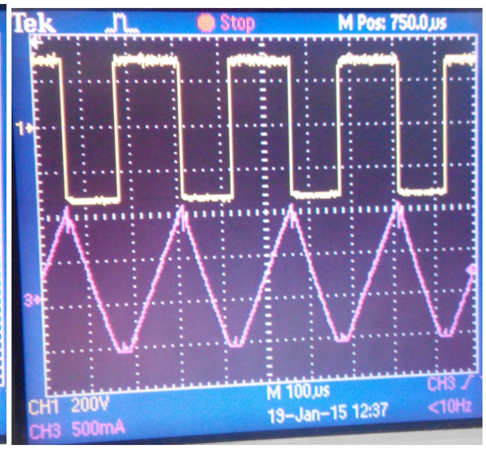
3.2 DSP

The control of the IM drive in actual hardware set-up is carried out through Digital Signal Processor (DSP). TMS320F28335 is used for the purpose, TMS320F28335 is MCU based control-CARD by Texas instruments having High-Performance Static CMOS Technology and clock frequency of 150MHz. TMS320F28335 is single-precision floating point DSP having 32 bit CPU. TMS320F28335 having six-channel DMA controller for ADC, ePWM. This DSP is well suited for motor control applications.

3.3 Hardware Experimental Results

ApplyingD.C. in two phases in terms of fixed duty cycle pulses is not feasible as sufficient back emfappears in off period and as a result average D.C. is low as shown in Figure 7. Hence, this paper proposes a technique where very low frequency of 1/100Hz sine wave with less modulation index of 0.2 is applied for the time duration of 200msec for each phase. For such small time the sine wave can be approximated as D.C. signal and the problem of back emfcan be avoided.





ratio.

Figure 8 represents the phase current of IM Drive during D.C.braking done onleading Japanese Drive at 800Rpm.The results from the actual experimental set-up are shown as shown in Figure 9, 10 and 11.

