Blackstart of Power Grids with Inverter-Based Resources

Preprint

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Vahan Gevorgian, and Benjamin Kroposki

National Renewable Energy Laboratory

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Blackstart of Power Grids with Inverter-Based Resources

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***Abstract*— This paper presents the findings of our investigation into inverter-based resource- (IBR-) driven blackstart of electric grids. Four potential black-start configurations with different setups are presented. To evaluate the technical feasibility of IBR-driven black start in the four configurations, a behavioral model of inverters that mimics current-limited inverter operation is developed using variable resistors in the MATLAB Simulink/Simscape environment. The inverter model is connected to an induction motor through transformers and a transmission line to simulate its startup. Simulation results show that even with the limited current supply capability of inverters because of their physical constraints, IBRs can black-start a motor under certain conditions. Results also show that by using soft-start techniques, such as ramped supply voltage, inrush currents can be reduced, thereby expanding the conditions under which IBRs can provide black-start support. Simulation results with different scenarios lead to discussions and key takeaways that could be valuable for further IBR-driven black-start research.**

***Index Terms*--Black start with inverters, collective black start, inverter-driven black start, inrush current, soft start.**

I. Introduction

A black-start resource is a generation asset that can start without support from the grid [1]. Black-start capability is almost exclusively provided by synchronous machine-based power plants, and the various approaches to black-starting large power systems using these generators are well understood [2].

In recent years, increasing penetration levels of inverter-based resources (IBRs)—e.g., wind, photovoltaics (PV), and battery energy storage systems (BESS)—have created interest in understanding the technical potential and associated costs of using these resources to provide black-start support [3]–[9]. Some demonstration projects have been undertaken to use BESS to black-start conventional generators [7], [8]. The ability of a voltage source converter-based high-voltage DC system to black-start large inductive loads was demonstrated in [10]. Work on grid-forming inverter control with virtual oscillator has demonstrated potential black-start capability with grid-forming IBRs [11]. Although these demonstrations provided some evidence regarding the ability of IBRs—particularly BESS—to provide black-start support, many important aspects of black-starting with IBRs have received little attention so far, including (i) addressing the increased risk associated with the stochasticity of wind and solar PV-based IBRs; (ii) evaluating the ability of protective relays on the cranking path to operate reliably during a black start in view of the limited short-circuit current capability of IBRs; (iii) understanding the impact that IBRs might have on black-start criteria, such as the minimum time for which a black-start resource must provide rated power; and (iv) modeling and simulation to understand the performance of IBRs for a black start. This paper focuses on this last aspect and it is an initial attempt at modeling IBRs and evaluating their performance while trying to start an inductive load.

This paper focuses on the modeling and simulations required to black-start inductive loads because (i) these loads are encountered during a black start of critical loads, such as natural gas compressors and auxiliary equipment of the next-start power plant; and (ii) they can result in large transient inrush currents (typically six to eight times the rated current), which the typical inverters used in similarly rated IBRs are unlikely to be able to provide. A behavioral model of a current-limited, grid-forming inverter is developed and used in four configurations to black-start an induction motor that might represent an auxiliary motor required to start a large synchronous generator and critical loads or an equivalent motor that represents the aggregated behavior of multiple small motors in a load to be black-started. Through these simulations, the performance of IBRs to start inductive loads is evaluated, and interesting observations are made that highlight the importance of and motivate further research on detailed modeling and simulations of black start using IBRs.

The rest of the paper is organized as follows. Section II presents the four configurations in which IBRs can be used to black-start the grid. Section III provides details of the modeling and simulation approach used in the paper; it also discusses the key observations from the simulations. Section IV concludes the paper with key takeaways and future research directions.

II. FOUR POTENTIAL CONFIGURATIONS FOR A BLACK START USING IBRS

We propose four potential configurations in which IBRs can be used for a black start. Fig. 1(a)–(d) show the one-line diagrams of these configurations. Full details of the potential IBR black start configurations can be found in [12].

