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(Review Article)

Braking Methodologies in Short Circuit Generators

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Abstract

Conventional stopping methodologies of a machine comprise a massive waste of energy stored in its rotating masses. This energy is generally dissipated in the atmosphere in form of heat. There is substantial amount of energy consumption and time lapses involved in the whole braking process. This paper focused on the braking methodologies applied on two large short circuit generators. Out of these generators one is employed with the old conventional technique named as DC injection braking whereas second generator is having the benefit of regenerative braking. Both these means of applied braking are deliberated in this paper with technology, advantages and disadvantages.

Keywords: Generator, induction motor, short circuit test, static frequency converter, static excitation system, regenerative braking.

1. Introduction

Most of the electrical rotating machine is stopped by disconnection of its power supply from the source. The machine comes to standstill only due to friction thus takes a long time for a heavy machine with high inertia. This method is called 'coast to stop'. But sometimes it is not advisable to allow the machine to coast down to standstill due to safety reason or in case of an emergency situation. In case of machine tools, cranes, hoist quick stopping is essential. Quick stopping is more vital than quick starting in many cases as it may cause damage to the product or other machineries even to the human life. Many literatures are available on braking systems of induction motors deployed in electric traction, hoist, lift and vehicle [1]-[3]. In electrified railways the thought of regenerative braking is very common by using motors as generators whilst braking [4]. Regenerative braking is quite common in electric vehicles which employ BLDC motors [5]. This paper discusses different electric braking mechanisms applied to stop short circuit generators with a special emphasis on regenerative braking system.

2. Braking Purposes

Any rotating machine needs braking due to the following reasons:

- Stopping time reduction.
- Limiting the speed to a safer value.
- Pre-defined time to stop.
- To feedback stored energy in some other forms.

Reliability of any braking system is most important. It should be designed in such a way that its action is very quick and the braking torque can be regulated as per the need. Energy produced during braking must be absorbed by a suitable mechanism. For safety reasons the braking system is designed in such way that braking must be applied even in case of failure and the machine is locked.

3. Types of Braking

Forced stopping mechanism can be mechanical or electrical. In mechanical braking, kinetic energy stored in rotating parts is dissipated in the form of heat either in a brake shoe, brake drum or similar system. For small machine, these devices may be implanted but for large machine where high inertia is involved mechanical device won't work due to excessive wear & tear. In that case electrical braking is the only solution for stopping any electrical rotating machine.

3.1 Electrical braking: Electrical braking is also acknowledged as electrodynamics braking. Because here, kinetic energy is transformed to electrical energy which is further dissipated as heat in the resistances or returned back to the source.

Another method is popular nowadays is to store this regenerated electrical energy in energy storage system (ESS). ESSs are a worthwhile solution to reclaim regenerated energy

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from the braking system. Electrochemical Double Layer Capacitors and power batteries are the most appropriate devices for ESSs [6]. It is commonly used in electric vehicles. Competency of any electrical braking is recognised by areas in the braking quadrants of an electric machine's torque-speed plane. These competency areas are split into regenerative and non-regenerative braking zones. Regenerative electrical braking increases energy to the ESS, whereas non-regenerative electrical braking withdraws energy from the source [7].

There are various types of electrical braking. It depends on size and applications of the machines. The most popular braking methods are:

- Plugging
- Dynamic
- Regenerative

3.1.1 Plugging method: Amongst all this is the simplest type of braking. To provide counter torque either we have to reverse the motor winding or reverse the direction of flow of current. The easiest method is to change the current flow direction. By current reversal an opposite torque is induced and the machine tends to drive in reverse direction thus comes to standstill. It has to be taken care to cut off the power supply accurately at zero rotation otherwise the machine may rotate in reverse direction. A tripping circuit may be incorporated with a speed sensor.

This method of braking can be applied to DC motors, Induction motors and Synchronous motors.

Though plugging method gives greater braking torque but it draws high inrush current from the source. This current is restricted with a series resistor. An ample amount of electrical energy is transformed to heat and dissipated in the current limiting resistor. During application of plugging motor gets a mechanical shock, another shortcoming of this method. But for quick stop or reversal this is the best method.

3.1.2 Dynamic method: In this method no energy is required from the source like the plugging method but only field power is required to magnetise the air gap. When urgent stop or reversal is not mandatory, dynamic or rheostatic braking is useful in electrical machines. Here the machine is disconnected from the source and it is operated as generator under the influence of field power. This is mostly applicable for high inertia machines where very high kinetic energy is stored in the rotating bodies. This energy is converted into electrical energy which is dissipated as heat in the external resistances.

