Starting of induction motor fed with stand-alone DFIG

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Article Info

Article history:

Received Jun 19, 2020
Revised Feb 20, 2021
Accepted Jul 27, 2021

Keywords:

3-phase induction motor
Constant V/f control
Indirect FOC
Stand-alone DFIG
WECS

ABSTRACT

This paper presents dynamic simulation and control of stand-alone doubly fed induction generator (DFIG) loaded with 3-phase induction motors (IMs). The study reveals that direct on-line starting of large IMs causes a large voltage sag across the generator terminals as the starting current drawn reaches up to 8-9 times the rated load current. Traditionally, this problem has tackled by oversizing of the generator or employment of special starters, under the pretext of mitigating voltage sag. This work explores ways that the starting current can be reduced economically by applying constant V/f control side by side with indirect field-oriented control (FOC) applied on the rotor side converter of the DFIG. This methodology enables starting of larger IMs and mitigation of voltage sag that occurs during the start-up period. Two different rating of IMs loaded with speed-squared mechanical torque are mainly considered. Simulation results of the system behavior under study confirm the capability of the proposed control.

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1. INTRODUCTION

Stand-alone wind energy conversion systems (WECSs) employed with doubly fed induction generator (DFIG) are a reliable solution for supplying small power consumers in areas isolated from the grid [1], as the numerous advantages such as reduced power converter rating, operation under variable speed, less losses with improved efficiency, decoupled active and reactive power control, and economically wise [2], [3]. DFIG can supply power to an isolated load at constant voltage and frequency (VF) irrespective of the variation of wind speed and the connected loads. In order to achieve constant VF most of authors have suggested the field-oriented control (FOC) strategy [1]. The output voltage is regulated indirectly by controlling the amplitude of the excitation current of the rotor (regulating the flux in the machine) while the output frequency is kept constant by imposing rotor currents with slip frequency [1]. If a bi-directional alternating current-alternating current (AC-AC) converter is connected to the rotor circuit, the range of speed can be expanded above synchronous speed and enables power production from both the stator side and rotor side. This converter consists of rotor side converter (RSC) and load side converter (LSC). RSC is used to control the stator VF and LSC is used to regulate the direct current (DC) bus voltage, harmonics compensation and load balancing [4]-[7]. Other advantage of usage of a this converter is that the converter rating is a fraction of the total output power, where this fraction is depending on the allowable operating speed range [8]-[10].

In isolated area applications, the static loads like heating and lighting are mostly used. A large amount of researches have been done on different aspects of the static loads (balanced, unbalanced, linear, and non-linear) on DFIG dynamic performances [2], [5]. However, a few amount of them are focused on the dynamic loads such as induction motors (IMs) [6], [11]. References [6] and [11] presented the control strategies for both RSC and LSC to regulate stator output VF at rated values for variable speed operation with dynamic loads. The control strategy is tested by directly connected IM of small size compared to DFIG rating

The IM loads like farm irrigation pumps, ventilation fans used in livestock housing, air compressors, and small pistons are used in the agricultural areas [12]. Hence, the dynamic interactions studies between the IM loads and DFIGs are needed. As known, IMs which are directly connected to the supply draw several times (8-9 times) their rated motor current with low power factor. Also, they consume a high amount of reactive power during start-up period. As a result, a voltage dip is produced which its amount is directly related to the reactive power need of the motor during start-up [13]. This voltage dip causes a reduction of the motor torque the during start-up period and repeated tripping for relays especially in separated power systems [14].

In a specific installation in which the major load is a 3-phase IM and directly online start-up method is used, the generator rating is sized to the apparent power that is consumed by the motor during the start-up period. Hence, in order to meet the IM power requirements, the generator rating must be sized up to 8-9 times the capacity of the motor power [13]. Hence, high cost is required for the electrical system equipment such as transformers, cables, and circuit breakers as they require to be scaled to the value higher than the required value at steady-state condition to sustain the motor start-up requirements [14]. A several methods in [15], [16] have been employed to mitigate the voltage sag caused by the start-up process for IMs in order not to exceed the permissible values for IM loads which is about 21% [17]. These methods are: a) reduced voltage electromechanically by using auto-transformers, dampers, resistors, and star-delta start), b) capacitor assisted starting, c) reduced voltage by using solid state switches such as soft starters, d) adjustable speed AC drives, e) starting duty rated]16[, [18]. The usage of those methods to maintain the supply voltage at acceptable levels is considered as expensive solutions.