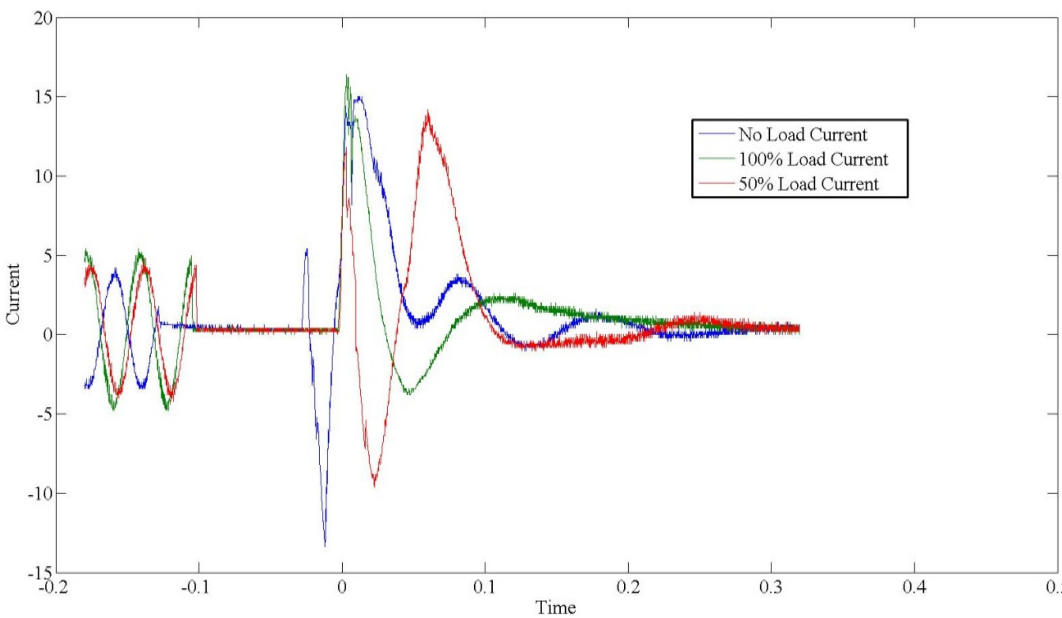


Figure 8.Stator current when applied D.C. Braking at 800 rpm on Japanese Drive

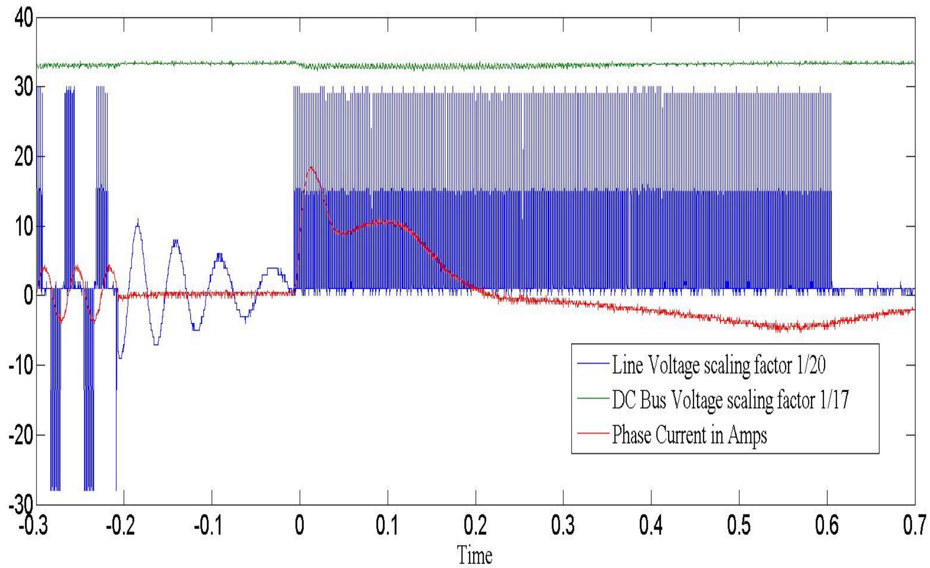


Figure 9. Drive DC Voltage (Green), Motor Line to line voltage (Blue), and Motor current (Red) for IM Drive when applied Advance D.C. Injection Braking.

Figure 10 and 11 represents the phase current when D.C. Braking is applied at 800 rpm and 1200 rpm for various load conditions respectively by proposed techniques of the paper. Before applying D.C.braking base-block time of 200msec is given to de-magnetise the stator coils. After base-block time D.C. Braking applied for short period. It has been observed that the peak of injected current is reduced as load is increased.Also, a comparative analysis can be shown that in the proposed topology the effect of back emf is totally suppressed as compared to the previous IM drives. Hence current direction is purely unidirectional.

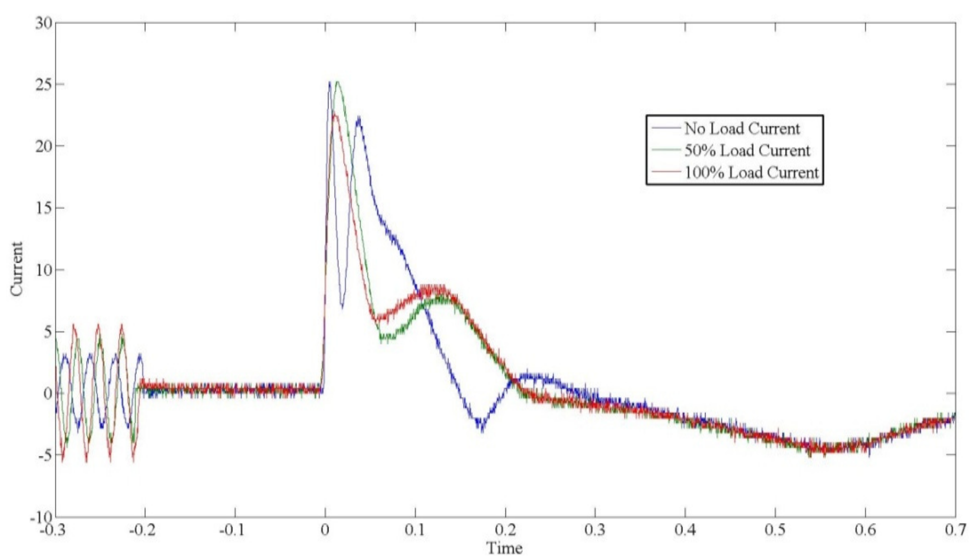


Figure 10.Stator current when applied advanceD.C. Injection Braking at 1200 rpm.