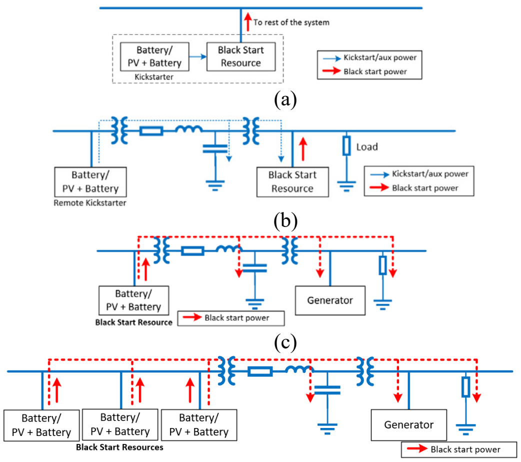

Fig. 1. Four black-start configurations for IBRs. (a)–(d) show configurations 1–4, respectively.

A. Configuration 1: On-site Kick-Starter for a Black Start

A kick-starter here is defined as a resource that helps start a black-start resource. In this configuration, the IBR is co-located with the conventional black-start-capable resource, such as a gas turbine. Requirements applicable to a black-start resource [13] are not applicable to the IBR in this configuration.

B. Configuration 2: Remote Kick-Starter for a Black Start

The IBR in this configuration provides kick-starting power to the black-start-capable resource over a transmission line and/or transformer and is therefore subject to charging or inrush current transients associated with these elements when they are re-energized after a blackout. The connection between the IBR and the black-start resource is configured so that the IBR does not need to pick up any other system load.

C. Configuration 3: Fully Functional Black-Start Resource

The IBR will act as a fully functional black-start resource. It will need to meet all the black-start resource requirements specified by a system operator and should have the ability to manage more severe load variations than those encountered in configurations 1 and 2.

D. Configuration 4: A Collective Black Start

The key difference in this configuration is that it allows multiple units to collectively black-start a system. This would eliminate the need for a fully rated black-start storage unit, implying that a black start could be conducted by a combination of smaller storage units to achieve increased reliability and resilience. Synchronization and load-sharing between inverters that can be separated by a distance are the key technical challenges to overcome to realize this configuration.

III. IBR-BASED BLACK-START MODELING APPROACH

We used MATLAB Simulink/Simscape to simulate the start of a 1.5-MW motor with a behavioral model of a current-limited, grid-forming inverter. The choice of induction motor load was primarily driven by the vast variety of blackstart loads that use induction motors including fans and pumps at generating stations and compressors at large critical loads such as natural gas compressors. Moreover, induction motor loads can result in large transient inrush currents at the time of startup. We used the same induction motor load for the four configurations so that the relative performance of the IBR to start induction motor load in each configuration could be compared. The black-start performance was also compared with that obtained from black-starting the motor load with the voltage source having 10 times more current limit, which ensured unrestricted supply of maximum transient inrush current required by the motor. The simulation circuit is shown in Fig. 2. The key elements of the circuit are described next.

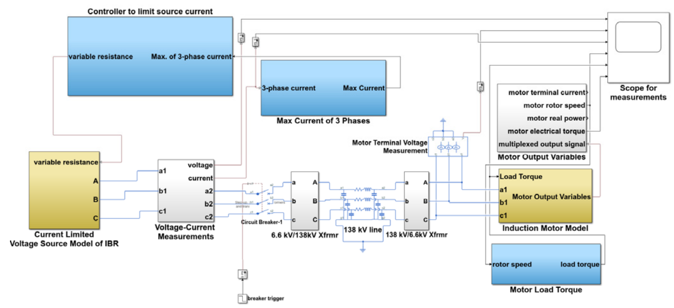

Fig. 2. Black-start simulation circuit in MATLAB Simulink/Simscape.