In this paper, the dynamic performance and control of a stand-alone DFIG feeds a 3-phase IM loaded by speed-squared mechanical torque is presented. The output VF of the DFIG is controlled through the RSC by applying a constant V/f control during start-up period of IM side by side with indirect FOC. The main goal of the proposed control strategy is to overcome the voltage sag across the DFIG terminals caused by direct on-line start of relatively large IM with respect to the size of the DFIG. Before the connection of IM, the controller starts the DFIG at low values of stator output VF. The reference values of stator output VF are chosen so that the ratio V/f maintained constant. After the IM is connected, the DFIG output VF is gradually increased, with V/f ratio maintained constant, until they reach their nominal values.

The results show that by applying this procedure the starting current of IM is reduced and voltage sag problem is mitigated during start-up period and not exceeding the allowed limits. Thus, the advantage of this method is that the problems of the high start-up current and consequentially the voltage sag are solved with a cost-effective control scheme without oversizing for the DFIG ratings or employment of special starters. Simulation results of the system behavior during transient and dynamic phases using MATLAB/Simulink package confirm the capability of the proposed control system.

2. SYSTEM CONFIGURATION

The stand-alone WECS configuration of DFIG based with IM load is shown in Figure 1. It consists of wind turbine (WT) drives a DFIG via a gear box (GB). A battery is connected to the DFIG through bi-directional 3-phase pulse width modulation (PWM) RSC to control the DFIG output VF via the rotor currents. The IM is directly connected to the stator of DFIG via a circuit breaker (CB). The motor drives a mechanical load with speed squared torques characteristics such as an irrigation pump. A C-filter is used to reduce stator output voltage harmonics.

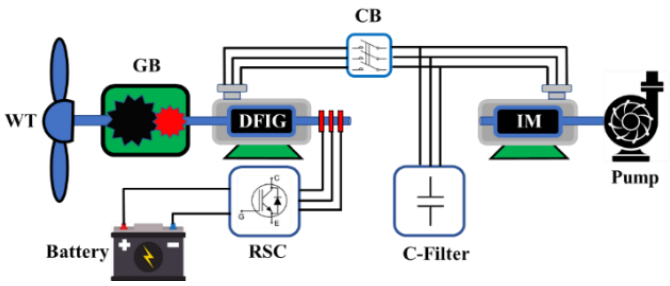


Figure 1. System configuration of DFIG-based stand-alone WECS with IM load

3. DYNAMIC PERFORMANCE OF 3-PHASE IM DIRECTLY CONNECTED TO DFIG AT RATED OUTPUT VF

When a 3-phase IM connected to stand-alone DFIG, the terminal VF must be constant. This can be implemented by controlling the rotor input currents through RSC and battery. Figure 2 shows the indirect FOC algorithm scheme of RSC connected to DFIG based on direct voltage control [4]. The main purpose of the RSC is to maintain the stator output VF of DFIG constant at rated values irrespective of wind speed and loads variations. The advantages of direct voltage control method such as being independent of machine parameters and regulating stator voltage more accurately [19]. Controlling RSC strategy is implemented using two independent control loops, one of them controls the DFIG stator output frequency (frequency control loop) and the other one controls the magnitude of the DFIG stator output voltage (voltage control loop). Rotor current *d* and *q*-axis components, i_{dr}, and i_{qr} are used as the independent control variables to force stator-flux space vector to be aligned with the *d*-axis of the synchronously rotating reference frame [20].

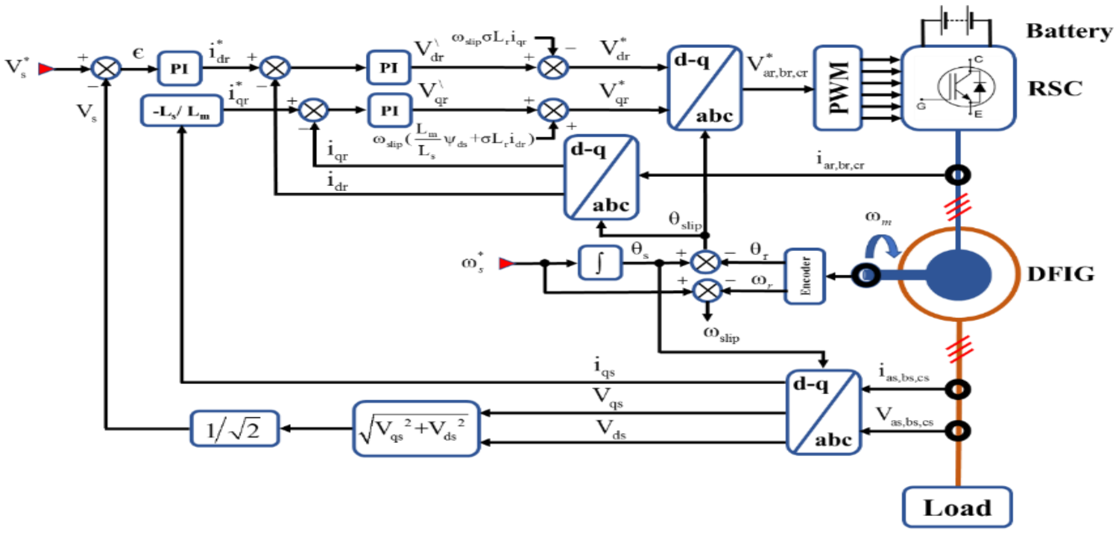


Figure 2. Indirect FOC algorithm scheme of RSC for stand-alone DFIG based on direct voltage control

