Soft and Fast Starting Induction Motors Using Controllable Resistive Type Fault Current Limiter

Naderi Seyed Behzad and Michael Negnevitsky, Senior member, IEEE
School of Engineering, University of Tasmania Hobart
TAS 7000, Australia
Naderi.Seyedbehzad@utas.edu.au

***Abstract*—This paper proposes a controllable resistive type fault current limiter for soft and fast starting of induction motors (IMs) based on the primary resistance method. Two methods of constant current and minimized torque pulsations starting for the proposed FCL are presented. A comparison is done and it is shown that method of minimized torque pulsations by the proposed structure leads to a fast and soft starting for IM. Analytical analyses are performed in details and simulation results using PSCAD/EMTDC software are involved to validate the effectiveness of the proposed FCL and its control methods for the soft and fast starting up of IMs.**

Keywords-induction motor; soft starter; primary resistance; constant current; torque pulsations

I. INTRODUCTION

Three phase squirrel-cage induction motors (IM) 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 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 2 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 under voltage 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, excessive acceleration of rotor by the full voltage starting, when the mechanical load is small, 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 startup of IMs, especially in case of big motors in literature and also those compared each other [6-13].

In this paper, a Fault current limiter for the soft starting of IM 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 startup. Two control methods of the proposed structure are presented. This structure with its control methods is able to limit the starting current and minimize the torque pulsations of motor by inserting the controlled resistor to the current path. Analytical analyses are presented and simulation results provided by PSCAD/EMTDC software to show the performance and effectiveness of the proposed FCL.

II. INDUCTION MOTOR EQUATIONS

Equivalent circuit of IM is shown in Fig. 1. At the first moments of starting, slip, s, has a value near to 1. So, the value of $\frac{1-s}{s}r_2$ will be negligible. Considering Fig. 1, equivalent impedance of IM, at the first moments of starting can be written as follows:

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

Therefore, starting current of IM can be calculated by (2).

$$I_1 = U / Z_{eq} \tag{2}$$

which U is the utility voltage. Starting torque of IM can be achieved by (3).

$$T_{st} = \frac{3pU^2 r_2'}{2\pi f . Z_{eq}{}^2} \tag{3}$$

that p and f are motor poles number and source frequency, respectively.

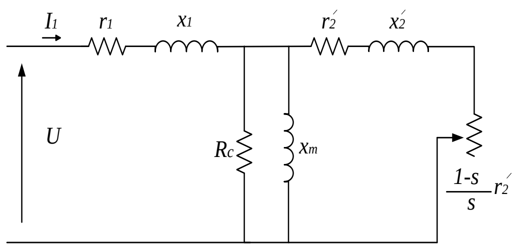

Figure 1. Single phase equivalent circuit of IM

Starting current of IM has a transient part that is caused by leakage and magnetizing inductances. This transient current leads to torque pulsations at the first moments of starting. Magnitude of transient current depends on the value of $1/Z_{eq}$ and its duration is related to the time constant of Z_{eq}; it means L_{eq}/R_{eq}, which L_{eq} and R_{eq} are the equivalent inductance and resistance of Z_{eq}, respectively. When R_{eq} increases, value and time constant of Z_{eq} decrease. As a result, transient part of starting current and torque pulsations will be minimized and damped during short time. To increase R_{eq}, it is possible to insert a resistance in series with IM (primary resistor). Variation of time constant versus primary resistance is shown in Fig. 2.

Three issues are considered in starting IM: starting current, starting time and torque pulsations. These issues are in race at the various methods of starting. Next sections deal with the proposed structure and its effect on them.

III. Operation Principles of the Proposed FCL as a Soft and Fast Starter

Three phase power circuit topology of the proposed FCL is shown in Fig. 3. This topology is composed of three main parts which are as follows:

1. A three phase transformer in series with utility that is named as "*isolation transformer*".
2. A three phase diode bridge rectifier.
3. A self semiconductor turn off switch in parallel with a large resistor (R). This part of FCL has the main effect in limiting current.

In the normal operation of power network, the self turn switch is ON and the resistance is bypassed. If the small voltage drop on the semiconductor devices is neglected, total voltage across the proposed FCL is almost zero. So, it has not any effect on the normal operation of power system. In addition, a small dc reactor (L_d) is placed in series with the self turn off switch to protect it against severe di/dt.