A. Induction Motor Model

A standard squirrel cage induction motor model of Simscape was used to model the induction motor. The motor's magnetic circuit saturation was assumed to be absent. No-load torque was assumed to be zero. The parameters for the 1.5-MW motor were obtained as listed in TABLE I by calculating the motor resistance and inductance values required for Simscape simulations from the specification sheet of a 6.6-kV, 1.58-MW motor [14].

TABLE I. INDUCTION MOTOR PARAMETERS.

Parameter Name	Value
Rated or base MVA (three phase)	1.8
Rated or base voltage (r.m.s; line-line)	6600
Stator resistance (p.u.)	0.0048
Stator leakage reactance (p.u.)	0.0412
Referred rotor resistance (p.u.)	0.0050
Referred rotor leakage reactance (p.u.)	0.0412
Magnetizing inductance (p.u.)	2.12
Stator zero-sequence inductance (p.u.)	0.0412
Inertia (kg-m^2)	10

B. Behavioral Model of Current-Limited Grid-Forming Inverter

The inverter model, as shown in Fig. 3, comprises an ideal, Y-connected, three-phase sinusoidal voltage source that is connected in series with a variable resistor whose default value, minimum resistance, is 0.7455 ohms, which results in 3% voltage drop across the source at the motor's rated current. The variable resistance is controlled during the simulation using a proportional-integral controller so that the current injected by the voltage source does not exceed its specified current limit. Inverter current limit was set at 1.2 times the rated current of the motor because (i) inverters are typically designed to provide very small over current, in general, no more than 1.2 times the rated current, and (ii) assuming the IBR's rating is equal to the motor rating will stress the inverter to its limit while trying to blackstart the motor.

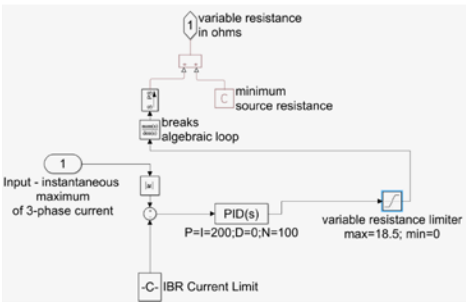

Fig. 3. Variable resistor-based inverter current limit controller.

C. Transformer and Transmission Lines

Two linear transformers connected by a 138 kV transposed transmission line were used to connect the IBR with the motor as shown in Fig. 2. The transformer and line models from Simscape were used in the simulation. TABLE II lists the line and transformer parameters.

TABLE II. TRANSFORMER AND TRANSMISSION LINE PARAMETERS.

	Parameter Name	Value
Transformer	Rated MVA (three phase)	100
	Rated voltage (r.m.s, line to line)	6600/138000
	Turns ratio (primary to secondary)	1:138/6.6 (6.6 to 138 kV), 1:6.6/138 (138 to 6.6 kV)
	Combined primary and secondary resistance (p.u.)	0.0033
	Combined primary and secondary leakage reactance (p.u.)	0.0833
	Core loss resistance (p.u.)	642,791
	Magnetizing inductance (p.u.)	520
Transmission line	Line resistance (p.u.)	0.001
	Line reactance (p.u.)	0.00266
	Total shunt charging (line-ground) admittance (p.u.)	0.00061

D. Load Torque

The load torque for the motor was modeled based on the transient torque profile given in [15]. The torque profile was scaled and its shape modified to ensure that the load torque was always below the torque-speed curve (at rated voltage) corresponding to the Y-connection of the motor. As a result, the possibility of motor stall was avoided if supplied at rated voltage and without a current limit on the source because a motor will be designed to be able to accelerate and pick up the load torque. The torque-speed characteristic of the motor and the torque-speed profile of the load torque are shown in Fig. 4. The "modified load torque-speed curve" was used in the simulations.