3.1. Frequency control loop

The stator-flux space vector electrical angular-speed should be constant to produce a stator output voltage at desired frequency despite of the connected loads or speed variations. The frequency control is achieved by defining a synchronous reference-frame according to the required output frequency and forcing the stator-flux space vector to be aligned with its *d*-axis. The alignment can be implemented by forcing the reference value of i_{qr}^* so that [4], [6], [21]-[23]:

$$i_{qr}^{\ *} = -\frac{L_s}{L_m} i_{qs} \tag{1}$$

Where L_s and L_m are the stator and mutual inductance respectively of the DFIG.

3.2. Voltage control loop

The voltage control loop is responsible for controlling the magnitude of the DFIG stator output voltage at desired value. This can be achieved directly by controlling the magnitude of the direct axis component of the rotor current i_{dr}. The reference direct axis rotor current i_{dr}^* is produced by regulating the terminal voltage error ϵ between reference and estimated actual terminal voltage, where $\epsilon = V_s^* - V_s$, respectively, through PI controller as shown in Figure 2. The actual terminal voltage per phase can be calculated from the measured output voltages after transformed to *d-q* reference frame is being as [4], [21]-[23]:

$$|V_s| = \sqrt{V_{qs}^2 + V_{ds}^2} \tag{2}$$

Then *d* and *q*-axis reference rotor current components (i_{dr}^* and i_{qr}^*) are compared with the measured rotor current components (i_{dr} and i_{qr}) and the current error is passed through the PI controller to give $V_{dr}^{\backslash}$, and $V_{qr}^{\backslash}$ signals respectively. To ensure good tracking of these currents, compensation terms are added to $V_{dr}^{\backslash}$, and $V_{qr}^{\backslash}$ in order to obtain the reference voltages V_{dr}^*, and V_{qr}^*. Finally, *d* and *q*-axis reference rotor voltage components (V_{dr}^*, and V_{qr}^*) are converted into 3-phase reference rotor voltages $V_{ar,br,cr}^*$ using inverse park transformation with slip angle (θ_{slip}) which can be determine is being as [4], [6], [21]-[23]:

$$\theta_{slip} = \theta_s - \theta_r \tag{3}$$

Where θ_s is the angle calculated by integrating the fixed electrical angular speed (ω_s rad/sec) and θ_r is the electrical rotor angle calculated from the encoder pulses. These reference rotor voltages ($V_{ar,br,cr}^*$) are used to estimate the modulating signals which is compared with the fixed frequency PWM for switching the RSC.

3.3. Simulation results and discussion

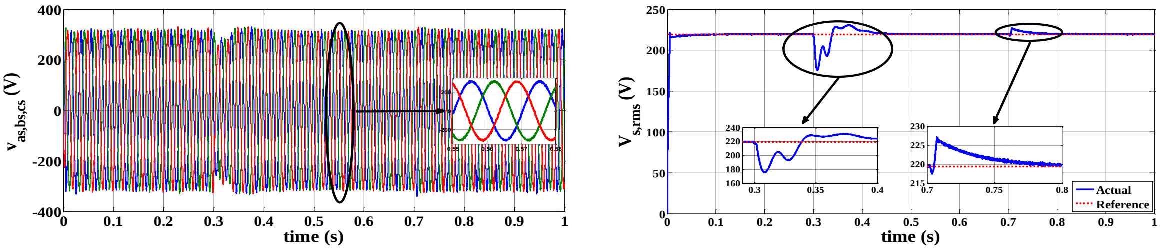
The previous control strategy is applied on 15 kW, 380 V, 32 A, 50 Hz DFIG to produce rated stator output VF during starting of 3-phase IM. Two 380 V, 50 Hz, 3-phase IMs are chosen with smaller rating of 5.4 hp (4 kW), and larger rating of 10 hp (7.5 kW). The IMs are loaded with speed-squared mechanical torque. All parameters of the DFIG and IMs are shown as:

a. DFIG parameters [24]:
   15 kW, 3 Phase, 4 pole, 50Hz, R_s=0.161 Ω, R_r=0.178 Ω, L_s=L_r=49.5 mH, L_m=46.5 mH, Stator: 380 V, 32 A, Rotor: 380 V.
b. IMs parameters [25]:
   2.1) 5.4 HP (4 kW), 380 V, 50 Hz, 4 pole, 1430 rpm, R_s=1.405 Ω, R_r=1.395 Ω, L_s=L_r=178 mH, L_m=172.2 mH, J=0.0131 kg.m^^{2}, F=0.002985 N.m.s.
   2.2) 10 HP (7.5 kW), 380 V, 50 Hz, 4 pole, 1440 rpm, R_s=0.7384 Ω, R_r=0.7402 Ω, Ls=L_r=127.1 mH, L_m=124.1 mH, J=0.0343 kg.m^2, F=0.000503 N.m.s.

