Soft Starting of Medium Voltage Induction Motors Using a Resistive Type Fault Current Limiter

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Abstract

This paper proposes using a fault current limiter (FCL) for soft starting of induction motors (IMs). The base of this approach is on the primary resistance starting method. The proposed FCL which is installed at the beginning of an industrial feeder helps to soft starting of induction motors by controlling the current during the starting process. The current of motors starting is controlled by inserting a resistance to the current path. Using this method not only reduces the stresses on both motor's windings and power system equipments by controlling the magnitude of starting current, but also suppresses motor torque pulsations. In addition, it restores voltage of point of common coupling (PCC) and helps to other loads of power system. Control strategy of the proposed structure is presented and analytic analyses are performed in detail. Simulation results using PSCAD/EMTDC software are involved to validate the effectiveness of this structure for soft start up of IMs.

1. INTRODUCTION

Three phase squirrel-cage induction motors (IMs) are widely used in industry applications due to their low cost, high reliability and less maintenance. These motors consume about 60 % of the electrical energy generated in industrialized countries [1-2].

However, Direct-On-Line (DOL) starting of large IMs in medium voltage range lead to a surge current around 6-7 times larger than its normal current. In addition, transient pulsations of torque occur at starting stage that can be several times larger than its normal operation value. Large starting current of IMs results in some problems for itself and for the utility such as: large voltage drop on point of common coupling (PCC) and consequently, effect on normal supply of parallel loads; cause a undesired trip on overload and either undervoltage relays and starting failure; generating joule heat on the winding of stator and damage the winding insulation and so, reduce the motor life. On the other hand, when the mechanical load is small, excessive acceleration of rotor by the full voltage starting can produce torque oscillations in the shaft causing severe wear to transmissions, gears and drives [3-5].

Reducing starting current not only reduces the stresses on the power utility equipments, but also decreases the stresses on the motor and driven equipment. Many methods are used to soft start up of IMs in literature, especially in case of big motors and also those compared each other [6-14]. Most of these methods have the capability of speed controlling, too. However, in some cases, application of IMs in industry is in a way that it is not necessary to control their speed and they are used in constant speed. Therefore, only controlling the starting current of them is needed. Star-delta starting, starting by liquid resistance and magnetic controlled reactors are some of these alternatives [12].

In this paper, a resistive type fault current limiter (FCL) which is capable of controlling a current to a desired value for the soft starting of a group of medium voltage IMs is introduced. Base of this structure's operation is categorized in the primary resistance soft starting. These types of soft starters insert a resistance in one or more often in each of the phase connections to the stator at start up. The proposed structure is installed at the beginning of an industrial feeder which has a group of IMs in addition to other loads. When the IMs start up and the line current increases instantaneously, the proposed structure controls the starting current of IMs by inserting the resistance to the starting current path. Analytical analyses are presented and simulation results are provided by PSCAD/EMTDC software to show the performance of this structure in controlling the starting current of IMs, reducing their torque pulsations and restoring the PCC voltage. Note that the fault current limiting feature of the proposed structure is introduced in our previously published works [15-16].

2. INDUCTION MOTOR EQUATIONS

Equivalent circuit of an IM is shown in Fig. 1. r_1, x_1 and r_2', x_2' are the stator and rotor winding resistance and leakage reactance, respectively. Also, R_c and X_m are the core losses symbol and magnetizing reactance of motor, respectively. At the first moments of starting, slip, s, has a value near to 1. So, the value of $(1-s)r_2/s$ will be negligible. Therefore, considering Fig. 1, equivalent impedance of motor at the first moments of starting can be written as follow:

$$Z_{eq} = (r_1 + jx_1) + (R_c \| jx_m) \| (r_2' + jx_2') \qquad (1)$$

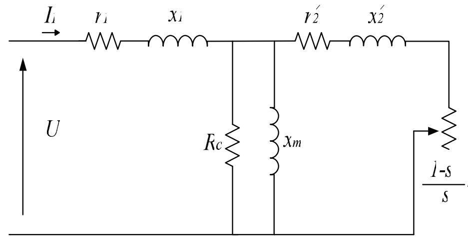


Fig. 1. Single phase equivalent circuit of IM

So, starting current of IM can be calculated by Eq. 2:

$$I_{st} = U / Z_{eq} \quad (2)$$

where, U is the utility voltage.

The starting current of IM has a transient part which is caused by leakage and magnetizing reactances. Magnitude of current transients depends on the value of $1/Z_{eq}$ (see Eq. (2)) and the duration of this current depends on the time constant of Z_{eq}, i.e. L_{eq}/R_{eq}, where L_{eq} and R_{eq} are the equivalent inductance and resistance of Z_{eq}, respectively.