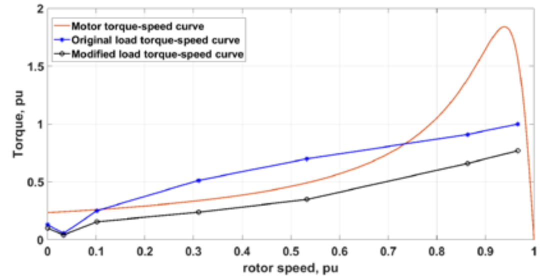

Fig. 4. Motor and load torque-speed curves.

IV. SIMULATION CASES AND RESULTS

Several simulations were performed to simulate a black start in the four configurations, as shown in Fig. 5. Only one set of simulations was performed for configurations 2 and 3 because they are very similar in the context of the simple simulations that are performed here. The simulation results for the no-load cases are not presented when the inverter current is limited to 1.2 times its rated current because it is captured in the simulations with load torque applied after the motor starts. The simulation results and observations are discussed next.

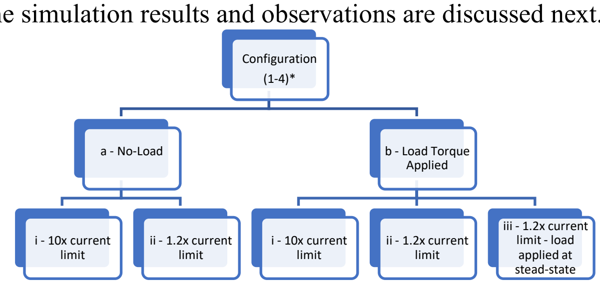

Fig. 5. Simulations run for the black-start configurations. (For configuration 4, 10-times current limit simulations were not run because one source was able to start the motor under loaded and unloaded conditions)

TABLE III summarizes the voltage and current magnitudes and start times for different configurations. Fast Fourier transform (FFT) was used to calculate the 60 Hz voltage and current magnitudes by applying it to the waveforms over the time interval during which the motor speed reaches 95% of the synchronous speed; in case the motor did not start, entire data were used for FFT. The start time was taken as the time when the motor reached 95% of its synchronous speed.

TABLE III. FUNDAMENTAL FREQUENCY MAGNITUDES OF VOLTAGES AT MOTOR TERMINALS AND SOURCE CURRENT AND MOTOR START TIMES.

Simulation label from Fig. 5	Voltage (Mean 3-phase, voltage in p.u.)	Current (Mean 3-phase, current in p.u.)	Start Time (s)
1/a/i	0.98	4.00	1.86
1/b/i	0.97	4.03	4.50
1/b/ii	0.29	1.21	No start
1/b/iii	0.29	1.18	20.67
2–3/a/i	0.95	4.13	1.89
2–3/b/i	0.96	4.17	4.75
2–3/b/ii	0.28	1.21	No start
2–3/b/iii	0.27	1.19	22.43
4/b/ii	0.72	1.05 per IBR	Unstable
4/b/iii	0.71	1.03 per IBR	3.40

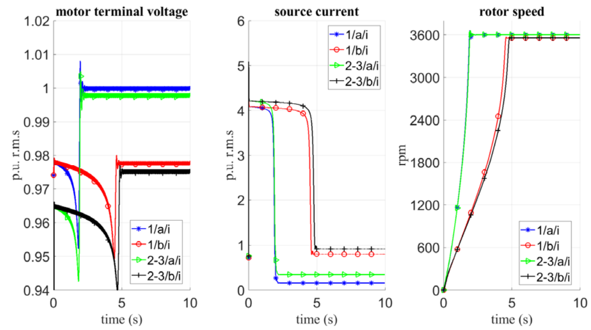

Fig. 6. Phase A voltages, currents, and rotor speeds in configurations 1/a/i, 1/b/i, 2–3/a/i, and 2–3/b/i.