The DFIG is operated at super synchronous speed mode of operation with constant speed equal 1550 rpm. The two IMs are directly connected and disconnected separately to the stator terminal of DFIG in each case. Results recorded for DFIG are instantaneous stator phase voltages $v_{as,bs,cs}$, currents $i_{as,bs,cs}$, rotor direct i_{dr} and quadrature i_{qr} current components, phase rotor currents $i_{ar,br,cs}$,stator output phase voltage magnitude $V_{s,rms}$, and stator output phase current magnitude $I_{s,rms}$. Also, the results recorded for the connected IMs such as motor torque T_m and motor speed N_m.

3.3.1. Dynamic performance of 5.4 hp (4 kW) 3-phase IM

The dynamic performance of 5.4 hp (4 kW) IM directly connected to DFIG at rated output voltage 220 V per phase and frequency F_s=50 Hz with rotor frequency F_r=1.67 Hz is implemented with simulation time t=1 sec. The DFIG firstly started at no loaded from t=0 to t=0.3 sec. At t=0.3 sec. the IM is directly connected to DFIG terminals until it reaches to steady state. At t=0.7 IM is disconnected. Figure 3 (a) and Figure 3 (b) show the instantaneous and magnitude of stator output voltage, $v_{as,bs,cs}$ and $V_{s,rms}$ respectively. As shown the voltage dip and overshot reaches to 20% and 5% respectively from its rated value during transient period for connection of IM. Hence the voltage dip does not exceed the permissible limits of 21% from its rated value. Also, the voltage overshot reaches to 3.2% during transient period at disconnection of IM. Figure 3 (c) and Figure 3 (d) show the instantaneous and magnitude of stator output currents, $i_{as,bs,cs}$ and $I_{s,rms}$ respectively. As shown the starting current is about 5 times the rated current of IM and 1.5 times the rated current of DFIG. Figure 3 (e) shows the corresponding abc rotor currents $i_{ar,br,cr}$. The IM motor torque T_m and speed N_m are shown in Figure 3 (f) and Figure 3 (g).



(a) (b)

Figure 3. Dynamic performance of 5.4 hp (4 kW) IM directly connected to DFIG at rated VF; (a) $v_{as,bs,cs}$, (b) $V_{s,rms}$