Application of dynamic braking is most convenient with DC motors and synchronous motors. It can also be useful for induction motors with a separate DC source.

3.1.3 Regenerative method: In both the previous braking systems energy is lost to the atmosphere in the form of heat. Plugging requires extra electrical energy from the source. In regenerative braking, instead of dissipating stored kinetic energy in the form of heat, it is converted back to electrical energy. Further this energy can be stored if small in amount [8] or can be fed back to the source. It is similar to dynamic braking. This braking technique is useful for the motor with very high inertia e.g. electric traction, hoist, elevator etc. During braking the energy drawn from the source is interrupted and the running motor is made to operate acts as a generator. The generated emf is maintained at higher potential than the source voltage thus power follows from generator to the source. Merit of this scheme is that electrical energy can be fed back either in DC or AC depending on the feasibilities [9]. In this way the kinetic energy stored in the rotating masses is converted to electrical energy and the speed of the machine starts falling due to reverse torque. As long as the generating action with sufficient emf is there the braking is applied. Later the source is disconnected and the machine is left over in idling mode till is comes to standstill due to friction.

Figure 1. Generator G1 setup

At the beginning of regenerative braking, during machine's full speed, the braking efficiency is relatively high. Efficiency reduces with the decrease in speed [10]. There is substantial increase in overall drive efficiency with regenerative braking [11].

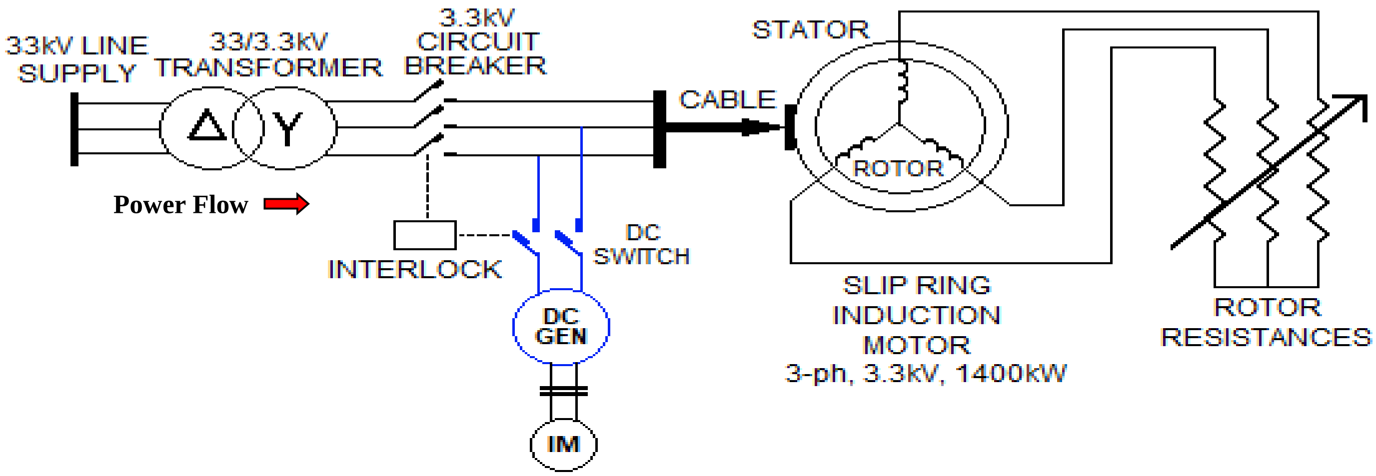

Figure 2. Braking system for generator G1

4. Application of Electrical Braking in Short Circuit Generator

After a brief overview of electric braking methodologies, further paragraphs explain the braking methods applied to short circuit generators at the laboratory of Central Power Research Institute (CPRI) Bhopal. These generators are specially designed three phase alternators used to supply high amount of electrical energy for conducting short circuit tests on electrical power equipment. Unlike power generators these are driven by distinctive drives. These generators are designed in such a manner that it can provide high surge of energy which is the basic need for short circuit tests. Short circuit generator is not a continuous rated machine, but it is run only when requirement for test arises. During short circuit test the energy supply is mainly from the rotating masses of this high inertia machine without loading the supply grid.

CPRI Bhopal laboratory has two short circuit generators named as G1 & G2. Generator G1 is coupled with 3-phase, 3.3kV, 1400kW slip ring induction motor (Figure 1). G1 is stopped with the method of DC injection to the slip ring induction motor. Generator G2 (Figure 2 & Figure 3) is connected with static drive called static frequency converter (SFC) [12-14]. G2 is stopped with regenerative braking technique. Details of both the systems have been discussed further.

