Sensorless flying start method for starting of induction motors

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Abstract— **Electrical variable speed drives (VSDs) are the most widely used power-electronics-based equipment in the industry that controls the performance (speed and torque) of AC induction motors (IMs). One of the main tasks of the VSDs is soft starting the IM. VSDs are usually programmed to start the IM from standstill (zero speed). In many industrial applications, due to high inertia of load or external forces such as wind, the IM may spin while the drive is in standby or off state. In such cases, high electrical and mechanical shock will be applied to the IM (and VSD) if the start command is sent. However, in cases that the IM rotation speed and direction is estimated, the VSD can control the IM from the estimated speed without any stress. The starting method without any sensor (or encoder) is called sensorless flying start (SFS). In this paper, a new SFS method for VSDs is introduced and verified in MATLAB/SIMULINK environment.**

Keywords—flying start, drive, variable frequency, variable speed, SFS, IM

I. INTRODUCTION

Nowadays, various soft starting methods are existing for induction motors (IMs). The application of variable speed electric drives (VSDs) is one of the popular methods for soft starting and controlling of IMs. Start-up methods with VSDs usually bring the IM from zero speed to nominal speed [1].

In many applications, the IM may be in rotating state before starting command. There are several reasons for this unwanted IM spin. For example, the 3-phase power supply of VSDs may be suddenly cut off for few seconds [1], [2]. Especially in large IMs with high inertia, it may take several minutes to stop [3]. Also, external forces such as wind can also cause IM to spin before starting [3]. If the spinning IM is started without considering the initial speed from zero frequency, the high electrical and mechanical stress will be applied to the IM and VSD [4]. Therefore, it is necessary to determine the IM speed before starting. One simple solution to detect IM speed before starting is to use an encoder. But using encoder is not a common method in all industries due to cost and installation issues [5]. Another more practical solution is using sensorless flying start (SFS) methods.

Different SFS methods have been introduced in the literature such as: frequency sweep method [6], enhanced method [4], residual voltage application method [7], model reference adaptive system (MRAS) method [8].

In the Frequency sweep method, the drive sweeps the output frequency while tracking the current in order to find the IM's speed. Then the appropriate torque is applied to the IM for bring it to the reference speed. Leaving a frequency that starts at maximum speed and decreases according to a predetermined slope, it reconnects until there is a change in the displayed current, which indicates the speed of the spinning. The VSD starts this process in the forward direction, and when detects that the IM is not moving forward, repeats the same process in the reverse direction [4], [6].

The Enhanced method uses Counter-Electromotive Force (CEMF). The variable frequency drive calculates the CEMF value by sending current pulses to the IM, and when it finds the value, it sends the appropriate current to the IM and then adjust to correct speed [4], [6].

The Residual voltage approach consists of the Phase-Locked Loop (PLL) and Double Second-Order Generalized Integrator (DSOGI). This method is based on the input voltages magnitude on the side of the IM and the voltage compensation. The amplitude, frequency and phase angle of the residual voltages are estimated with PLL and DSOGI and the induced initial voltage is compensated according to the operating conditions [7].

In the sensorless vector control, the speed estimation and the flux linkage are inseparable, so the accurate estimation of the rotor flux linkage is very important. The MRAS method has a reference model and an adjustable model. The voltage model is selected as the reference model, and the current model as the adjustable model. The two outputs produce the same state under the same conditions, and the difference is entered into the adaptive mechanism after comparison, and the amount of input deviation is adjusted, thus the parameters are modified in the adjustable model. The adjustable module will be continuously adjusted until the system errors are met [8].

When the IM is rotated by an external force, there is no residual flux and residual voltage in the windings because there is no source to generate current and flux, and if it is very low and affected by environmental conditions, it cannot be the basis for decision. Accordingly, the residual voltage and MRAS methods do not work in this case. EMF-based methods are very sensitive and can cause errors due to changing environmental conditions. Residual voltage and MRAS methods have more complex calculations and are more dependent on IM specifications. Therefore, many parameters change with the change in the consumption of the electric drive. Sweep and enhanced methods have simpler calculations and also have the ability to control the reverse speed of the IM, which other methods do not offer. Enhanced and residual voltage methods require voltage measurement and MRAS method requires voltage and current measurement. But the sweep method only needs to measure the current of one phase.

The sweep method is not able to measure very low speeds, but other methods have this capability. In the sweep method, the IM speed is calculated without encoder sensor, this feature can be used for other control goals.

