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A Novel Fast Braking System for Induction Motor

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***Abstract*—An effective and reliable fast braking system for three-phase induction motor designed with the combinations of two or more conventional braking methods are discussed in this paper. A series of experiments were conducted in order to find out the speed range at which the most effective and efficient braking occurs corresponding to each conventional braking method and also to determine the minimum capacitance required for self excitation. It is observed experimentally that the most effective and efficient braking may occurs by combining two or more different conventional braking methods in a particular sequences at the speed range where they are most effective, provided the switching is done in proper sequences and the time delays between successive stages of switching are correct. For proper switching and proper time delay a microcontroller can be used so that the switching and time delay are made easy and reliable. Finally, the experimental results for different conventional braking methods are presented in this paper.**

***Index Terms*—Capacitor Self Excitation Braking, Magnetic Braking, DC Injection Braking, Zero Sequence Braking.**

I. Introduction

In many industrial applications the use of induction motor is extensively increasing because of their high robustness, reliability, low cost, high efficiency and good self starting capability. For the use of industrial applications one of the most important control parameter in the motor drive system is braking. There is a need to bring a drive system quickly to rest to hold a drive at standstill after some operation has been completed, or under the condition of faulty operation to save the machinery parts or operating personal. Basically, the braking system for electric motor fundamental is one mechanism to create retarding torque to stop the motor rotation with sudden or slow stop depending on application in the system. In other word, braking is essentially the removal of stored kinetic energy from a mechanical part of the system. Development of efficient and effective braking system for induction motors used in industrial applications has been a subject of continuous study over the years. A number of braking techniques used in induction motor has been reported in literature. The technique of braking system can be divided into two,

i. Friction braking
ii. Electrical braking

Further, the conventional electric braking system can be divided as given;

Electric Braking

i. Regenerative Braking
ii. Plugging or Reverse Voltage Braking
iii. Dynamic (or Rheostatic) Braking
   a) AC Dynamic Braking
   b) Self-Excited Braking using Capacitor
   c) DC Dynamic Braking
   d) Zero-Sequence Braking

When an induction motor's rotor is turning slower than the synchronous speed set by the drive's output power; the motor is transforming electrical energy obtained from the drive into mechanical energy available at the drive shaft of the motor. This process is referred to as "motoring". When the rotor is turning faster than the synchronous speed set by the drive's output power; the motor is transforming mechanical energy available at the drive shaft of the motor into electrical energy that can be transferred back into the utility grid. This process is referred to as "regeneration" or "braking" mode. The most suitable braking system for a particular process would depend on various factors such as application, energy requirement and cost, complexity of the control circuit, effectiveness, and reliability. In this paper an attempt is made to design the most suitable braking system for failsafe application of a process with combination of two or more conventional braking techniques.

II. Conventional Braking Techniques

A. Regenerative Braking

If an induction motor is forced to run at speeds in excess of the synchronous speed, the load torque exceeds the machine torque and the slip is negative, and also the induced emf and rotor current will reverse. In this situation the machine will act as a generator with energy being returned to the supply. This mode of operation is known as regenerative braking. A regenerative brake is an energy recovery mechanism which slows a vehicle by converting its kinetic energy into another form, which can be either used immediately or stored until needed [1]. This is the key technology of hybrid vehicles, one of the important means to reduce fuel consumption of hybrid vehicles but regenerative effect drops off at lower speed and cannot bring the motor to a complete halt [2].

B. Plugging

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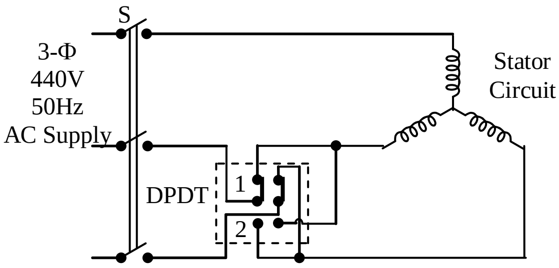

Fig.1. Plugging

Plugging is one of the electrical braking methods applicable in induction motor. The principle of traditional plug braking, shown in Fig.1, is that changing the direction of revolving magnetic field to oppose the direction of former magnetic field by changing the phase sequence of three-phase voltages supply to the stator windings, and then the motor will be brought to a halt by opposing torque in a short time. As the rotor always tries to catch up with the rotating field, it can be reversed rapidly simply by interchanging any two of the supply leads [3]. If the leads on the stator windings are reversed suddenly, the direction of rotation of the stator field is reversed. The resulting slip is larger than one. The motor will come to an abrupt stop. Very rapid reversal is possible using plugging but large cage motors can only be plugged if the supply can withstand the very high currents involved, which are even larger than when starting from rest. Frequent plugging will also cause serious overheating, because each reversal involves the “dumping” of four times the stored kinetic energy as heat in the windings. Moreover, there is a possibility of reversing the rotation of motor if it fails to remove the braking as soon as the motor speed reached to zero rpm.