By beginning the starting process of IM, the line current, $i_L(t)$, and consequently the dc side current, $i_{dc}(t)$, rises rapidly. When $i_{dc}(t)$ reaches to a pre-defined value, I_0, the self turn off switch starts to switch with special frequency, f_s, and duty cycle, D, which are driven by the control circuit. Therefore, The proposed FCL inserts a controlled value of the resistance to the current path. However, if D is considered 1, equivalent resistance will be in the maximum value. In the other words, the self turn of switch is OFF during the proposed FCL's operation. In this condition, note that the value of resistance is a constant value.

During fault current limiting, to achieve a desired value of resistance from power system point of view, R_{ac}, the relation between R_{ac} and R_{dc} (equivalent average of resistance in dc side of the FCL) should be calculated. By neglecting power losses in diode bridge rectifier and self turn off switch, (4) can be expressed as follows:

$$P_{ac} = P_{dc} \tag{4}$$

where, P_{ac} is ac side active power of the proposed FCL and P_{dc} is its dc side active power.

So:

$$3\frac{\left(V_m/\sqrt{2}\right)^2}{R_{ac}} = \frac{\left(V_{Ds}\right)^2}{R_{dc}} \tag{5}$$

where:

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

Consequently:

$$R_{ac} = \left(\frac{\pi^2}{18}\right)R_{dc} \tag{7}$$

In addition, the value of R_{dc} can be calculated from D and R as follows:

$$R_{dc} = (1-D)R \tag{8}$$

Therefore, for a given R and by considering the defined function for D from 0 to 1, it is possible to have a desired value of resistance on the ac side of the proposed FCL and control the starting current and torque pulsations to the desired level.

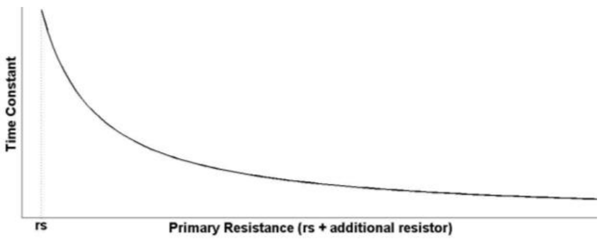

Figure 2. Time constant respect to primary resistance

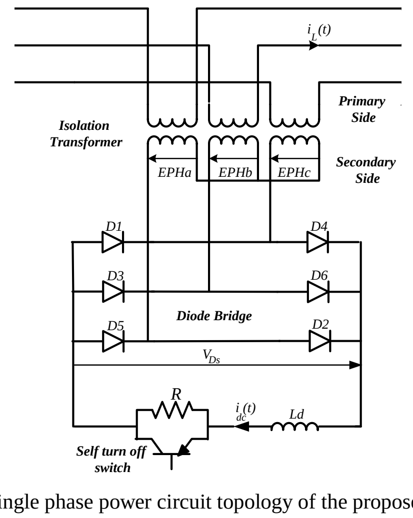

Figure 3. Single phase power circuit topology of the proposed soft starter

The proposed FCL have two control methods for soft starting of IM as follows:

A. Constant current starting
B. Minimized torque pulsations starting

A. Constant current starting

In this method, the proposed structure should insert the resistance to the network and control the level of IM's starting current. Note that this value for resistance is a constant value due to constant value of 0 for *D*. Constant current starting which controls the starting current level increases the time of starting.

B. Minimized torque pulsations starting

Minimizing both torque pulsations and starting time of IM which leads to soft and fast starting for IM is the main approach of the proposed FCL. For this purpose, a variable resistance which has a large value at the first moments of the starting and small value at the end is used. The proposed soft starter can make a time variable resistance in the power system due to its control method. It is clear that D may change in a time discrete manner in each switching period of self turn off switch. So, the value of R_{dc} and consequently R_{ac} in each switching interval is controlled. By increasing switching frequency as possible, an almost smooth variation of D and consequently R_{dc} and R_{ac} will be generated. However, some technical issues must be taken to account such as voltage drop on switch, power losses and switching frequency during the high level of current. Some ways such as using auxiliary circuits and parallel-series connections of self turn off switches have been introduced which are applicable to satisfy the requirements of a wide range of power applications [14].