In this paper, the sensorless flying start (SFS) method is introduced. The introduced SFS method has high accuracy in finding IM speed. The general principles of this method are modeled on frequency sweep. The introduced SFS has the ability to operate in conditions of IM rotation with external force, and is not affected by environmental conditions. Also, it doesn't need the encoder and the burden of calculations is low. It can be applied to different IMs.

The remainder of the paper is organized as follows. In Section II the proposed SFS method is described. Section III shows simulation results in MATLAB/SIMULINK environment to validate the proposed control algorithm and finally the main conclusions are summarized in Section IV.

II. Proposed SFS

In the proposed SFS method, by controlling the voltage and frequency applied to the IM and checking the current, the IM speed can be estimated. In this way, the IM is started without any mechanical and electrical stress although it is spinning.

In this method, to perform the flying start process, it is necessary to measure the current of only one phase.

Also, a low amount of voltage (less than 10% of the rated voltage of the IM) with a variable frequency is applied to the IM to create the necessary IM flux. At the initial point, the frequency is selected equal to the maximum operating frequency (speed) of the IM. Then, the frequency remains constant for a short time until the current signal fluctuations due to a sudden change in the frequency to be damped. Then the frequency starts to decrease with a certain slope. During this process, the amplitude of the current is measured. As the frequency decreases, a relative minimum of amplitude is generated in the current signal when the applied frequency equals the IM speed. Before the applied frequency reaches the actual speed, the amplitude of the current has a decreasing trend, and if the frequency continues to decrease after equalizing the applied frequency and actual speed, the amplitude of the current will increase. At the moment when the current reaches the minimum value, the applied frequency is equal to the IM speed. If no speed is found at this stage, it is clear that the motion is not in this direction and the frequency is sent in the opposite direction.

Once the speed of IM is found, the frequency reduction process stops and the IM startup from this speed. The voltage also increases in proportion with volt/Hertz (V/f) pattern.

A. SFS algorithm

The flowchart of SFS method is shown in Fig. 1. The SFS unit is responsible for controlling the amplitude and frequency of the inverter reference voltage. The four time steps of the SFS method are shown in Table I. When the startup command is found, the time to receive the command is saved (t_0). Upon receiving the start command, the voltage range is set to a constant value of about 10% of the rated voltage. During this process, the time elapsed from the start of operation is continuously calculated. The time length of each step is also calculated. In this way, by comparing these two values, the correct step is identified.

In the first step, the frequency is equal to the maximum frequency (f_{max}). The duration of this step is equal to the initial delay determined by the user (d_1). With the initial delay, the second step begins. In this step, the frequency decreases with a certain slope (f_{slope}). The frequency at time t is calculated according to (1).

TABLE I. Time Length of Each Step

Number of Step	$\Delta t = t - t_0$
Step 1	$0 < \Delta t < d_1$
Step 2	$d_1 < \Delta t < d_1 + d_2$
Step 3	$d_1 + d_2 < \Delta t < 2 \times d_1 + d_2$
Step 4	$2 \times d_1 + d_2 < \Delta t < 2 \times d_1 + 2 \times d_2$