4.1 Braking system for generator G1: Generator G-1 is driven by a 3.3kV, 1400kW, 3000rpm induction motor. Rotors of driving motor and generator are coupled mechanically (Figure 1). To stop the running generator normally 3.3kV power supply is switched off by a circuit breaker and let the machine coast to stop. Without input energy source the machine takes nearly 50 minutes to become standstill from the rated speed. In case of emergency i.e. when it is needed to stop the machine quickly, DC injection braking is applied to the driving motor.

4.1.1 Working of DC injection braking in G1: DC injection braking is a method of stopping an induction motor without the use of a frictional braking mechanism or additional braking resource, like a dynamic brake resistor. In this system driving motor of generator G1 is a slipring induction motor where starting and speed control is done through variable rotor resistances (Figure 2). 3.3 kV three phase supply is fed to stator winding of this motor. Rotor being stationary in the starting, induced very high emf. Rotor emf is passed through 3 slip rings which are connected with 3 sets of variable resistances connected in star configuration. Rotor energy is absorbed in these resistances and further dissipated as heat in the atmosphere. These resistances are cooled by an air blower. As the rotor picks up speed stator current starts to reduce. The resistances connected in rotor are cut automatically by sensing the stator current. There are 17 steps in resistances which are cut one by one and finally shorting the whole resistances at full speed. In this way the starting current is controlled otherwise it will be abnormally high. Similarly in every disconnection-reconnection to the source the rotor resistances are automatically inserted into the circuit according to the stator current.

While applying braking to the motor the three phase stator supply is disconnected by opening the 3.3.kV circuit breaker (Figure 2). Simultaneously DC switch is closed to feed the DC supply into the two phases of three phase stator winding. DC power is provided by the DC generator which is coupled with another induction motor. Normally purpose of this DC generator is to feed the field winding of generator G1 for magnetising the air gap. Output of this DC generator is utilised for braking purposes. It has to be taken care that circuit breaker and DC switch are not closed together. An interlock has been provided between the two.

In the existence of DC supply in two stator windings a stationary magnetic field is created. This fixed magnetic field tends to stop the revolving rotor by aligning with it thus creating a strong braking torque by virtue of Lenz's law. DC voltage is controlled in such a manner that stator current never crosses its rated value. Though more current creates more braking torque still it has to be taken care that braking current is not very low otherwise it will take more time to stop thus unnecessary heating will occur in stator and rotor. In this procedure whole energy is dissipated in the form of heat so thermal and electrical limitations have to be taken care while designing this braking system. Like other types of electrical braking systems the limitation of this methodology is that it cannot be applied without powers source hence not a fail-safe braking mechanism. Still for most applications, quick stopping of high inertia motor loads can be achieved with DC injection braking, which does not add to system cost or complexity.
The coupled load in generator G1 is approximately 40 tons. Application of DC injection braking is quite successful to bring the machine from 3000 rpm to standstill.

4.2 Braking system for generator G2: Like generator G1, generator G2 (Figure 3) also has coast to stop feature which normally takes 50 minutes to standstill. This feature is seldom in nature, happened in case of grid supply failure or under the circumstances of faults. In healthy situation most commonly stopping process is the regenerative braking mechanism.