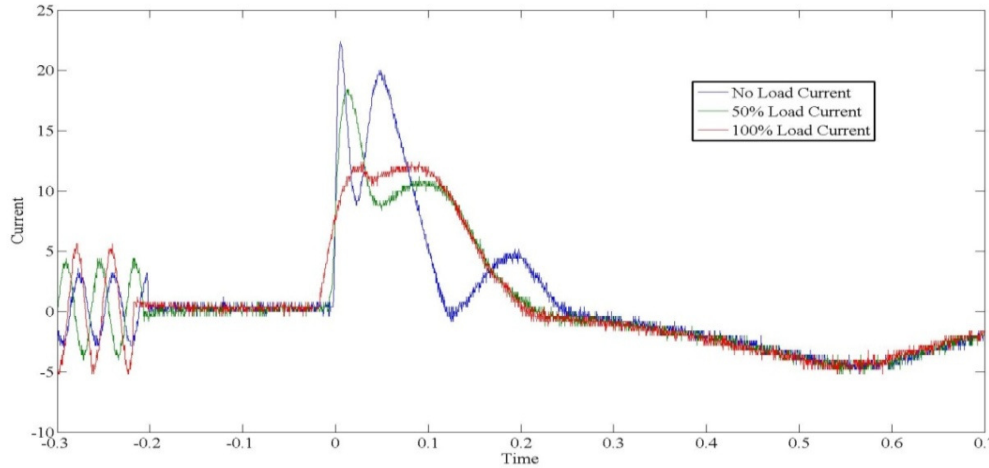


Figure 11.Stator current when applied advanceD.C. Injection Braking at 800 rpm.

In figure 12, speed characteristics of the IM drive is shown when D.C. Braking is injected at 1200 and 800 rpm respectively. It can be observed that the speed comes to zero in lesser time when D.C. is injected at 800 rpm than 1200 rpm.Tests have provided some amazing results. Motor have been able to stop from spins speeds in less than 0.5 seconds without noticeable motor heating. This same machine would take 40 to 50 seconds to coast to stop.

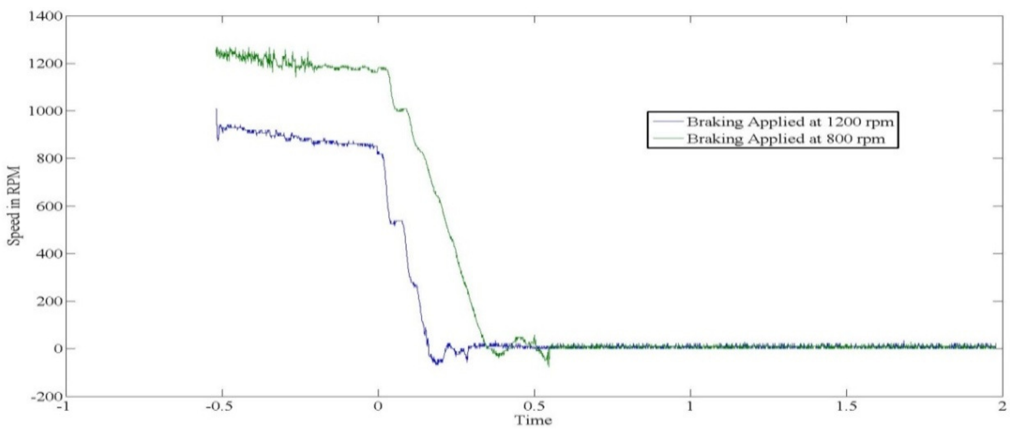


Figure 12. Speed-time curves when D.C. Braking applied at 1200rpm and 800rpm.

Lastly, in Table 1, a comparative observation has been shown between different D.C. braking schemes It is clearly visible that the advanced D.C. injection brake system is better and more efficient than the rest braking schemes in terms of the amount of braking torque and the ability to stop motors with high inertia loads rapidly.

Table 1.Comparison between regenerative/non-regenerative braking schemes in VFD

Parameters	D.C. injection braking	Dynamic braking	Advance D.C. injection braking	Flux braking
Braking Type	Non-regenerative	Regenerative	Non-regenerative	Regenerative
Braking Torque	Up to 66%	100 to 150%	100%	Limited
Motor Heating	High	None	Controlled	High
Sink of energy	Both Stator & Rotor*	External braking resistor	Both Stator & Rotor	Stator (core)
Power Range	Low to medium	High	High	upto 7.5KW
High Inertia Load	Not required	Not required	Required	Not required
Control Required	VFD	VFD + Brake Chopper & Resistor	VFD	VFD
Cost	0	Additional 20 to 30%	0	0

* In case of Non-VFD, energy is dissipated only in stator.

3.4. Influence of Bus Voltage on D.C. Braking Curve

At any given slip, the air-gap flux density is proportional to the applied voltage, and the induced current in the rotor is proportional to the flux density. The torque, which depends on the product of the flux and the rotor current, therefore depends on the square of the D.C.voltage. This means that a comparatively modest fall in the voltage will result in a much larger reduction in torque capability.

4. THERMAL BEHAVIOUR OF INDUCTION MOTOR DURING D.C. INJECTION

It is the fact that IM are the key elements in most industrial process or daily life, and the most important consideration is the stator winding insulation property during thermal overload conditions because motor life is greatly dependent on stator winding insulation.Most of the energy absorbed during proposed advanced D.C. braking is dissipated in the stator and rotor of the induction motor. This is analogous to standard D.C. injection braking. For best utilization, a VFD system that incorporates this braking method should also include a thermal model of the motor, estimating both the rotor and stator temperatures, and providing alarm and shut-down signals.