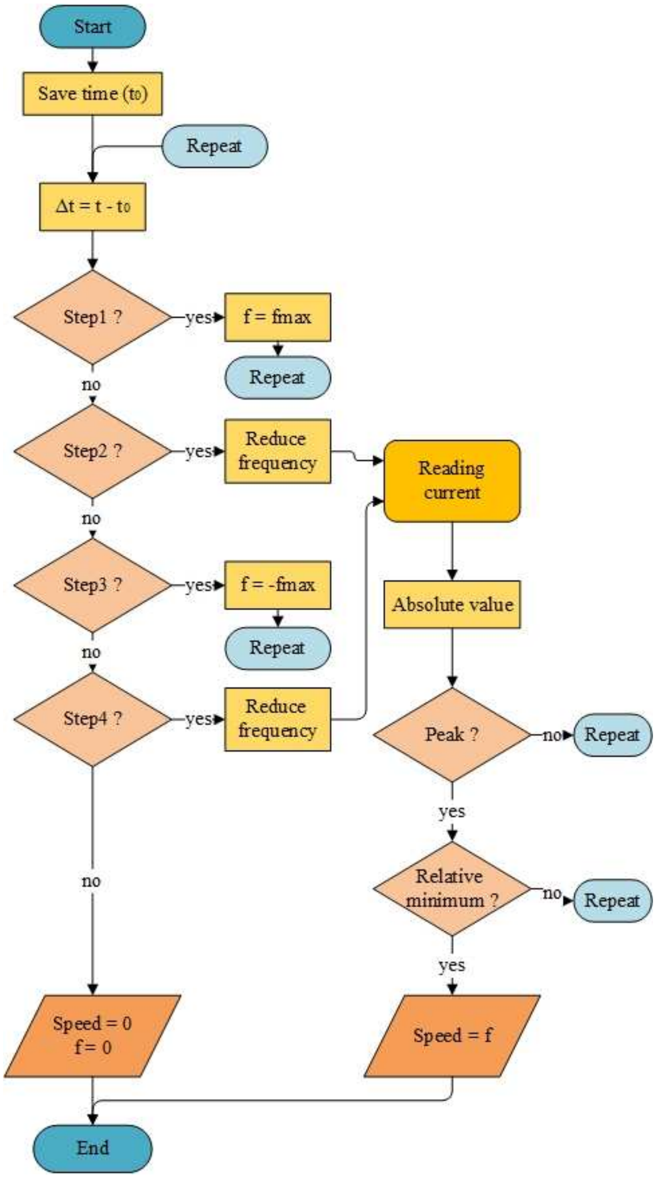

Fig. 1. SFS method algorithm

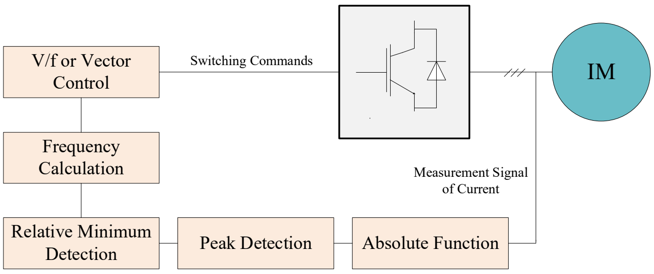

Fig. 2. SFS circuit configuration

$$f = f_{max} - f_{slope} \times (t - t_0 - d_1) \tag{1}$$

This step continues until the frequency is equal to the minimum frequency (f_{min}). The time interval that the frequency reaches the minimum value (from the maximum value) is calculated according to (2).

$$d_2 = \frac{f_{max} - f_{min}}{f_{slope}} \tag{2}$$

Passing through these two stages, the third step begins. The third and fourth steps are similar to the first and second steps. But in this section, the voltage is applied in the opposite direction. In the third step, the frequency is equal to the maximum value (f_{max}) and its duration is equal to the initial delay (d_1). In the fourth stage, the frequency is gradually reduced. The frequency is calculated according to (3).

$$f = -f_{max} + f_{slope} \times (t - t_0 - 2 \times d_1 - d_2) \tag{3}$$

The duration of this stage is equal to the second step (d_2). After the above 4-step period, the frequency is set to zero.

B. Current Signal

During the stages when the frequency is changing (second and fourth steps), the current signal is continuously monitored. The output currents of VSD are measured, therefore, the value of current is known at each moment. According to Fig. 2, the current measurement of the one phase is sufficient to perform the proposed SFS method. The current signal during this process has a sinusoidal shape with different frequencies. Due to the variable frequency, the value of root mean square (RMS) cannot be used, so the peak value of current are the basis for calculating the current amplitude. Absolute magnitude currents are taken from the measured values to account for positive and negative peaks in the calculations.

The current value is compared sequentially. At each instant, the current value is stored in three consecutive instantaneous moments, i.e., at the moment of execution and at the previous two moments, and these three values are compared. When the local maximum condition is met according to (4), the peak is detected and its value is stored.

$$I_{k-2} < I_{k-1} > I_k \tag{4}$$

The peak value of current was calculated and the last five peaks were stored. The stored five peaks are updated when a new peak is detected. In the next step, by comparing the value of the peaks, where the current has decreased and started to increase again is considered as the relative minimum of the current. The relative minimum condition is according to (5). Having three values of peaks can also find the relative minimum current, but considering five peaks increases the reliability. Fig. 3 shows how to detect the relative minimum.