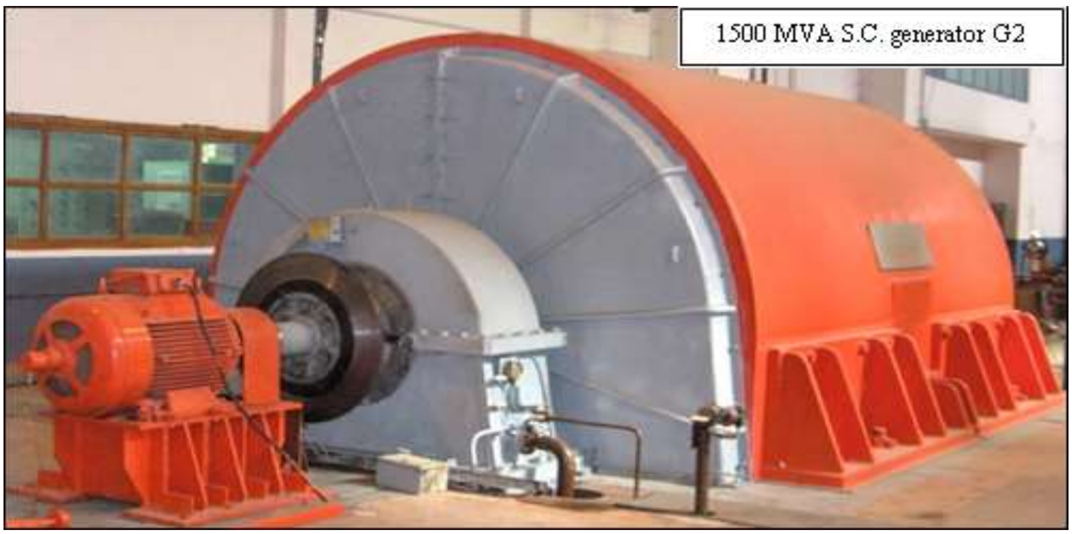

Figure 3. Generator G2 setup

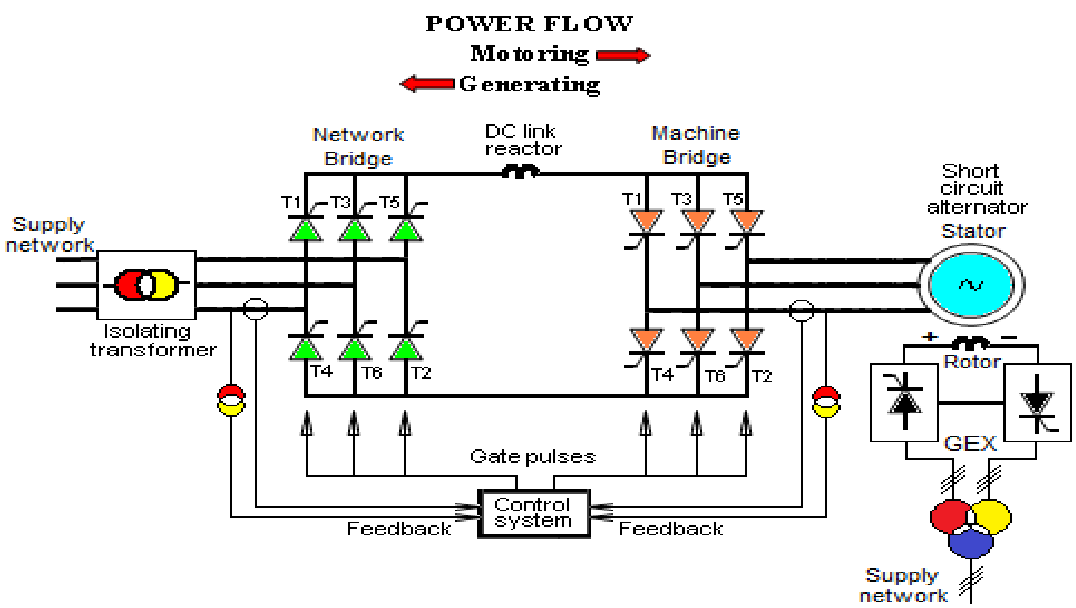

Figure 4. Generator G2-sngle line diagram

4.2.1 Starting principle of generator G2: It is already stated that Generator G2 is driven by a static drive. Static drives or AC power converters are of various types but most frequently used are single phase to three phase [15] and three phase to three phase. Stator of Generator G2 is connected to a three-phase to three-phase power converter named as static frequency converter (SFC). SFC has a feature of bi-directional power flow [16]-[19]. Being a synchronous machine, G2 can operate as motor and generator both. Initially it starts as synchronous motor. As it is known that synchronous motor is a doubly fed machine, its stator winding receives three phase power supply from the output of SFC. A 33/1.72 kV step down transformer connected to the supply grid feeds this SFC (Figure 4). Other than stator supply rotor winding requires DC field excitation to magnetise the air gap. Here also static devices are used to convert AC to DC [20]-[24]. This static excitation system is named here as generator excitation system (GEX) which is shown in figure 4. In motor mode, power flows from network to machine. SFC has four quadrant operation features, i.e. other than bi-directional power flow it can reverse the direction of rotation of machine. Two fully controlled thyristor bridges are the main components of SFC. These bridges are called Network Bridge (NB) and Machine Bridge (MB). A reactor is connected in between for transferring energy between the bridges (Figure 4). During motor mode NB and MB acts as rectifier and inverter respectively. MB converts rectified DC to three phase AC output. This AC output is fed to the stator windings of synchronous motor. At the same instances GEX sets rotor field supply according to the requirement. SFC and GEX interlinked together to achieve the machine speed from standstill to its rated value i.e. 3000 rpm.

