Evaluating the Black Start Capacity of a Power System

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Abstract: A method for determining the required power capacity of black start (BS) for a practical restructured power system is proposed. Restructured Jordanian electric power system (RJEPS) was taken as a case study where the capacity of BS was evaluated by using previously developed models and algorithms.

The BS capacity was calculated based on the characteristics of starting auxiliary loads for different power plants. The needed BS capacity of real power (kW) is required when dealing with supplying a power plant with its power for starting from black out using the grid; While the needed BS capacity of apparent power (kVA) is required when dealing with choosing a diesel generator for supplying power plant auxiliary loads to start from black out.

Keywords: ancillary service, black start, power plant, auxiliary load, capacity.

1. Introduction

Ancillary services are defined as those functions that help grid operators maintain the reliability of the electricity system over very short periods of time up to one day, by providing flexibility to respond to variations in supply and demand, as well as maintaining frequency and voltage[5], These services include frequency regulations, spinning reserves, voltage control and black start capability.

The process of restoring the system back to normal operation involves crucial steps and considerations. Most of the generating units of the grid do not have the ability to restart by themselves, i.e., unless there is already an existing energized grid to connect to. For that reason, the system operators rely on a few units, called Black Start (BS) units that can start independently. Clearly, the location and technical specifications of these units will directly affect the restoration time and security of the power grid[3], Black Start Unit is a single generator that can start without an outside electrical supply; or the demonstrated ability of a base load unit to remain operating, at reduced levels, when automatically disconnected from the grid.[4]

2. DEVELOPED WORK

There are principally two types of auxiliary generating plants which are used for Black Starting the main generating unit of a power station, namely:

a. Diesel engines which seem to be the preferred choice by parties who are interested in providing BS services, due to their robust nature and general cost considerations.
b. Open Cycle Gas Turbines (OCGT) where costs are dependent on whether existing OCGT units are already on site or new generating units need to be installed. The costs relating to existing (i.e. older) plant tend to be limited to annual maintenance and any remedial / necessary overhaul work. For generators requiring new OCGT auxiliaries, similar typical all-inclusive prices are slightly higher than for diesel plant (10% or more depending on the unit size).

2.1 Starting of Auxiliary Loads

The transient and steady state load profiles of all the BS switched loads, added together in their correct start up sequence, will give a good indication of the kW and the kVA requirements of the needed BS capacity.

In case of starting motor loads by diesel generators, which have relatively high impedances compared to a main supply which has a constant voltage supply, these impedances will result in a voltage depression at the generator terminals [2], Generating plants using steam turbines require station service power of up to 10% of their capacity for boiler feed water pumps, boiler forced-draft combustion air blowers, and for fuel preparation. It is uneconomical to provide such a large standby capacity at such plants, so black-start power must be provided over the electrical transmission network from other plants.

2.2 Motor Type Loads

Power plants contain induction motors, synchronous motors and sometimes DC motors. Three-phase induction motor is the most used type of motors in industrial applications such as electric power plants.

At the instant of switch on, the induction motor draws approximately six to eight times of its rated full load current at a very low lagging power factor and continues to do so with only a slight reduction until it reaches about 75% of its rated speed as shown in figure 1, The low initial power factor and large starting currents produce large initial transitory apparent power (kVA).

This starting current has been standardized and defined by a series of code letters which group motors based on the amount of starting current in terms of kilovolt amperes kVA's. The starting characteristics of induction motors can be determined through locked rotor test. The test is done by applying rated voltage and frequency while mechanically holding the motor shaft from turning (speed rpm=0, Slip S=1). [6]

The kVA required by a motor starting at full voltage is quite close to the "locked rotor kVA" requirement of the motor, which is usually easily determined either from the actual motor's nameplate or from the manufacturer. The National Electrical Manufacturer's Association (NEMA) sets design standards for motors and has established a NEMA Code letter designation to classify motors by the ratio of locked rotor kVA per horsepower.

Efficiency of a motor is defined as output power divided by input power expressed as a percentage:

Efficiency % = (Output power / Input power) × 100

NEMA nominal efficiency represents an average efficiency of a large population of like motors. The actual efficiency of the motor is guaranteed by the manufacturer to be within a tolerance band of this nominal efficiency.

2.3 Calculation of BS Capacity

Based on the NEMA standards stipulated above, one can calculate the needed BS capacity for each power station considering that the load profile for each starting load is divided into 2 states, the transient state, and the steady state.

The transient state involves high starting current compared to the steady state currents. Hence for an accurate calculation of the needed BS capacity for a power station both states must be included as follow:

Motor Starting kVA=Motor horse power (hp)×$(\text{kVA/hp})_{\text{ratio}}$ …(1.1)

Motor Starting kW= Motor starting kVA×Starting Power Factor(SPF) …(1.2)

Motor Running KW=Rated KW / Efficiency (Eff) …(1.3)

Motor Running kVA = Motor Running KW/Running Power Factor (RPF) … (1.4)

In case of sequential switching of loads, the cumulative (kVA, kW) can be calculated as follow:

Cumulative kVA for the i^{th} step = Starting $\text{KVA}|_i + \sum_{n=1}^{i-1}$ Running KVA   n = (1, 2… i-1) … (1.5)

Cumulative kW for the ith step =Starting $\text{kW}|_i + \sum_{n=1}^{i-1}$ Running KW   n = (1, 2… i-1) … (1.6)

Where the cumulative kVA represents the needed BS capacity for each power station.

