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A novel induction motor starting method using superconduction

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ABSTRACT

In this paper, an alternative method for starting up induction motors is proposed, taking into account experimental measurements. The new starting current limitation method is based on using a high-temperature superconductor. A prototype of the superconducting starting current limiter was constructed with a commercially available second-generation high-temperature superconductor YBCO tape, and this was tested with a 55-kW industrial induction motor in a 440-V/60-Hz three-phase power grid. Performance evaluations of the superconducting limiter method (applied to startup of the induction motor) were performed and were compared with a direct-on-line starter and an electronic soft starter. In addition, a computational model was developed and used for electromagnetic torque analysis of the system. As significant characteristics, our method offers the ability to limit the starting current of the induction motor with greater electromagnetic torque, reduced current waveform distortion and therefore lower harmonic pollution during startup when compared to the soft starter method.

1. Introduction

The use of superconducting devices such as transformers [1], motors/generators [2], transmission power cables [3] and fault current limiters [4] is promising, in light of the possibility of transporting high current values and reducing the Joule effect. In the specific case of superconducting fault current limiter (SFCL) devices, there is an instantaneous change of the device from the superconducting state to the normal state when the current drawn exceeds the critical current. This is an innovative and unique technological characteristic.

Superconductors have been used successfully applied as current limiters in power systems aimed at restricting the levels of short-circuiting of a given electrical grid [4]. The superconducting fault current limiter (SFCL) uses the critical current density value, which determines the switch over between the superconducting and resistive states, as a threshold for the high starting current. In short, above a certain high current level, usually under short-circuit conditions, we have the resistive state, and below the normal current level, the SFCL operates in the superconducting state with zero resistance. Because the inrush current of a three-phase (3-Φ) induction motor (IM) is up to 10 times higher than the normal current, it is possible to use the operating principle of fault current limiters to limit the IM starting current.

The conceptual analysis of a new starting current limitation for induction motors is presented in this paper, along with the first prototype of a superconductive starting current limiter (SSCL) design. Tests are carried out using a squirrel cage induction motor with 55 kW, four poles, 440 V and 60 Hz. In addition, total harmonic distortion (THD) analysis of the motor current is performed to compare the new starting method SSCL with an electronic soft starter. This is done with a focus on the power quality during the motor startup. Next, a computational simulation for the system is run to estimate the performance of the electromagnetic torque developed by the motor in both methods.

1.1. The asynchronous motor

Currently, the three-phase (3-Φ) asynchronous or induction motor (IM) is the most commonly used electrical equipment in industry. This is because of its well-known low cost of manufacture, robust construction, reliability and low maintenance requirements.

Despite its simplicity and low cost, this motor has one great drawback—a large initial current surge. Until the motor reaches its rated speed, over durations that can last for hundreds of milliseconds to a few seconds, the current remains in the range of five

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to ten times the rated current. The mechanical load driven by the electric motor defines this time. In addition, because the electrical circuit is highly inductive, the peak of the current can be further increased due to the asymmetry of the current waveform [5].

In this work, we will specifically discuss the three-phase squirrel cage induction motor or simply the induction motor (IM).

1.2. Induction motor starting current

The conventional way of running this type of motor is by direct-on-line (DOL) startup. For an induction motor, direct-on-line startup presents no problem because the IM is designed to withstand this type of startup. Although the IM is able to handle this high current during DOL startup, from the power grid point of view, the high inrush current may cause various problems that affect the electrical installation. In this context, the main drawbacks are a significant voltage drop in the supply from the power grid, electromagnetic interference in other electric equipment during operations, mechanical stress caused by the sudden increase in torque, and a need to oversize the electrical system [5].

To reduce the starting IM current, several starting current methods are available for the various types of industrial motors. Based on the literature, we can list the following [6]:

- Direct-on-line starting.
- Wye–delta starting.
- Autotransformer starting.
- Series impedance starting.
- Electronic soft starter.
- Electronic 3-Φ inverter (variable-frequency drive) starting.

However, the common choices to limit the inrush current for large power asynchronous machines (typically above 37 kW) are confined to power electronic devices such as soft starters or variable-frequency drives (VFDs) [7]. Actually, the VFD is not exactly a starting current method because its main function is to control the speed of the motor.