In addition, starting torque of IM can be achieved by Eq. 3:

$$T_{st} = \frac{3pr_2'}{2\pi f} I_{st}^{\,2} \quad (3)$$

where, p and f are motor poles number and source frequency, respectively. On the other hand, from *(d, q)* reference frame point of view, motor's electro-mechanical torque equation can be achieved by:

$$T_{em} = 2pL_m(I_{rd}I_{sq} - I_{rq}I_{sd}) \quad (4)$$

where, L_m is the mutual inductance of stator and rotor windings and (I_{sd} , I_{sq}) and (I_{rd} , I_{rq}) are *(d, q)* components of the stator and rotor currents, respectively.

Considering Eq. (3) and (4), motor torque and its variation depends on the motor current and its transients. So, the current transients lead to torque pulsations at the first moments of motor starting. As a result, by increasing the value of Z_{eq} and decreasing its time constant, it is possible to decrease the current transients and consequently torque pulsations in the starting process. On the other hand, by increasing R_{eq}, the value and time constant of Z_{eq} become larger and smaller, respectively. Therefore, the current transient and the torque pulsations will be minimized and damped in a short time. As a solution for increasing R_{eq}, the proposed structure is capable to place a resistor in series with the IM (primary resistor).

3. Operation Principles of the Proposed Structure and its Control Method

The Single phase power circuit topology of the proposed structure is shown in Fig. 2. This topology is composed of two main parts which are as follows:

- A diode bridge rectifier,
- An IGBT switch in parallel with a large resistor (R) which is the most important part of structure.

Before starting of IMs, IGBT is ON and line current $i_L(t)$ passes through "D_1, L_d, *IGBT* and D_4" in positive alternatives (Fig. 3a) and from "D_2, L_d, *IGBT* and D_3" in negative alternatives of power system frequency (Fig. 3b). Therefore, the feeder provides demand of other connected loads.

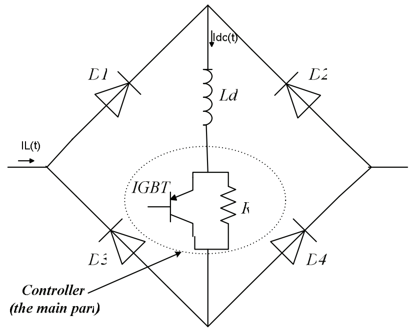
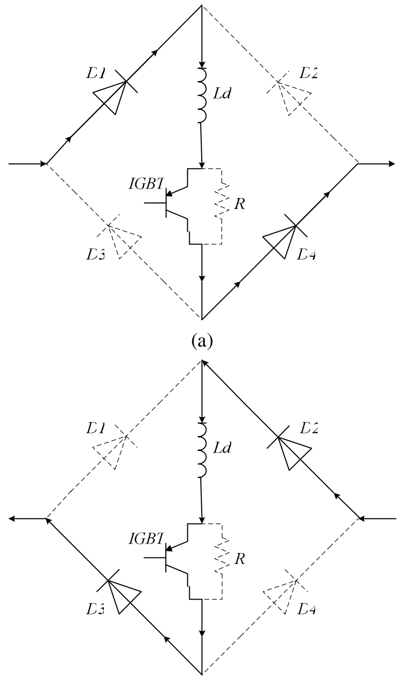


Fig. 2. Single phase power circuit topology of the proposed FCL



(a)

(b)

Fig. 3. Operation modes of the proposed structure: (a) positive and (b) negative alternatives of line current

By beginning the starting process, the line current and consequently dc side current $i_{dc}(t)$ rises rapidly. A small dc reactor (L_d) is placed in series with the IGBT to protect it against severe *di/dt*.

When the current reaches to a pre-defined value, I_0, which can be set by the system operator, control circuit turns the IGBT off. Therefore, the proposed structure inserts the resistor R to the current path. In such condition, starting current will be controlled by this resistor. As pointed previously, inserting this resistor to the motors current path has two advantages: firstly, it can control the surge current and consequently helps to the motors for soft starting and restores the PCC voltage which provides better quality for PCC voltage and its loads; secondly, the resistor can decrease the time constant of current transients which leads to torque pulsations at the first moments of starting. Therefore, motors can start up safely from these transients point of view. It is important to note that starting by the reactors has not this capability.