4.1 Analysis of D.C. Signal Injection on Stator Temperature

It has already been discussed that once D.C. signal is injected, it induces the non-rotational magnetic field which opposes the rotational magnetic field. This may result in unbalanced motor magnetic saturation which later increases the losses in stator and rotor cores as stated in reference [4]. This magnetic saturation may also cause heat dissipation in the stator and rotor and thermal stress on motor components. Thus accurate monitoring and estimating of stator winding temperature is necessary to protect the motor.

4.2 Effects of Magnetic Saturation

When D.C. signal is injected,the resultant magnetic flux consists of 2 components: stationary flux and rotating flux.As a result in each cycle the magnitude of the flux is varying due to injected D.C. bias.

The magnitude of the flux decreases when the rotating flux is in phase with the stationary flux and magnitude of flux increases when the rotating flux is in opposite phase with stationary flux.

4.3 Losses in Induction Machine

The injected D.C. current i_{dc}in stator windings has direct relations with the losses taken place in stator, mainly in terms of an additional stator copper loss as denoted in equation (3).

$$P_{s,copper} = \frac{3}{2} i_{dc}^2 R_s \tag{3}$$

$R_s$is stator resistance, $P_{s,copper}$is loss in stator

The rotor copper loss by D.C. injection can be stated in equation (4).

$$P_{r,copper} = \frac{3(wdcL_m)^2}{2({R_r}^2+(w{L_r}^2))} i_{dc}^2 R_r \tag{4}$$

$R_r$is rotor resistance, $P_{r,copper}$is loss in rotor, L_m is mutual inductance.

Since rotor resistance and rotor leakage inductance are negligible,compared to mutual inductance,rotor copper loss can be estimated as given in equation (5).

$$P_{s,copper} = \frac{3}{2} i_{dc}^2 R_r \tag{5}$$

4.4 First Order Thermal Model of Induction Machine

The thermal model based on temperature estimation of stator winding help us in realizing the Motor thermal protection. The stator winding insulation is normally the weakest component during thermal overload,since its thermal limit is reached before that of any other motor component. About 35-40% of induction motorfailures are related to stator winding insulation failure. It is commonly assumed that the motor's life is reduced by50% for every 10°C increase above its stator winding temperature limit.Figure 13 depicts the first order thermal model of IM.

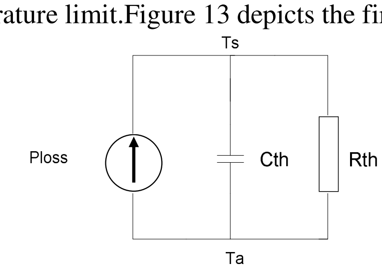


Figure 13. First order thermal model of induction motor.

Here $T_s$and $T_a$represent the stator winding temperature and the ambienttemperature, respectively;R_{th} represents the equivalentthermal resistance, which models the cooling capability fromthe stator winding to the ambient; C_{th} represents theequivalent thermal capacitance, which models the intrinsicthermal characteristic of the stator winding; $P_{s,copper}$represents the heat dissipation in the stator winding. The stator temperature can be calculated by using the first-order thermal model as illustrated in equation (7).

$$T_s(t) = P_{losses}.R_{th}\left(1 - e^{-\frac{t}{\Gamma}}\right) + T_{so}e^{-\frac{t}{\Gamma}} + T_a \qquad (7)$$

$\Gamma$is RC time constant, $\Gamma = {}^{1}/_{R_{th}C_{th}}$, $T_{so}$is the initial stator winding temperature.

P_{losses}Represents the heat dissipation in the stator windings, principally the copper loss.

5. CONCLUSIONS

In this paper a method has been described for providing occasional braking torque from a non-regenerative VFD, without additional power circuits. The control strategy and the inherent limitationsof the method have been analysed. The method has been shown to give significantly greater braking torque per ampere than D.C. injection braking. A possible implementation has been presented,and supported with experimental results on low-voltage. The distinguished features of the proposed scheme are fast start of braking operation (approx. 200ms) and braking torque and braking time-out separately adjustable, requiring no external braking contactors. The most important advantage of the proposed technique is that no D.C.bus overshoot occurs during braking. Moreover, currents in all the phases are perfectly balanced. Performance of advancedD.C. braking has beencompared to other recently-proposed methods.Proposed technique is not the answer for all application. However, it is a very cost-effective method for stopping high-inertia loads, in the order of five times motor inertia.Proposed method offers slightly higher deceleration time when compared with dynamic braking but offer many advantagesin many applications that require occasional braking.

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