C. Dynamic Braking

Dynamic braking is a process in which kinetic energy of the rotor is dissipated in the internal/external resistor as heat energy after disconnecting the main supply. It is an electrical braking process used in many industrial applications. Dynamic braking allows sudden stop of electrical motor without mechanical wear and tear. In dynamic braking, stator has no supply (main) at the time of braking. However, rotor is rotating due to the inertia. In synchronous motor, rotor has a supply even when stator is disconnected from supply. In permanent magnet synchronous motor, rotor is a permanent magnet. In case of induction motor, rotor is very likely to have a residual magnetism. Therefore, in major types of motors, there is source of magnetic flux in rotor. When stator has no supply and rotor is rotating, this flux induces voltage in stator. In other words, motor is acting as generator and rotors kinetic energy is now transferred to stator as electrical energy. If we can just arrange a system that dissipates this energy, we actually can devise a dynamic braking. There are different techniques of dynamic braking, they are discussed below.

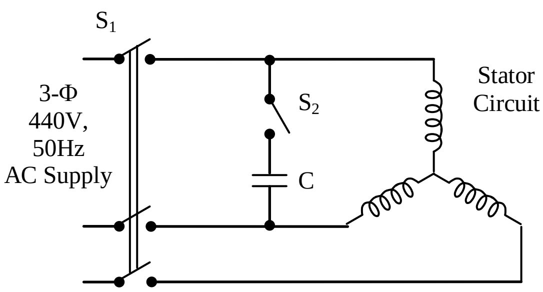

Fig.2. Capacitor Braking

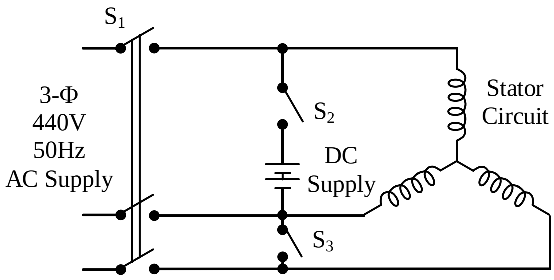

Fig. 3. D.C. Injection Braking

i) Capacitor Self-Excitation Braking

As soon as a three phase induction motor is disconnected from the supply, rotor of the motor continue to run due to the inertia of the load and an emf will be induced in the stator windings, assuming residual magnetism exists in the rotor [4]. If a capacitor of suitable value is connected across any two of the stator terminals (with third kept open) excitation will be sustained by the terminal capacitor but magnetic saturation limits the induced emf [5]. This phenomenon is known as capacitor self excitation. The capacitor will store energy which comes from rotor magnetic circuit. Now the machine will acts as a generator. The generated electric power will be dissipated in the inherent resistance of the windings and thus braking is accomplished. Hence rotor loses its kinetic energy more rapidly and a brake is experienced [5]. This process is known as capacitive braking since capacitor is used in braking process and is shown in Fig. 2. For the machine to self-excite, a minimum value of capacitor is required, below which no excitation would occur. Normally excitation capacitance must be larger than some minimum value [6].

ii) DC Injection Braking

In the conventional dc-braking method, a zero-frequency current is fed to the stator winding, resulting in zero air-gap power. The poly-phase induction motor can produce a braking torque by replacing the ac voltage on the stator winding with the dc voltage which is shown in Fig. 3. When the dc voltage is applied to the stator winding of an induction motor across two of the three stator leads the induction motor becomes an inverted (or inside-out) synchronous generator, for which the stator now becomes the field and the rotor of the induction motor becomes a rotating armature [7]. At standstill, the rotor current and braking torque become zero [8]. DC braking is suitable only for stopping the motor and its braking torque is small at high speed.