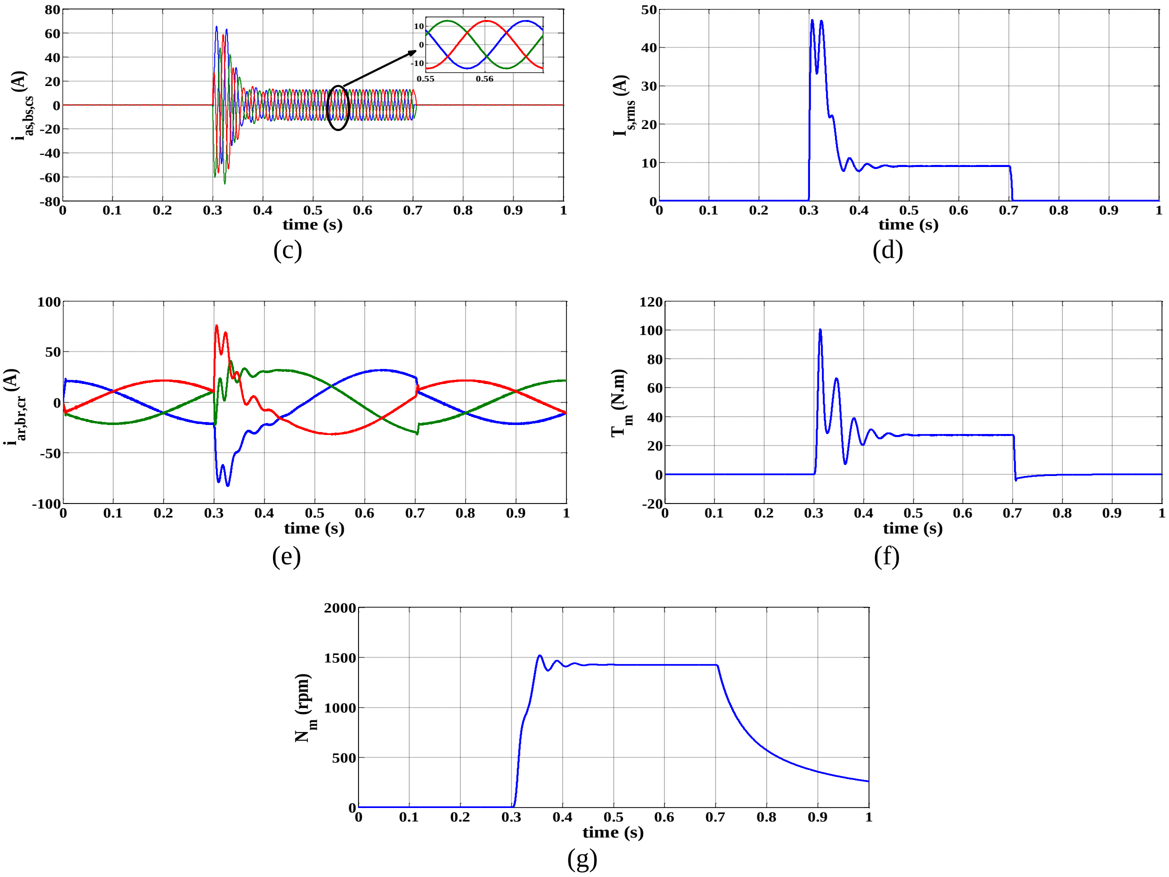


Figure 3. Dynamic performance of 5.4 hp (4 kW) IM directly connected to DFIG at rated VF; (c) $i_{as,bs,cs}$, (d) $I_{s,rms}$, (e) $i_{ar,br,cr}$, (f) T_m, (g) N_m (*continue*)

3.3.2. Dynamic performance of 10 hp (7.5 kW) 3-phase IM

The dynamic performance of 10 hp (7.5 kW) IM directly connected to DFIG at rated output voltage 220 V per phase and frequency F_s=50 Hz with rotor frequency F_r=1.67 Hz is implemented with simulation time t=0.5 sec. The DFIG firstly started at no loaded from t=0 to t=0.3 sec. At t=0.3 sec. the IM is directly connected to DFIG terminals. Figure 4 (a) and Figure 4 (b) show the instantaneous and magnitude of stator output voltage, $v_{as,bs,cs}$ and $V_{s,rms}$ respectively. As shown the voltage dip exceeds the permissible limits of 21% at the instant of start-up. So, the CB disconnect IM from the DFIG terminal to protect the IM from this undervoltage which may reach to 32% from its rated value at this instant. Figure 4 (c) and Figure 4 (d) show the instantaneous and magnitude of stator output currents, $i_{as,bs,cs}$ and $I_{s,rms}$ respectively. As shown the starting current is about 6 times the rated current of IM and 2.5 times the rated current of DFIG. Figure 4 (e) shows the corresponding abc rotor currents $i_{ar,br,cr}$. The IM motor torque T_m and speed N_m are shown in Figure 4 (f) and Figure 4 (g).

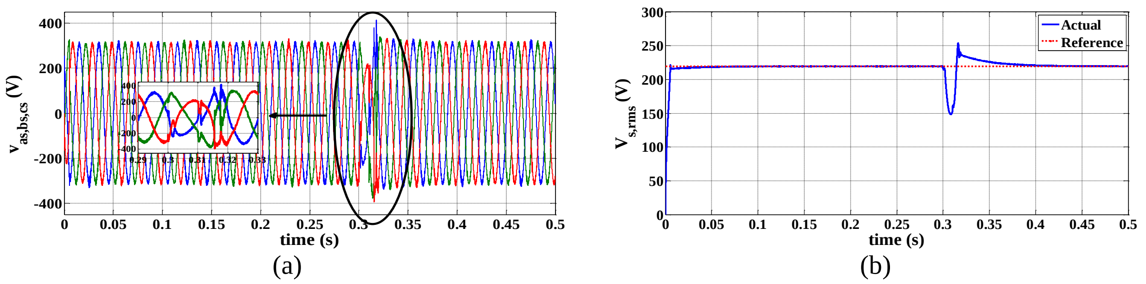


Figure 4. Dynamic performance of 10 hp (7.5 kW) IM directly connected to DFIG at rated VF; (a) $v_{as,bs,cs}$, (b) $V_{s,rms}$