Based on common knowledge, all of the types of limitations of the inrush current during the startup of induction motors are based on reducing the applied voltage to the stator of the machine [7].

Wye–delta starting applies an initial voltage that is reduced by a $\sqrt{3}$ factor. When the speed of the motor reaches approximately 90% of the nominal speed, the stator voltage is stabilized at the nominal voltage.

The autotransformer starting method uses more voltage levels than the star-delta method, typically 50%, 65% and 80% of the rated voltage.

The series impedance starting method uses an impedance to produce a drop in the applied stator voltage during the startup of the motor.

Finally, the electronic soft starter uses thyristors to supply a reduced RMS voltage by switching off the voltage waveform during a variable phase angle α. As the motor speeds up, the phase angle α is decreased, resulting in a rising RMS value of the voltage. Fig. 1 shows an illustrative example of soft increase of the voltage applied to a single-phase load.

2. The superconducting starting current limiter (SSCL)

2.1. Superconducting current limiters

The superconducting critical parameters are critical temperature – *Tc*, critical magnetic field – *Hc* and critical current density – *Jc*. For the superconductor to remain in the zero resistivity state, the temperature, magnetic field and current density values must be below the corresponding critical values. Fig. 2 illustrates this in the form of a phase diagram.

If the superconductor is inside the hatched region in Fig. 2, it will have zero electrical resistance. However, if any of the critical parameter values are exceeded, the superconductor will become resistive in behavior.

Superconductors have been used successfully as current limiters in power system applications, aiming to restrict the levels of short-circuit currents in a given electrical grid [5,8]. The superconducting fault current limiting (SFCL) devices use the critical current density as a sensor to detect a high starting current and to switch between the superconducting state and the resistive state.

In summary, above a high current level, usually under short-circuit conditions, we have the resistive state, and at a normal level of current, the SCFL works in the superconducting state with zero resistance.

The advances in materials engineering and the current manufacturing technologies of the second-generation high temperature superconducting (2G-HTS) tapes have enabled the use of superconductors in a wide variety of applications. Currently, 2G-HTS tapes are available with extended lengths and with a low range of variation of the critical parameters. The cost per ampere-meter ($/A m) of these tapes has decreased, enabling the construction of current limiters for many different applications [4].

2.2. The new startup method

The inrush current of a three-phase induction motor is up to 10 times higher than the nominal current. Therefore, it is possible to use the operating principle of fault current limiters to limit the starting current of an induction motor.

In the superconductive starting current limiter (SSCL), if the current in the superconductor is higher than the critical current, a fast transition from the superconducting state to the normal state inserts a resistance in series with the motor impedance. This causes a voltage drop as in the series impedance method. Fig. 3 shows the proposed topology in a single-line diagram.

2.3. Design of the SSCL method

The SSCL presented here was designed based on the topology shown in Fig. 4. It is made using AmSC (American Superconductor, Devens, MA) YBCO Coated Conductor (CC) tape with the following specifications: width 4.4 mm, thickness 0.29 mm, measured critical current 77 A, and linear resistance per unit length (@ 300 K) 0.32 Ω/m. The starting time of the motor can last a few seconds. However, YBCO CC tape cannot withstand high currents over any significant length of time. Therefore, it is necessary to disconnect the superconductor tape and drive the current to a shunt reactor. We used a microcontroller timer to control the opening of a 3-Φ solid-state relay (an electronic switch) that turns off the current to the tape. The superconductor tape needs to turn off before its temperature reaches 300 K. To accomplish this, the shunt reactor will take on the starting current after 80 ms. This procedure avoids damage to the superconductor [9–11].

The shunt reactor consists of a 3-Φ air core inductor with 1 mH and 0.05 Ω per phase. The reactor is able to withstand the starting current during the time necessary for the motor to reach its nominal speed.

The aim of the new method is to limit the maximum value of the inrush current to half of the DOL current. Therefore, the magnitude of the impedance of the SSCL ($|Z_{SSCL}|$) must be greater than or equal to the magnitude of the impedance of the motor ($|Z_{smot}|$) during startup. Based on the motor data, for a 55-kW, 440-V, 60-Hz, and 3-Φ IM, the rms value of the DOL current is I_{smot} = 650 A; then, $|Z_{smot}|$ = 0.39 Ω and $|Z_{SSCL}| \geqslant 0.39$ Ω.