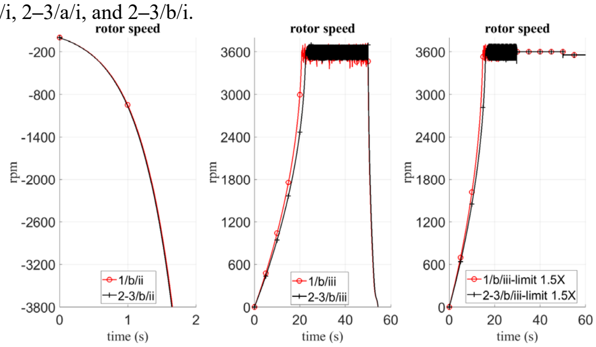

Fig. 7. Rotor speeds in configurations 1/b/ii and 2-3/b/ii (left), 1/b/iii and 2-3/b/iii (middle), and 1/b/iii and 2-3/b/iii with 1.5 times the rated current limit of the inverter (right).

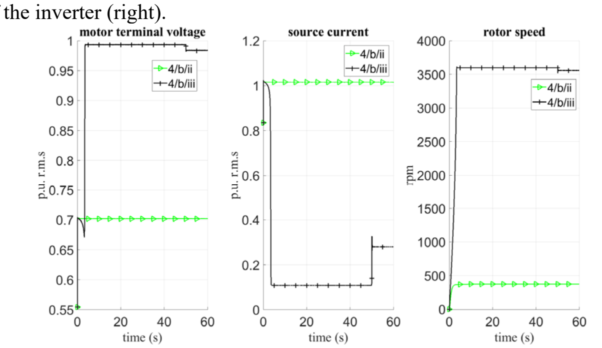

Fig. 8. Phase A voltages and currents (for one source) and rotor speeds in configurations 4/b/ii and 4/b/iii.

The plots of the root mean square values (rms) of Phase A voltages and currents (only one phase is shown because the system is balanced) and rotor speeds for the configurations in Fig. 5 and TABLE III are shown in Fig. 6 to Fig. **8**. The key observations and takeaways are:

- Fig. 6 shows that close to 5 times the rated rms current is drawn from the source almost immediately after the motor is connected to the source when the current limit is set to 10 times the rated value. The instantaneous maximum value was around 6 times, close to the value of 6.1 times the rated current given in [14] as the motor's locked rotor current, which indicates that the motor was correctly modeled.
- From Fig. 7 and Fig. 8 it can be observed that when current from the IBR is limited to 1.2 times the rated value, the motor starts under no load in all the configurations, but it takes longer than the case where 10 times the rated current was allowed from the IBR (Fig. 6) . This can be explained by the low voltage developed at the motor terminals (TABLE III), resulting in very small accelerating torque. In real applications, nonzero, no-load torque is always present and must be overcome (e.g., static friction torque). Actual tests can reveal if the near-rated-current-limited IBR can overcome such parasitic torques.
- It can also be seen that the IBR is unable to start the motor in configurations 1 and 2–3 if load torque is applied at the time of start of the motor (see negative rotor speeds in Fig. 7). This is because of the reduced starting torque generated by the motor caused by the degraded motor terminal voltage (TABLE III). In Configuration 4, the motor starts but settles at a very low speed and in the unstable operating region of the motor (Fig. 8). This implies that any small change in load will cause the motor to stall.
- Fig. 7 also shows that if the IBR current limit is set to 1.2 times the rated value and the load torque is applied after the motor has reached a steady state (at 50 seconds), the IBR is unable to supply the current required to serve the load, and the motor stalls as indicated by the sharply falling rotor speed. If, however, the current limit is increased to 1.5 times the rated value, the motor is able to sustain the load when it is applied at 50 seconds.
- In Configuration 4 (Fig. 8), when three IBRs were used to start the motor with each limited to 1.2 times the inverter's rated current, the starting time under delayed application of load is reduced significantly compared to configurations 2–3. This can be explained by the higher terminal voltage at the motor's terminals compared to the terminal voltages in configurations 1 and 2-3.