By choosing a ramp function for D that varies from 0 to 1, as shown in Fig. 4, R_{dc} will vary from R to 0. So, R_{ac} will be changed from maximum to zero. By this approach, first transient and large pulsations of torque will be damped, due to large resistance value during the first moments of starting. Furthermore, IM will start in less time, because of decreasing value of resistance in starting interval. The control circuit of this method and sample signal of self turn off switch are shown in Fig. 5.

IV. Simulation Results

Power system schematic of Fig. 6 is used for simulations. Parameters of simulation are presented in Table I. Three sets of simulations are performed and their results are presented in this section.

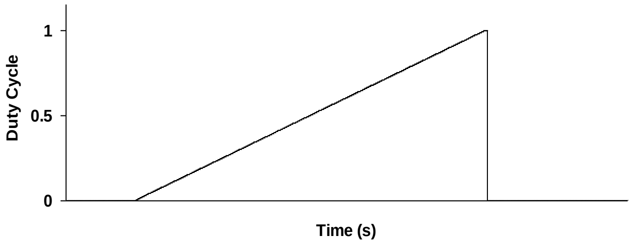

Figure 4. Ramp function for D

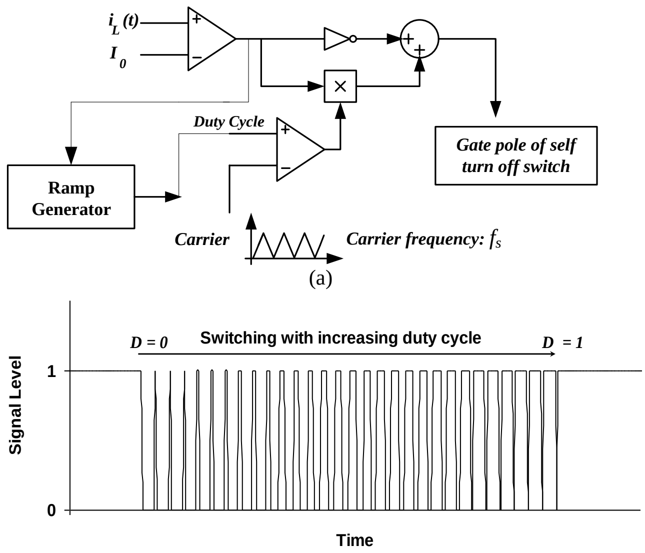

Figure 5. (a) Control circuit of torque minimizing startup and (b) sample signal of IGBT in this mode

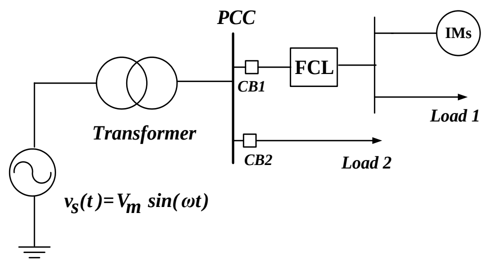

Figure 6. Power system schematic

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	$R_{L1}=5\Omega$, $L_{L1}=0.02\ H$
	Load 2	$R_{L2}=25\Omega$, $L_{L2}=0.15\ H$
Motor data	Electrical data	13.8 kV, $1.2MVA$ $R_s = 0.0034pu, L_s = 0.0102pu$
	Mechanical data	Damping = 0.01 pu

Set 1: Direct-On-Line (DOL) starting of motor is simulated and results of this simulation are shown in Fig. 7. Starting process begins at $t = 0.5s$. Fig. 7a shows the speed variation of motor for this starting mode. The torque variation curve of case study in this starting method is shown in Fig. 7b. It is observed that the torque pulsations occur at the first moments of starting. Point of common coupling (PCC) voltage is presented in Fig. 7c. Due to the large current level, there is a high voltage drop

on PCC which affects other loads. The current of motor at these moments becomes 1400A and has undesired swings (Fig. 7d). This large current settles to normal state value at $t = 1.5s$, i.e. the motor starts up in 1 seconds.