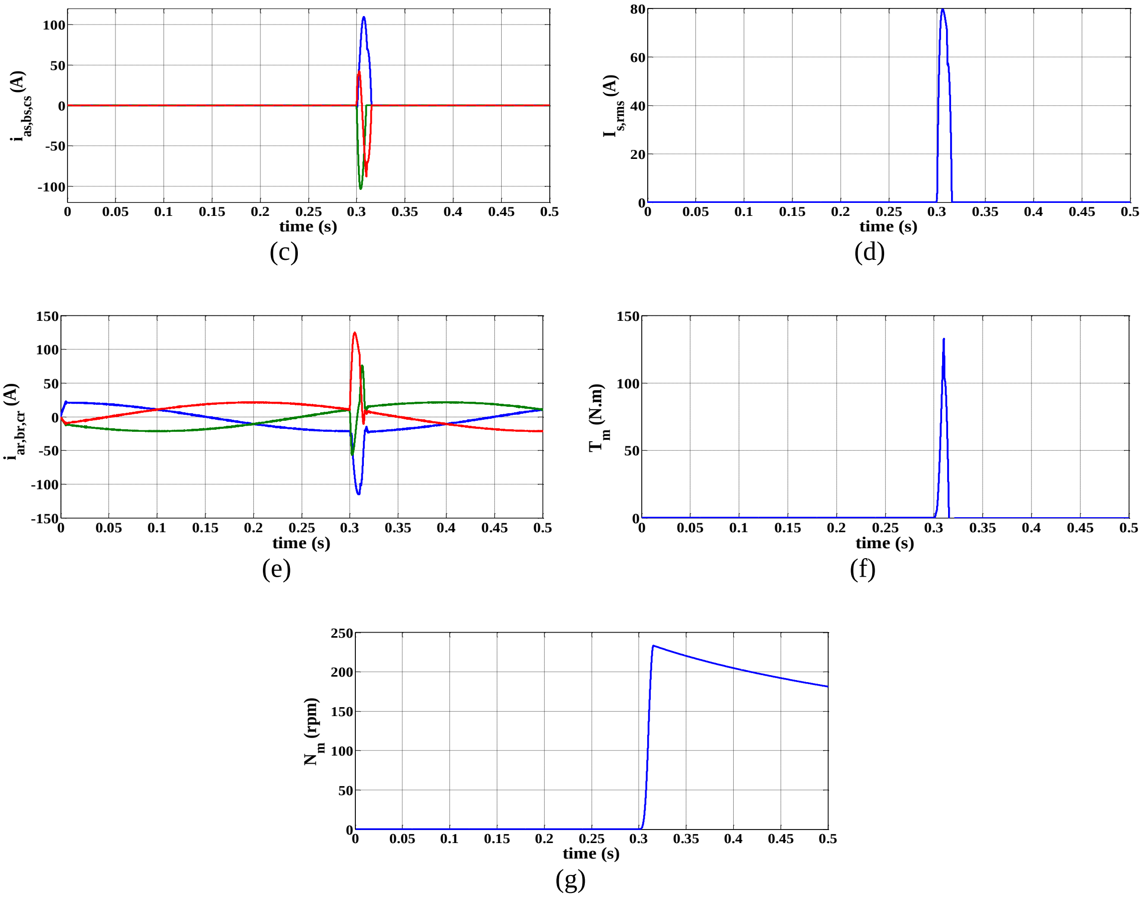


Figure 4. Dynamic performance of 10 hp (7.5 kW) IM directly connected to DFIG at rated VF; (c) $i_{as,bs,cs}$, (d) $I_{s,rms}$, (e) $i_{ar,br,cr}$, (f) T_m, (g) N_m (*continue*)

4. PROPOSED CONTROL STRATEGY FOR DFIG FEEDING 3-PHASE IM

As explained previously, the smaller rating IM succeed to start-up, but the larger rating IM failed to start-up when the two motors are directly connected to DFIG terminals at rated stator VF. By controlling the RSC, DFIG can be operated at any desired stator output VF as long as doesn't exceed the rating of the generator. Also, the generator can be operated at rated output VF or less than those rated values as long as keeping the ratio of V/f for the machine constant consequentially the flux of the machine maintain constant. Hence, the DFIG output VF can be set at low values at the start-up of 3-phase larger rating IM to overcome the starting problems.

4.1. Determination methodology for references values of stator output VF of DFIG

Figure 5 shows the proposed control methodology of RSC for choosing the references values of stator output VF for DFIG by changing the switch position between (a) and (b). For smaller rating of IM, the switch position is set at position (a) the controller set the generator frequency at rated value and hence rated output voltage. For larger rating of IM, the switch position is set at position (b) the controller operates DFIG at variable stator output VF with constant V/f ratio according to the ramp input function. The controller starts the DFIG at low values of stator output VF with constant V/f ratio before the connection of IM. When the IM is connected, the DFIG output VF is gradually increased, with V/f ratio maintained constant, until it reaches its nominal values. The saturation block limits the output frequency from controller from lower preset value to the rated value of the DFIG. By this procedure the starting current of IM can be reduced during transient period.