4.2.2 Regenerative braking in G2: Planned stopping method of a running generator is called shutting down. Regenerative braking is applied during this process. SFC plays a vital role by reversing the operational mode of MB and NB i.e. MB works as rectifier and NB as inverter. The high inertia machine runs as generator where output terminal voltage is converted to DC by the thyristor bridge and available at DC link reactor. This DC is inverted to three phase AC and further fed back to the grid network. In this process the regenerative braking is applied where the stored mechanical energy is transformed to electrical energy to supply back to the grid. In this process a small amount of electrical energy is required to magnetise the air gap between generator's stator and rotor. It is provided by the GEX controller.

5. Results

The machine stores most of the kinetic energy in the rotating masses i.e. in the rotor which is approximately 36 tons of weight and spinning at 3000 rpm. During regenerative braking this kinetic energy is transformed into electrical energy. In this procedure a torque is induced in the reverse direction of rotor rotation thus resulting quick drop in rotor rpm. Shaft power and rpm (Table 1) is recorded from the human machine interface (HMI) and plotted in Figure 5.

Table 1. Machine's RPM & shaft power

S. No.	RPM	Power in kW
1.	3000	850
2.	2700	697
3.	2500	590
4.	2300	580
5.	2000	518
6.	1600	466
7.	1400	425
8.	1200	360
9.	1000	298
10.	800	245
11.	600	175
12.	400	120
13.	200	48

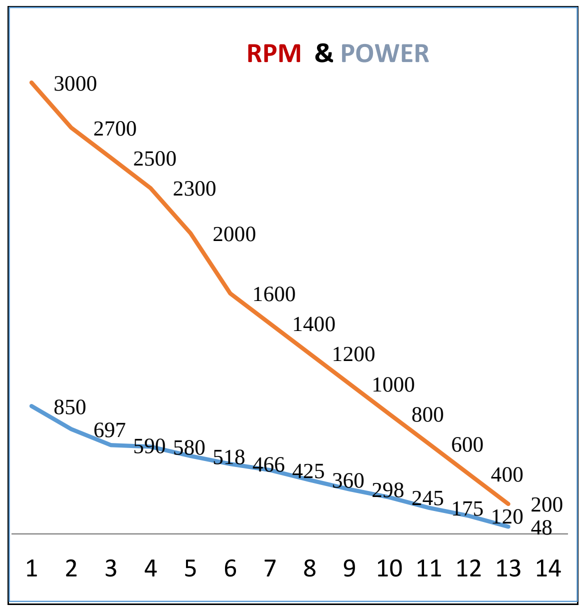

Figure 5. RPM and shaft power during braking

6. Cost Comparison

Cost of one SFC panel depends on the ratings of the power thyristors and its accessories embedded in it. Present cost of one similar SFC panel is approximately Rs. 5 Crores. This panel can be used for running a machine, applying regenerative braking and reversal of operation. By changing the firing angle of thyristors operating mode of the machine can be changed. On the other hand for DC injection braking one large DC generator and DC switching devices are needed which will be costing around Rs. 7 crores. The electrical energy is absorbed during braking of generator G1 whereas; in case of G2 electrical energy is delivered to the grid. Over the 10 minutes of single regenerative braking period approximately 60 kWh of electrical energy is generated. Daily two such braking is applied and on average 40 instances happened in a month i.e. around 2.4 MWh of electrical energy is feedback to the grid. If net metering is applied energy savings will be around Rs.5 lakhs yearly for braking of G2.

7. Conclusion

For heavy and large electrical machines mechanical braking system is not advisable due to excessive wear and tear in the braking devices which need frequent replacements. In applications where a high inertia load is present, coast-to-stop is also undesirable as it takes long time to stop. In some machine quick stop is essential for safety reasons. Electrical braking is the best option for force stopping of an electric motor. Short circuit generators discussed in this paper apply two braking methods. Generator G1 is very old and it is driven with a slipring induction motor. DC injection braking was the best available option at that period. Readiness of DC source was not a problem for this system. A permanent magnet generator was applied to cater the need of DC supply. In this process the heat generated in rotor resistances is completely safe as the resistances are cooled by blown air. As the DC current is controlled very precisely hence the braking is very smooth and no jerks observed.

For generator G2 the state of art technology is used i.e. SFC as static drive. By virtue of SFC it is possible to apply regenerative braking. 36 tons rotor mass revolving at 3000 rpm is made to stop within 10 minutes very smoothly whereas in coast to stop method (like generator G1) it would have taken more than 50 minutes. Instead of wasting energy in the form of heat the stored kinetic energy is back fed to the grid is the major benefit of this method. Thus the environmental factor is well addressed with this technology. Vibration, noise level, frictional and windage losses are also minimized in this process.

The regenerative braking is quite useful and successful but DC injection method of braking is not popular nowadays. It is being used only in the old systems where previously installed.

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