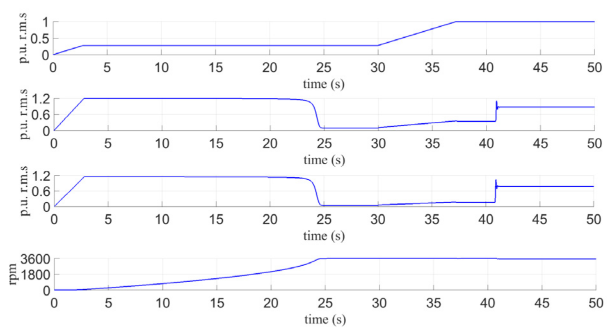

Fig. 9. Simulations results for an IBR-based motor blackstart with voltage ramp to soft start the system to suppress inrush current. Waveforms are from the top: source voltage, source current, motor current, and motor rpm.

To avoid excessive current in the beginning of a black start, including saturated-transformer inrush current, IBRs can gradually increase the terminal voltage. This approach will also help the synchronization of multiple IBRs at remote locations. To simulate this, an additional simulation is run whose setup is the same as in configurations 2–3/b/iii, and the results are shown in Fig. 9. The terminal voltage is sustained at the level that avoids the current exceeding the rated value. As expected, the ramping voltage eliminates the inrush current. Moreover, the motor can sustain the load applied after it reaches the steady state unlike the situation in 2–3/b/iii earlier where the motor stalled when 1.2 times the motor's rated current was allowed from the IBR. This further indicates the usefulness of soft-start for blackstart using IBRs.

V. Conclusion and Future Work

This paper presented modeling and simulation work that was performed to identify the technical feasibility and potential challenges of an IBR-driven black start. An inverter behavioral model to mimic current-limited operation was developed in the MATLAB Simulink/Simscape environment. The simulations show that a typically-sized current-limited inverter can black-start a large induction motor provided it is unloaded or the load is added after the motor has reached a steady state; however, the time required for the motor to reach a steady state is significantly longer when the source is current limited because of the reduced current and voltage. The start time can be reduced if multiple IBRs can collectively start the motor, which helps supply additional motor-starting current.

The presented results, however, should be taken as an initial study to identify the potential feasibility of an IBR black start in light of the assumptions in the simulations that might not hold in real-world implementation. Therefore, high-fidelity modeling of the system components and hardware validation are important follow-on research steps in this topic. Limitations of this work and future investigation opportunities are as follows:

1) Inverter Model

Ideal current sharing is assumed among multiple IBRs in the simulations, but the current-sharing behavior of inverters in parallel and/or at a distance would be greatly affected by their control algorithm, dynamic performance, interaction with IBRs, and other system assets that necessitate high-fidelity modeling and field demonstration. A study on harmonics generation and multiple inverter synchronization would also be necessary.

2) Motor Model

The non-zero no-load torque that is always present and must be overcome (e.g., static friction torque) was not modeled. Although the latter is typically small, actual tests can reveal if the near-rated-current supplied to the motor at the time of black start is enough to overcome such parasitic torques.

3) More detailed Modleing of the Four Configurations

Simulation of blackstart with IBRs in the four configurations can be made more accurate by adding details such as the sequence in which motor loads will be started in a power plant to black-start a generator, different load torque profiles, transformer saturation, and considering different IBR technologies and their capabilities to support blackstart. E.g., type 3 wind turbines operating in grid-forming mode that can provide high short circuit current to support in-rush current requirements during blackstart [16].

4) Protective Relay Modeling

Accurate modeling of motor protection functions is also important. It was observed that when the current that a motor can draw from the IBR during startup is limited to 1.2 times its rated current, it takes a long time to start. Although the current is not significantly above the motor's rated current, modeling of motor thermal protection can provide a more complete understanding of its performance during motor blackstart. In addition, modeling of protective relays in the path between the IBR(s) and the motors to be started is important to ensure that the black start with IBRs is safe and reliable. Such modeling will also reveal if protective relay settings and current strategies for setting relays during a black start need to be adjusted to facilitate a black start with IBRs.

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