4.2. Simulation results and discussion

The dynamic performance of 10 hp (7.5 kW) IM directly connected to DFIG at variable stator output VF with V/f constant is implemented with simulation time t=1.5 sec. The DFIG firstly started at no load with low stator output voltage equal to 44 V per phase and output frequency equal to 10 Hz from t=0 to t=0.4 sec. At t=0.4 sec. the IM is directly connected to DFIG terminals. The IM is disconnected at t=1.2 sec.

Figure 6 (a), Figure 6 (b), and Figure 6 (c) show the instantaneous, magnitude, and frequency of stator output voltage, $v_{as,bs,cs}$, $V_{s,rms}$ and F_s respectively. As shown the voltage dip is reduced and reaches only to 18% from its rated value at the instant of connection of IM which is below the permissible limits. Also, the voltage overshot reaches to 3.2% during transient period at disconnection of IM. Figure 6 (d) and Figure 6 € show the instantaneous and magnitude of stator output currents, $i_{as,bs,cs}$ and $I_{s,rms}$ respectively. As shown the starting current is reduced to 1.9 times the rated current of IM and 0.8 times the rated current of DFIG. Figure 6 (f) and Figure 6 (g) show the corresponding abc rotor currents $i_{ar,br,cr}$ and its frequency F_r. The IM motor torque T_m and speed N_m are shown in Figure 6 (h) and Figure 6 (i). As shown, by this method the larger rating of 3-phase IM is succeed to start-up without exceeding the permissible limits of voltage dip.

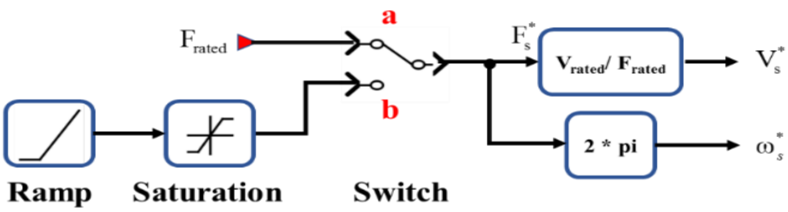


Figure 1. Proposed control methodology of RSC for choosing the references values of stator output VF references