Set 2: The proposed soft starter with constant current starting method is simulated and shown in Fig. 8. In this method, self turn off switch is off (*D*=0) and the fix value of the proposed FCL's resistance enters in series to the current pass. Speed and torque variation curves are shown in Fig. 8a and 8b, respectively. In comparison with DOL starting, torque pulsations in this method are less than the DOL starting. But the duration of starting process is larger. In addition, undesired swings of current are not exist anymore. Fig. 8c presents PCC voltage. Because of limiting characteristics of the proposed FCL, voltage drop is negligible. Fig. 8d shows the current of IM in this starting mode which is approximately 850 A and has constant value in starting interval. It is returned to the normal operation level at $t = 3.5s$ (IM starts up in 3 seconds). The FCL's resistance value is shown in Fig. 8e. For $R_{dc} = 15\Omega$ and considering (7), R_{ac} is equal to 8.22Ω. As a result, there is a good agreement between simulation results and analytical analysis.

Set 3: the proposed FCL with minimized torque pulsations starting control method is simulated. Fig. 9 shows results of this starting method. Torque, speed and PCC voltage curves are shown in Fig. 9a, 9b and 9c, respectively. It is clear that there is not any significant voltage drop on PCC voltage. The current level in this method is not constant (Fig. 9d), but, pulsations of the torque are minimized in a good manner. Due to the ramp function of *D*, the proposed structure has maximum value of resistance at the first moments of starting and decreases until the end of IM's starting up (Fig. 9e and 9f). So starting time is shorter than constant current method.

To sum up, the DOL starting method is good for cases that the time of starting is important. But, this method is not recommended. As mentioned before, on the one hand, due to high starting current and generated joule heat in windings, IM should have good windings thermal properties and because of high torque pulsations, IM needs strong mechanical connections. On the other hand, voltage drop on parallel loads will be considerable. Generally, for a motor which has a weak heat sink in its windings, constant current starting is better, because the current level in starting duration is controlled. Finally, for a motor with weak mechanical connections and middle heat sink in its windings, minimized torque pulsations starting method will be a good choice and the important feature of this method is both soft and fast starting IM.

However, for better comparison of three starting methods, their responses to important factors of starting are presented in Table II.

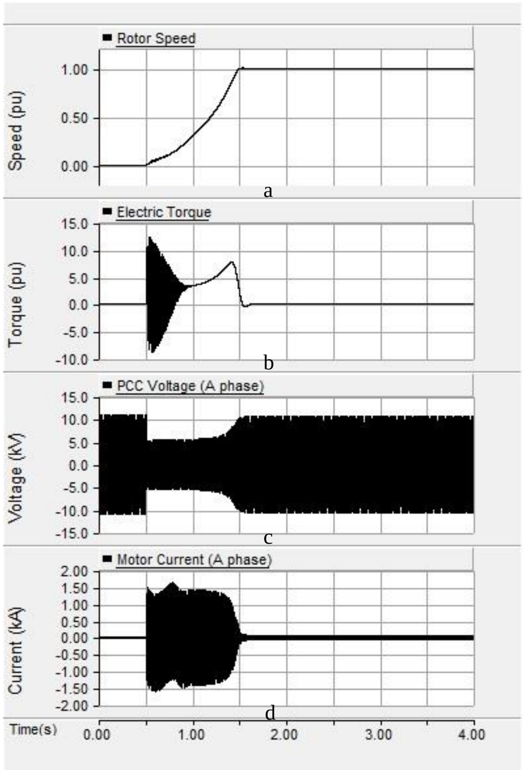

Figure 7. Direct-On-Line (DOL) starting: (a) speed, (b) torque, (c) PCC voltage, (d) current