For a 25% maximum voltage dips in case of using diesel generators; the motor starting KVA is reduced by 25%.

2.4 Case Study: Calculating BS Capacity for Restructured Jordanian Electric Power System (RJEPS) Power Stations

The Data of the starting loads for the following power stations of RJEPS were collected [1] to calculate the needed BS capacity for each one by applying Equations (1.1) - (1.6):

1. Al-Hussein Thermal Power Station (HTPS)
2. Aqaba Thermal Power Station (ATPS)
3. Rehab Electric Power Station (REPS)
4. Samra Electric Power Station (SEPS)
5. Amman East Electric Power Station (AEEPS)

2.4.1 Illustration

To illustrate the obtained results for the above power stations, this subsection consists of the followings:

a) The sequential steps of starting a 100 MW gas turbine in SEPS with its associated data are shown in Table 1.
b) A sample of calculations of the first two steps of the above gas turbine areas follows:

The first load to be started is the turning gear electrical motor with the ratings shown in Table 2:

- Motor Starting kVA = Motor hp× $(kVA/hp)_{ratio}$
  = 40.21 hp× 5.3 kVA/hp
  = 213.14 kVA
- Motor Starting kW = Motor Starting kVA x SPF
  = 213.14 × 0.39
  = 83.12 kW
- Motor Running kW = Motor Rated kW / Efficiency
  = 30 KW / 0.89
  = 33.71 KW
- Motor Running kVA = Motor Running kW / RPF
  = 33.71 / 0.90
  = 37.45 KVA
- Cumulative kVA for step 1 = First load Starting kVA = 213.14 kVA
- Cumulative kW for step 1 = First load Starting kW
  = 83.12 kW

The second load switched on after the first load is Diesel Fuel forwarding Pump motor with rating as in Table 3:

- Motor Starting kVA = Motor hp× (kVA/hp)$_{ratio}$
  = 49.6 hp× 5.3 KVA/hp
  = 262.87 kVA
- Motor Starting kW = Motor Starting kVA x SPF
  = 262.87 × 0.36 = 94.63 kW
- Motor Running kW = Motor Rated kW / Efficiency
  = 37 kW / 0.90
  = 41.11 kW
- Motor Running kVA = Motor Running kW / RPF
  = 41.11 / 0.90
  = 45.68 kVA
- Cumulative kVA for Step 2 = First load Running KVA + Second Load Starting kVA
  = (37.45 + 262.87) kVA
  = 300.32 kVA
- Cumulative kW for Step 2 = First load Running kW + Second Load Starting kW
  = (33.71 + 94.63) kW
  = 128.34 kW

c) The calculated cumulative kVA and kW for all sequential load steps are shown in Table 4,from this Table the maximum values of kVA and Kw can be observed to be 1952.32 and 8408.96 respectively. These values represent the required power capacity of the black start for SEPS.

By repeating the same above procedure for the other power stations, the required black start capacity for each one of them are shown in Table 5.

CONCLUSION

Ancillary services maintain the reliability and security of restructured power systems. This paper presented a case study of evaluating the ancillary service of the required black start capacity of a practical restructured power system. Although the obtained results show the required capacity of each power station, however these results can be used to show the optimum locations of black start generation at one or more power stations.

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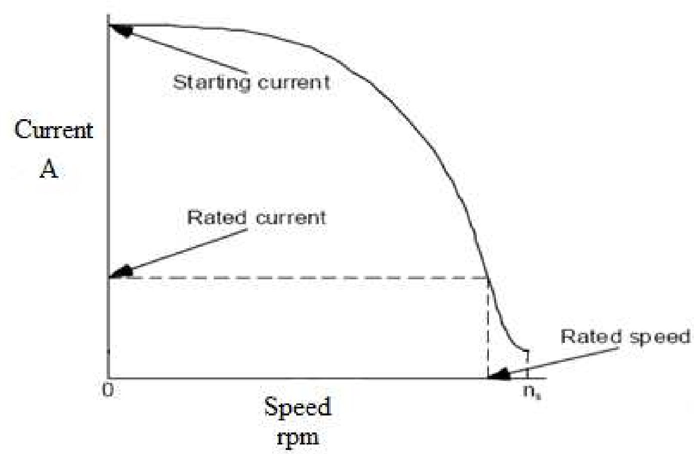

Figure 1.Starting current of induction motor.