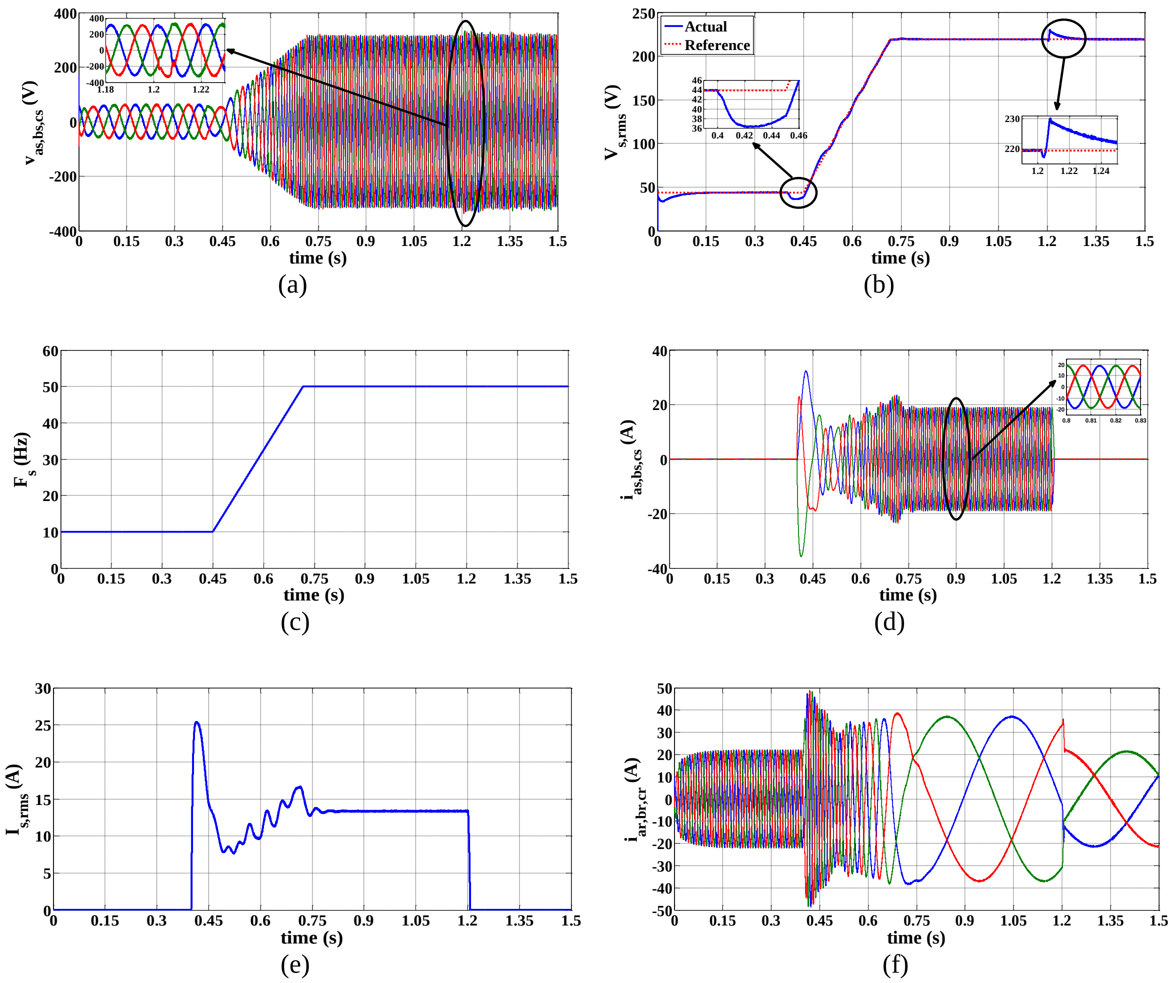


Figure 2. Dynamic performance of 10 hp (7.5 kW) IM directly connected to DFIG at variable stator output VF with V/f constant; (a) $v_{as,bs,cs}$, (b) $V_{s,rms}$, (c) $i_{as,bs,cs}$, (d) $I_{s,rms}$, (e) F_s, (f) $i_{ar,br,cr}$

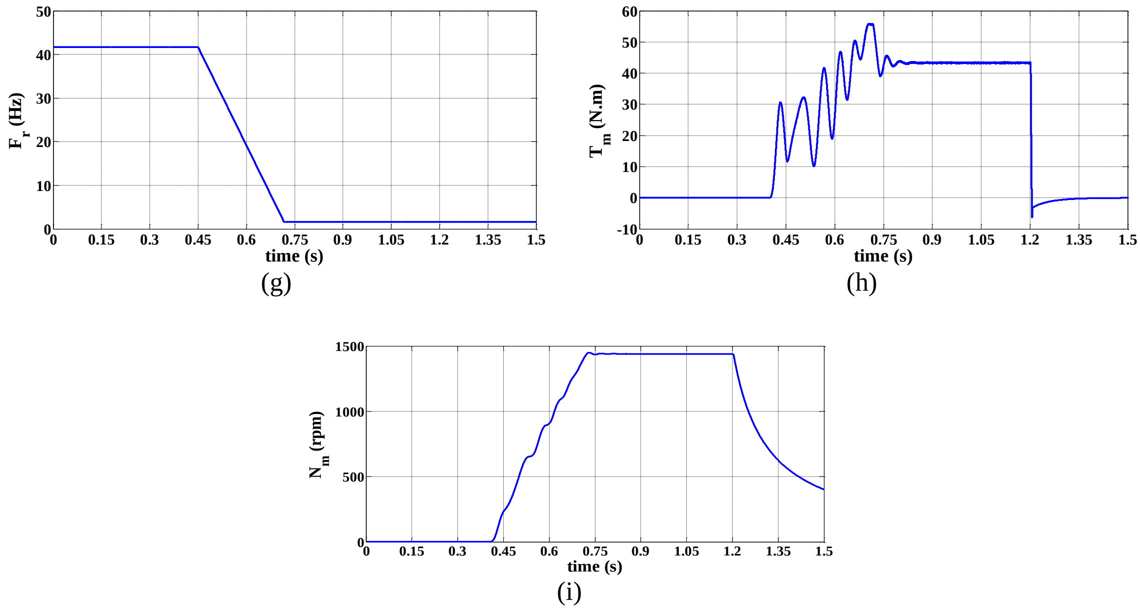


Figure 3. Dynamic performance of 10 hp (7.5 kW) IM directly connected to DFIG at variable stator output VF with V/f constant; (g) F_r, (h) T_m, (i) N_m (*continue*)

5. CONCLUSION

Direct online starting method of three phase IMs fed by DFIM in stand-alone WECS causes large starting current and consequentially large voltage dip which depending on the connected IMs rating. Two IMs with different ratings are directly connected to DFIG at rated VF. The voltage dip caused by smaller rating IM doesn't exceed the permissible limits during starting period while the larger one exceeds the permissible limits during starting period. A variable stator output VF with V/f constant control algorism is applied to RSC to control the stator output VF of DFIG during start-up period of IMs. This procedure contributed to reduce the IM starting current and mitigate the voltage sag within the permissible limits without oversizing of the DFIG rating or employment of special starters.

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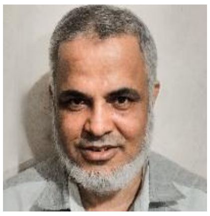

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