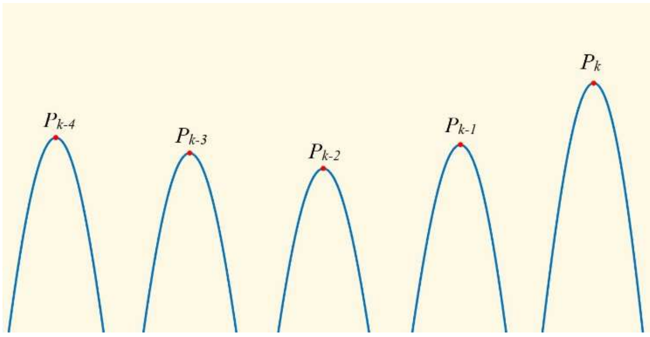

Fig. 3. Relative minimum detection

$$p_{k-4} > p_{k-3} > p_{k-2} < p_{k-1} < p_k \tag{5}$$

The relative minimum in the current signal occurs when the frequency and speed of the IM are equal. Therefore, by observing the relative minimum, the value of speed is known and is equal to the value of frequency at the same moment. When the IM speed is detected, the flying start process is stopped at the same moment and the frequency remains unchanged and equal to the same value. In this way, the conditions are ready to continue starting and delivering the IM at the commanded speed.

C. Adjustable Parameters

A number of parameters in the algorithm are determined by the user. Changing these parameters affects the speed and accuracy of the calculation. The following is a brief description of how to set each parameter and its effect.

- Voltage amplitude: To perform the flying start function, as described, the voltage is applied with a constant amplitude. The magnitude of this voltage should be less than 10% of the rated voltage, and the lower the voltage is better; because if the voltage range is high, the IM is forced to rotate with the applied frequency and applied electrical stress to VSD and IM. However, the voltage must be high enough to generate measurable current. A voltage greater than 2% of the rated voltage is usually sufficient. The amplitude of the current also increases if the voltage increases.

- Maximum frequency: The maximum applied frequency in the positive and negative part is determined according to the maximum rotation speed of the IM in the positive and negative direction In other words, in the case of each IM, it must be estimated how fast it can rotate in the right and left directions when the IM is disconnected. It is better to set the maximum frequency slightly higher than the maximum IM speed so that there is no error in speed detection.

- Minimum frequency: As explained, the frequency is reduced to some extent and enters the next stage of operation before reaching zero speed. This parameter is set to a value so that if the speed is less than this value, there will be no problem for normal starting of the IM. Because speeds less than the minimum frequency can not be measured and the IM starts from zero speed.

- Frequency slope: As mentioned, the frequency decreases with a certain slope. The higher the slope, the faster the detection because the frequency changes is more. Also, a larger slope size justifies an increase in speed calculation error. This is because it takes a while from the time the frequency equals the speed and the relative minimum occurs until the relative minimum is detected. Therefore, the larger the slope, the more the frequency changes during this time.
- Initial delay: At the beginning of the process of finding the speed in the positive and negative directions, the frequency equals the maximum possible speed and remains at this frequency for a few seconds. This time is defined by the user and is called the initial delay. This delay is due to the current signal fluctuations caused by a sudden change in frequency pass. This time interval does not cause any problems but increases the startup time; Therefore, it is better to adjust this parameter in low value to find the IM speed in lower time.

III. Simulation Results

Simulation in MATLAB/SIMULINK environment has been used to evaluate the proposed method. The used parameters in simulation are given in Table II.

A. *Simulation Steps*

First, the IM is running in nominal mode, then the IM is cut off. When the power is turned off, the IM continues to rotate free. After a while, the power supply is connected and this time the flying start unit applies the appropriate voltage and frequency. The start-up was also checked when the IM power was disconnected from the beginning and the IM was rotating due to external forces. By performing the flying start process, when the IM speed is found, its value is declared as the speed output and the frequency remains unchanged and equal to the same value. In this stage, no more operations will be performed and the conditions are ready to continue starting and delivering the IM at the commanded speed.

B. *IM Load*

To test of proposed method, the strategy must be implemented in a situation similar to practical application. Therefore, the IM load is determined based on real situation. IM load was adjusted in three modes of constant speed, constant torque and quadratic torque and the results were evaluated in these three modes. Quadratic torque is the most common type of load and the results of the algorithm in this load model are more important than others. In this case, the torque is proportional to a quadratic function of the IM speed [9], [10]. Examples of this type of loads are industrial fans and pumps.

C. *Control Unit*

To automate the speed finding function, the simulation uses a Matlab function block that is responsible for controlling the drive during startup. This function receives the execution command, time and current signal as input and adjusts the voltage, frequency and speed found at the output.

D. *Results*

The simulation was performed according to the method described. The results obtained in several cases of positive speed and negative speed are as shown in the following figures. In these results, the IM load is of the quadratic torque type. The diagrams below show the signals that are most important. The signals are presented in Table III. The names of these signals are also given in the corner of the charts.