After the starting process and reduction of line current, control circuit turns the IGBT on again and system returns to its normal operation. Note that the desired value for resistor in ac side of structure is not equal to its dc side value, *R*. So, the relation between R_{ac} (equivalent resistor value in ac side of FCL) and *R* must be calculated. By neglecting power losses in diode bridge rectifier and the IGBT, we have:

$$P_{ac} = P_{dc} \tag{5}$$

where, P_{ac} is ac side active power of FCL and P_{dc} is dc side active power of FCL. So, we have:

$$3\frac{\left(V_m/\sqrt{2}\right)^2}{R_{ac}} = \frac{\left(V_{Ds}\right)^2}{R} \tag{6}$$

where:

$$V_{Ds} = \frac{6}{\pi}\sin\left(\frac{\pi}{3}\right)V_m \tag{7}$$

Consequently:

$$R_{ac} = \left(\frac{\pi^2}{18}\right)R \tag{8}$$

For more information about the structure, the value of L_d is selected considering the current characteristics of the IGBT, because it is placed in the structure to protect the IGBT against severe *di/dt*. On the other hand, the value of *R* is selected by the maximum short circuit current considerations.

4. SIMULATION RESULTS

Power system schematic of Fig. 4 is used for simulations. Parameters of simulation are presented in Table I. Two numbers of IMs with same parameters as Table I are used in simulations. Two sets of simulations (DOL starting of motors and starting with the proposed structure) are performed and their results are presented in this section.

Firstly, the DOL starting of motors is simulated and results of this simulation are shown in Fig. 5. Starting process begins at *t=0.5s*. Before starting process, the line current is equal to load current. By starting of motors, line current increases severely and becomes about 1250 A. In addition, it has undesired swings (Fig. 5a). This large current settles to normal state value at *t=2.5s*, i.e. the motors start up in 2 seconds. Presence of this current in the power system leads to a large voltage sag on PCC which makes power interruption of other loads.

Line to ground voltage of PCC in such condition is shown in Fig. 5b. According to this figure, voltage sag with the magnitude of 43% happens in PCC. Torque variation curve of one of study motors in this starting method is shown in Fig. 5c.

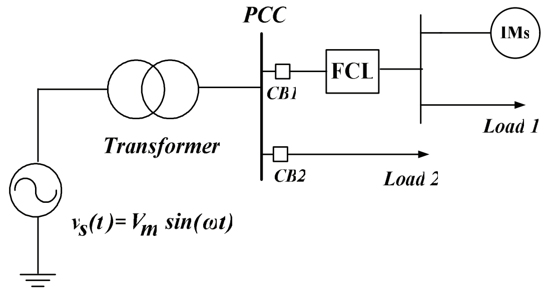


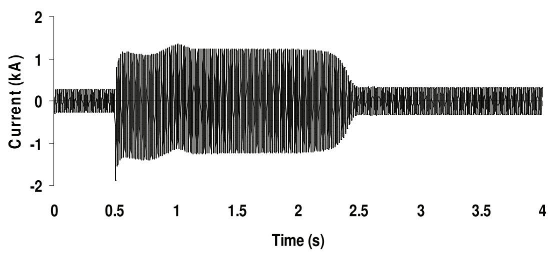
Fig. 4. Power system schematic for simulation

TABLE I. SIMULATION PARAMETERS

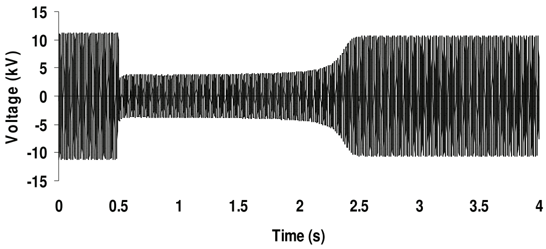
Source parameters	Power source	132kV, L-L RMS , 50Hz, $L_s = 0.03H$
	Transformer data	132/13.8 kV, $5MVA$, 0.02 pu
FCL data	dc side parameters	$R = 8\Omega$, $L_d = 0.03H$ Voltage drop on diodes =3V
Load data	Load 1	R_{L1}=5Ω, L_{L1}=0.02 H
	Load 2	R_{L2}=25Ω, L_{L2}=0.15 H
Motor data	Electrical data	13.8 kV, $1.2MVA$ $R_s = 0.0034pu, L_s = 0.0102pu$
	Mechanical data	Damping = 0.01 pu

It is observed that, torque pulsations occur at the first moments of starting which their peak to peak magnitude is larger than three times of normal operation torque. Fig. 5d shows the speed variation of this motor for this starting mode. Motor speed reaches to its nominal speed after 2 seconds and remains constant.