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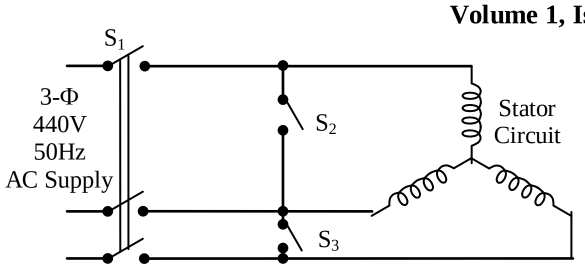

Fig. 4. Magnetic Braking

iii) Magnetic Braking

Magnetic braking of an induction motor is achieved by shorting two or three stator leads after the field is established and the main ac supply is disconnected. The circuit arrangement for magnetic braking is shown in Fig. 4. It does not require additional input energy and generates less heat because the only energy spent is the rotating drive shaft kinetic energy [8]. Magnetic braking works because of induced currents and Lenz's law. If you attach a metal plate to the end of a pendulum and let it swing, its speed will greatly decrease when it passes between the poles of a magnet. When the plate enters the magnetic field, an electric field is induced and a circulating "eddy currents" is generated. These currents will act to oppose the change in flux through the plate, in accordance with Lenz's law. The currents in turn will dissipate some of the plate's energy, thereby reducing its velocity.

iv) Zero-Sequence Dynamic Braking

The connection diagram for zero-sequence dynamic braking is shown in Fig.5. If the three stator windings of an induction motor are connected in series and either ac or dc voltage is applied across the two terminals then a resultant stationary field in space will be produced. Such a connection is known as a zero-sequence connection, because the currents in all the stator windings are co-phasal [9]. The mmf waveform caused by currents of zero sequence produces a magnetic field in space which has three times the number of poles for which the machine is actually wound. Zero-sequence dynamic braking cannot return any of the rotors' kinetic energy (KE) to the supply electrically (KE is not converted into a useful electrical energy).

III. DESIGN OF FAILSAFE BRAKING

With the above discussions, a failsafe braking can be designed using two or more conventional braking techniques. There are some possible combinations of conventional braking techniques for effective and efficient failsafe braking of induction motor. Some of the combinations discussed in the literature are as follows.

A. Combination of Capacitor and Magnetic Braking

This combination is already reported in [10] with the simulation results and this failsafe braking system does not required any power for braking unit except to operate the contactors. In this braking system, there is no provision for the effect of gravitational force as in the case of lift and other load which are affected by gravity. The system will sustain the brake for few second and afterward no braking will effect to the motor. To sustain self-excitation at lower speed a high value of capacitance is required but more capacitance will cause more heating in the windings.

B. Combination of Capacitor and dc Injection Braking

The combination of capacitor and dc injection will be more effective. The capacitor self excitation braking is applied at high speed and the speed of the motor will reduced 50% to 70% of the full speed and then dc injection braking is followed. The dc braking will bring the motor to standstill in few seconds. To limit the dc current during dc injection breaking a variable dc can be applied in sequences, since at higher speed a higher voltage is required and at lower speed lower voltage is required.

C. Combination of Capacitor, Magnetic and dc Injection Braking

Since magnetic braking requires no external energy in the braking system, the magnetic braking can be applied in-between the capacitor and dc injection so that dc voltage required to halt the rotor will reduce. As soon as the main supply is disconnected from the motor a single capacitor of suitable value is connected to any two of the stator terminals (the third terminal left open) followed by magnetic braking and finally a small amount of dc will be injected to bring the rotor at standstill. But sometimes this magnetic braking fails when emf does not develop in the windings. This combination will be very efficient and effective.

D. Combination of Capacitor, Magnetic and Zero Sequence Braking

In the above combination of capacitor, magnetic and dc injection braking, a rectifier circuit is required for dc injection; it is an additional to step-down transformer. This is an extra cost in the whole braking system. In the same sequence as above the capacitor self excitation braking will be applied as soon as the main supply is removed and the capacitor braking is followed by the magnetic braking. Finally a small amount of 1-Φ ac voltage will be applied to the series arrangement of stator winding.

E. Combination of Capacitor and Zero Sequence Braking (ac/dc)

As capacitor self-excitation braking is more effective at high speed and ac/dc zero sequence braking is effective at medium and low speeds. The combination of capacitor and zero sequence braking will be very effective for failsafe braking system of a 3-Φ induction motor. In the dc injection braking system the braking current flows in only two of the three stator windings. But in case of capacitor and zero sequence (ac/dc) braking combination the braking current due to the zero sequence (ac/dc) will flow in all the three windings of the stator and also distribution of magnetic field due to the braking current will be more uniform. But the arrangement of series connection of the windings is more complicated.

IV. EXPERIMENTAL RESULTS

A series of experiments of individual conventional braking system have been performed during the study of the above conventional braking systems. For these experiments,

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a 3-Φ induction motor of 3HP (Horsepower), 440V, 1420rpm was used. To calculate minimum capacitance (C_{min}) two tests were performed; no-load test and block-rotor test. For the switching arrangement a conventional two way switches were used. All the measuring devices (ammeter, voltmeter, wattmeter, stop watch tachometer etc.) used in the experiments were of laboratory standard. The experimental results are shown in the tables II to V below for different braking.