TABLE II. SIMULATION PARAMETERS

Parameter	Symbol	Value
Nominal voltage	V_n	380 *v*
Nominal frequency	f_n	50 *Hz*
IM nominal power	P_n	3000 *VA*
SFS voltage	V_{SFS}	10 *v*
Maximum frequency	f_{max}	60 *Hz*
Minimum frequency	f_{min}	10 *Hz*
Slope of frequency	f_{slope}	50 *Hz*

TABLE III. COLOR OF RAMETERS IN SIMULATION FIGURES

Parameter	Color
IM speed	Purple
Current	Green
Frequency	Blue
Detected speed	red

- In this case, the initial speed is 50 Hz.

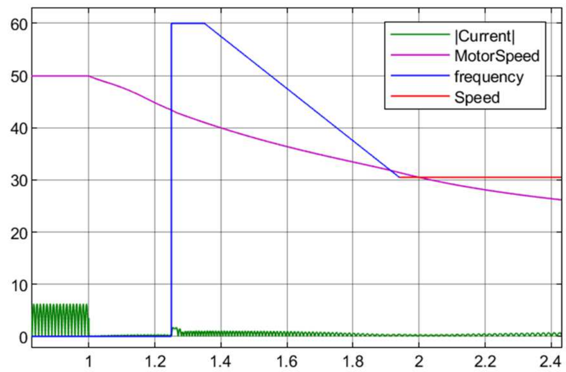

Fig. 4. Simulation result with an initial speed of 50Hz.

- In this case, the initial speed is 20 Hz.

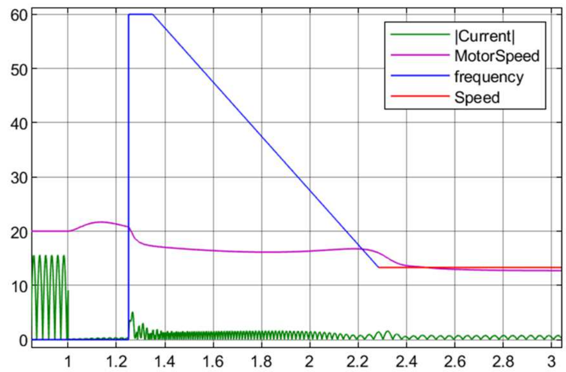

Fig. 5. Simulation result with an initial speed of 20Hz.

- In this case, the initial speed is -50 Hz.

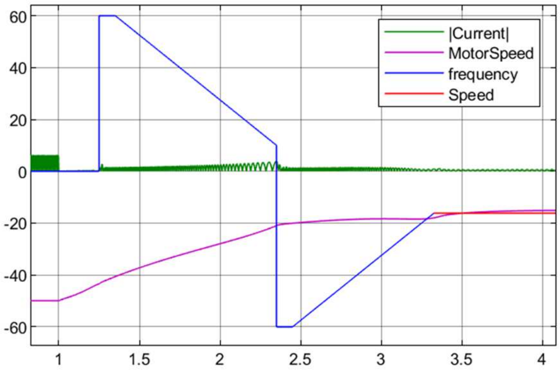

Fig. 6. Simulation result with an initial speed of -50Hz.

- In this case, the initial speed is -30 Hz.

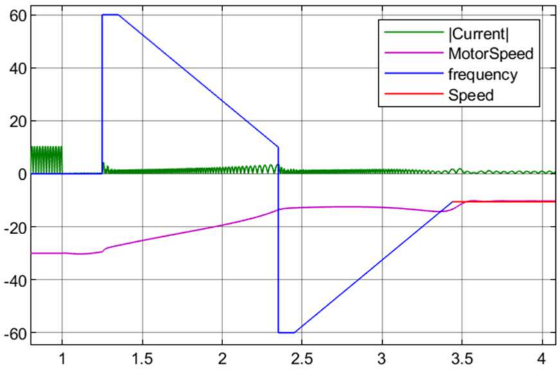

Fig. 7. Simulation result with an initial speed of -30Hz.

IV. CONCLUSION

In this paper, a method for flying start of VSD is introduced. In this method, the IM speed was detected by performing the minimum detection process. The introduced SFS method does not need any encoder sensor. The proposed system and designed algorithm were verified in MATLAB/SIMULINK environment. By implementing this algorithm, the startup process is done automatically. The proposed SFS method works properly in different conditions. The designed program can be applied in various industrial VSDs, without imposing any stress over IMs in startup process.

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