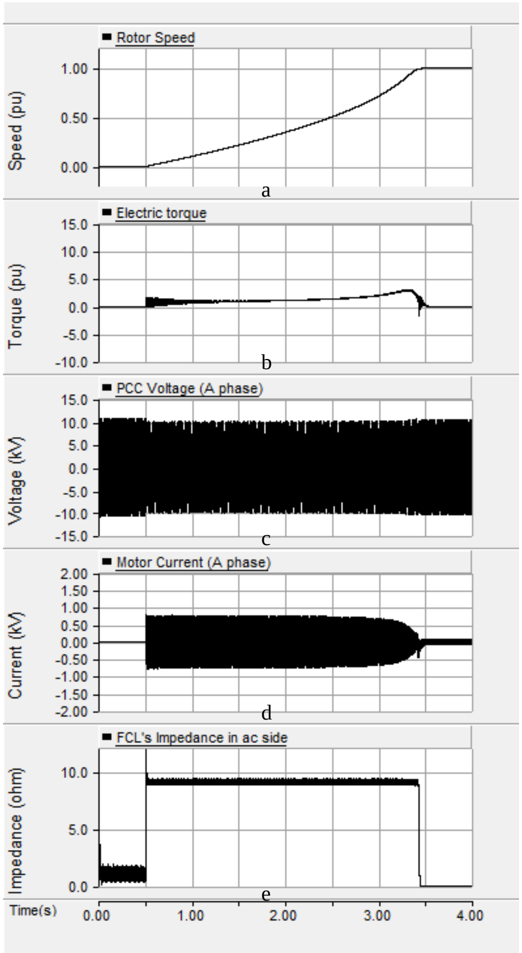

Figure 8. Constant current starting: (a) speed, (b) torque, (c) PCC voltage, (d) current, (e) The proposed FCL's impedance in ac side

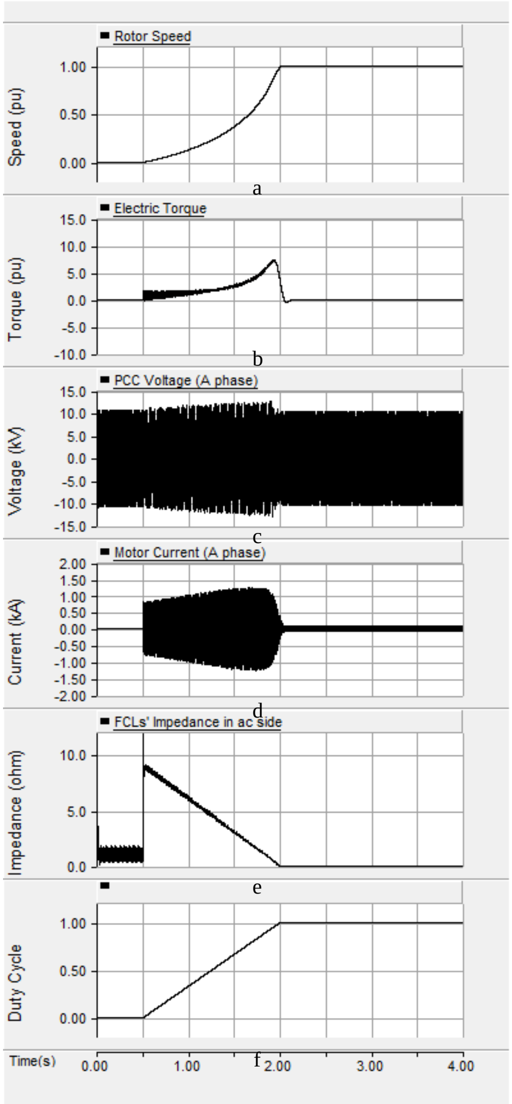

Figure 9. Minimized torque pulsations starting: (a) speed, (b) torque, (c) PCC voltage, (d) current, (e) The proposed FCL's impedance in ac side, (f) duty cycle.

TABLE II. COMPARISON OF METHODS

	Starting current	**Starting time**	**Starting torque pulsations**
DOL starting	high	short	high
Constant current	low	long	low
Minimized torque pulsations	First moments: low	short and close to DOL starting	low

V. CONCLUSION

In this paper, the proposed controllable resistive type fault current limiter for the soft and fast starting of induction motors has been presented. Two control methods including "constant current starting" and "minimized torque pulsations starting" have been proposed. Analytic analyses and simulations by PSCAD/EMTDC software have been done for the proposed structure in details. Simple structure and simple control system are the main advantages of the propose FCL. On the one hand, it has been shown that the constant current method of starting has good performance for soft starting up of IM from starting current view point but starting time is large. On the other hand, the minimized torque pulsations starting method offers both good damping characteristic for torque oscillations in the first moments of starting and lower starting up time of IM in comparison with the constant current method. In general, this structure can make a safe, soft and fast starting up condition for induction motors.

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