Table I: DC Injection to stop at 0.5 seconds

Sl. No.	Starting Speed (rpm)	DC Voltage (Volts)	Max. Current Drawn During Brake (Amperes)	Max. Current Drawn At Standstill (Amperes)	Duration of Stopping (Seconds)
01	1000	80	4.1	5.3	0.5
02	900	70	3.5	4.6	0.5
03	800	60	3.0	4.0	0.5
04	700	50	2.5	3.4	0.5
05	600	40	2.0	2.7	0.5
06	500	30	1.8	2.0	0.5
07	400	20	1.3	1.4	0.5
08	300	15	1.0	1.0	0.5

Table II: DC Injection for Same Speed

Sl. No.	Starting Speed (rpm)	DC Voltage (Volts)	Max. Current Drawn During Brake (Amperes)	Max. Current Drawn At Standstill (Amperes)	Duration of Stopping (Seconds)
01	1000	80	4.1	5.4	0.5
02	1000	70	3.4	4.6	0.8
03	1000	60	3.1	3.9	1.0
04	1000	50	2.4	3.4	1.6
05	1000	40	2.1	2.7	2.4
06	1000	30	1.7	1.9	3.5
07	1000	20	1.3	1.3	4.7
08	1000	15	1.0	1.0	5.2

Table III: Zero Sequence (dc injection)

Sl. No.	Starting Speed (rpm)	DC Voltage (Volts)	Max. Current Drawn During Brake (Amperes)	Max. Current Drawn At Standstill (Amperes)	Duration of Stopping (Seconds)
01	1000	80	3.1	3.5	0.5
02	900	70	2.6	3.0	0.5
03	800	60	2.2	2.5	0.5
04	700	50	1.8	2.1	0.5
05	600	40	1.5	1.7	0.5
06	500	30	1.1	1.3	0.5
07	400	20	0.8	0.9	0.5
08	300	15	0.7	0.7	0.5

Table IV: Zero Sequence (ac injection)

Sl. No.	Starting Speed (rpm)	AC Voltage (Volts)	Max. Current Drawn During Brake (Amperes)	Max. Current Drawn At Standstill (Amperes)	Duration of Stopping (Seconds)
01	1000	80	3.1	3.5	0.5
02	900	70	2.6	3.0	0.5
03	800	60	2.2	2.5	0.5
04	700	50	1.8	2.1	0.5
05	600	40	1.5	1.7	0.5
06	500	30	1.1	1.3	0.5
07	400	20	0.8	0.9	0.5
08	300	15	0.7	0.7	0.5

Table V: Capacitor Self-Excitation

Sl. No.	Full Speed (rpm)	Value of Capacitance (μF)	Max. Current Drawn Starting (Amperes)	Max. Current Drawn During Braking (Amperes)	Speed After 0.5 Sec. of Braking (rpm)
01	1420	144	7.4	6.4	650

Table I shows that at low speed a low voltage is required to bring the motor to standstill at a particular duration of braking period (0.5s) and vice versa. Table II gives the idea of braking time requirement to bring the rotor to standstill with different injected dc voltage at a particular speed .Table III give the experimental data for zero sequence braking with dc injection to the series connection of stator windings. This table show that at lower speed lower dc voltage is required and the current flowing through the stator windings is within the limit of rated current of the motor. Table IV is also similar to the table 3 but the injected voltage is ac. Table V is the reading taken during the experiment performed for capacitor self excitation braking. From this data it is seen that the capacitor self-excitation braking is very effective at high speed. With suitable value of capacitance the motor can reduce its speed to 50% of the full speed at 0.5 seconds.

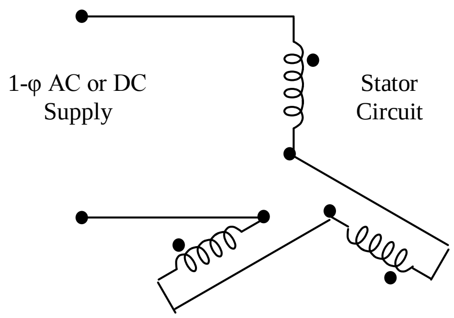

Fig. 5. Zero Sequence

V. CONCLUSION

The experimental results show that an effective and efficient failsafe braking system of induction motor can be designed using suitable combination of two or more conventional electrical dynamic braking system with the utilisation of all the properties of individual conventional braking. With proper arrangement of switching circuit and giving proper delay the combine braking system can stop the motor within one second safely without any over voltage, over current and overheating in the motor windings. The proposed design can be used in many industrial applications mainly in case of emergency to protect costly machinery equipments and operating personals.

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