Secondly, controlling the motors current in a constant value by the proposed structure is simulated and shown in Fig. 6. Fig. 6a shows the line current in this starting mode, which is approximately 900 A and has constant value during starting process. As it is observed, the current has not considerable transients and its undesired swings do not exist anymore. The line current returned to the normal state value at *t=3.5s* (motors start up in 3 seconds). Line to ground voltage of PCC during motors starting with the proposed structure is shown in Fig. 6b. Percentage of voltage sag in this method is 12% approximately. Torque and speed variation curves are shown in Fig. 6c and 6d, respectively. Torque pulsations in this starting method are less than the DOL starting one, but, the duration of starting process is larger (about 1sec.).



(a)



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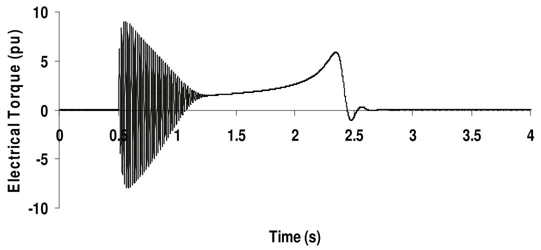

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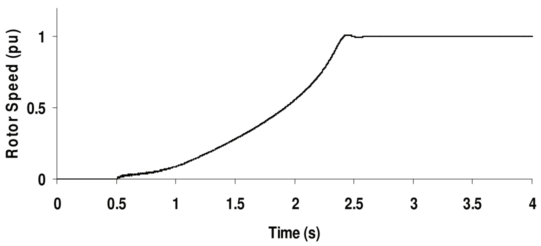
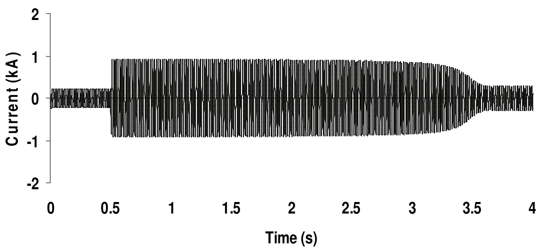
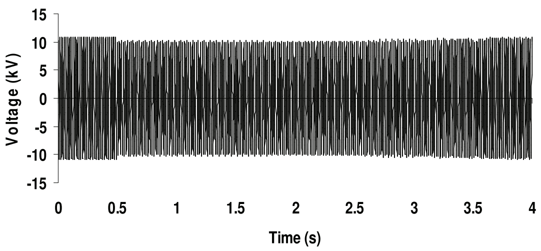


(d)

Fig. 5. Direct-On-Line (DOL) starting of IMs: (a) line current, (b) PCC voltage, (c) motor torque and (d) speed



(a)



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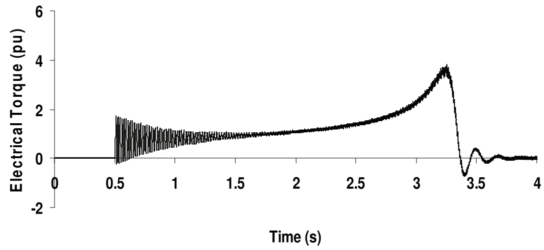

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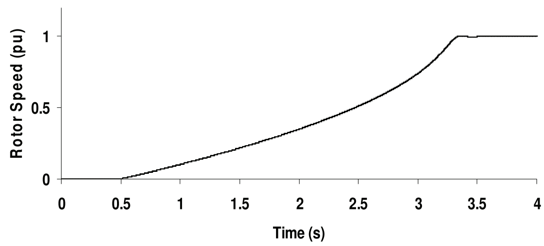

(d)

Fig. 6. Starting with the proposed structure: (a) line current, (b) PCC voltage, (c) motor torque and (d) speed

These results show that the DOL starting of IMs is not recommended. Since, for this method, because of high starting current and generated joule heat in windings, motor windings should have good thermal properties and because of high torque pulsations, motor should has strong mechanical connections. On the other hand, large starting current leads to considerable voltage sag on the PCC. Therefore, it reduces the voltage quality of other loads which are connected to PCC. However, starting of IMs using the proposed structure which is installed at the beginning of feeder controls starting current and its transients makes safe condition for the motors, power system series equipments. In addition, it provides proper voltage quality for other loads of the PCC.

5. CONCLUSION

In this paper, a structure of resistive type FCL for the soft starting of large induction motors is presented. The proposed FCL is installed at the beginning of an industrial feeder and controls IMs starting current by inserting a resistor in the line current path. This resistor not only reduces the PCC voltage sag during the starting by controlling the current, but also damps the torque pulsations of motors at the first moments of starting. Therefore, the proposed structure makes a safe condition for both motor and power system in the starting process. The analytic analyses and simulations using PSCAD/EMTDC software are performed for this structure to validate its effectiveness in controlling the starting current magnitude, reducing the voltage sag in PCC and damping the torque pulsations during the starting process.

6. REFERENCES

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