Tab 1. The sequential steps of starting a 100 MW gas turbine in SEPS

Sequential Load step	Starting Loads	NEMA Code	KVA/hp	Qty	hp	Rated KW	Eff.	SPF	RPF
1	Turning gear electrical motor	F	5.3	1	40	30	0.9	0.4	0.9
2	Diesel Fuel forwarding Pump motor	F	5.3	1	50	37	0.9	0.4	0.9
3	Gas module cooling air fan motor	H	6.7	1	5	4	0.8	0.6	0.9
4	The auxiliary oil pump motor	G	5.9	1	121	90	0.9	0.3	0.9
5	Oil mist eliminator fan motor	F	5.3	1	25	19	0.9	0.4	0.9
6	Generator lift oil pump motor	F	5.3	1	25	19	0.9	0.4	0.9
7	Torque adjuster drive motor	K	8.5	1	2	2	0.8	0.7	0.8
8	The auxiliary hydraulic supply pump motor	F	5.3	1	20	15	0.9	0.5	0.9
9	Cooling water pump motor	F	5.3	1	50	37	0.9	0.4	0.9
10	Atomizing air booster motor	F	5.3	1	20	15	0.9	0.5	0.9
11	Flow divider starting motor	M	10.6	1	1	0	0.7	0.8	0.7
12	Generator Space Heater	-	-	1	4	3	0.9	0.9	0.9
13	Battery charger Unit	-	-	1	27	20	0.9	0.9	0.9
14	Unit Circuit Breaker	-	-	1	4	3	0.9	0.9	0.9
16	Gas Reducing Station	-	-	1	80	60	0.9	0.9	0.9
17	Al Fajer Gas	-	-	1	67	50	0.9	0.9	0.9
18	The starting motor	G	5.9	1	1,340	1,000	0.9	0.2	0.9
19	Cooling water fan motor set (8)	G	5.9	1	80	60	0.9	0.3	0.9
20	Turbine compartment ventilation	F	5.3	1	40	30	0.9	0.4	0.9
21	Ventilation of the power compartment	F	5.3	1	15	11	0.9	0.5	0.9
22	Turbine exhaust frame cooling blower & motor 1	F	5.3	1	60	45	0.9	0.4	0.9
23	Turbine exhaust frame cooling blower & motor 2	F	5.3	1	60.3	45	0.9	0.4	0.9

Tab. 2 First load step switched on in SEPS

Load step	Starting Load	NEMA Code	(KVA/hp) ratio	Rated KW	hp	Eff.	SPF	RPF
1	Turning gear electrical motor	F	5.3	1	40	30	0.9	0.4

Tab. 3 Second load step switched on in SEPS

Load step	Starting Load	NEMA Code	(KVA/hp) ratio	Rated Kw	hp	Eff.	SPF	RPF
2	Diesel Fuel forwarding Pump motor	F	5.3	1	50	37	0.9	0.4

Tab. 4 the cumulative results for each load step

Sequential Load step	Starting		Running		Cumulative	
	KW	KVA	KW	KVA	KW	KVA
1	83.12	213.14	33.71	37.45	83.12	213.14
2	94.63	262.87	41.11	45.68	128.34	300.32
3	21.91	35.92	4.76	5.60	96.73	119.06
4	220.66	711.80	98.90	108.68	300.24	800.53
5	57.83	131.43	21.02	23.62	236.31	328.85
6	57.83	131.43	21.02	23.62	257.34	352.47
7	11.96	17.09	1.90	2.40	232.49	261.75
8	49.02	106.57	17.24	19.37	271.45	353.63
9	94.63	262.87	41.11	45.68	334.30	529.30
10	49.02	106.57	17.24	19.37	329.80	418.68
11	4.00	5.26	0.51	0.72	302.02	336.74
12	3.00	3.70	3.33	3.70	301.53	335.91
13	20.00	24.69	22.22	24.69	321.86	360.61
14	3.00	3.70	3.33	3.70	327.08	364.31
16	60.00	74.07	66.67	74.07	387.42	438.38
17	50.00	61.73	55.56	61.73	444.08	500.11
18	1502.68	7908.85	1063.83	1156.34	1952.32	8408.96
19	151.85	474.53	65.93	73.26	1665.32	2130.98
20	83.12	213.14	33.71	37.45	1662.53	1942.85
21	38.29	78.15	12.64	14.37	1651.40	1845.31
22	115.09	319.71	50.00	55.56	1740.85	2101.23
23	115.09	319.71	50.00	55.56	1790.85	2156.79

Tab. 5 The required BS capacity for each power station

Power Station	Needed BS Capacity (KW)	Needed BS Capacity (KVA)
Al-Hussein Thermal Power Station	2,687.19	9,127.47
Aqaba Thermal Power Station / Stage 1	8,429.39	32,866.15
Aqaba Thermal Power Station / Stage 2	13,332.74	54,982.74
Rehab Electrical Power Station	1,994.66	8,455.78
Samra Electrical Power Station	1,952.32	8,408.96
Amman East Electrical Power Station	4,244.70	4,701.35