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Blackstart capability planning for power system restoration

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ABSTRACT

Blackstart capability is essential for power system restoration following a blackout. System restoration planners determine the restoration sequences to provide cranking power from blackstart units (BSUs) to non-blackstart units (NBSUs), pick up critical loads, and energize the necessary transmission paths. This paper proposes a new algorithm for optimization of the restoration actions. An optimal search algorithm is proposed to determine the plan to crank NBSUs through the selected paths of transmission lines. Assuming that the generation capability of a BSU is constant, the method is used to optimize the overall system MWHr generation capabilities from NBSUs. To reduce the computational complexity of system restoration planning, a new generator model is proposed that results in a linear integer programming (IP) formulation. Linearity of the IP problem formulation ensures that the global optimality is achieved. The optimal power flow (OPF) is used to examine the feasibility of planned restoration actions. Test cases from the IEEE 39-bus system, ISO New England system, and Duke-Indiana system are used to validate the proposed algorithm. Numerical simulations demonstrate that the proposed method is computationally efficient for real-world power system cases.

1. Introduction

Although major outages of power systems rarely occur, widespread blackouts are a threat to the grid's operational reliability. Massive blackouts, such as the August 2003 blackout in Northeastern U.S. [1] and 2012 power outage caused by Hurricane Sandy [2], highlight the need for efficient power system restoration strategies and decision support tools for system restoration planning.

Following a partial or complete shutdown, PSR is aimed to efficiently restore a power system from an outage state to a normal operating state with the available blackstart resources. In power system restoration planning, it is critical to develop a feasible restoration plan for cranking NBSUs, energizing the needed transmission paths, and picking up sufficient load to stabilize the power grid. On the topic of PSR, extensive research has been conducted in the last decades. The general requirements and specific considerations are elaborated in [5–9]. Three stages of system restoration are proposed in [10,11], i.e., blackstart stage, network configuration, and load restoration. The overall system MWHr generation capability over the system restoration horizon is an index for evaluation of the restoration plans including the blackstart capabilities. To maximize the MWHr generation capability, start-up of generating units needs to be optimized [12]. An MILP algorithm is proposed in [13] to identify the optimal start-up sequence of NBSUs. Issues on PSR are addressed [14–20], e.g., restoration planning based on wide area measurement systems [14], blackstart resource allocation [15], and islanding schemes [16,17]. When blackstart resources are to be provided for cranking NBSUs, necessary transmission paths need to be established. Path search methods and estimated restoration duration based on critical path method have been proposed in [21–24]. Methodologies [25–34], such as rule-based method [26], dynamic search method [27,28], and knowledge based method [29], have been developed to solve these problems.

Per the EOP-005-2 standard from North American Electric Reliability Corporation (NERC), each transmission operator is responsible for timely update of the system restoration plan [3]. Within 90 calendar days after any planned or unplanned permanent system modifications are identified that would change the implementation of a scheduled restoration plan, the system restoration plan should be updated [3]. To comply with the NERC standard, an

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Nomenclature

Acronym

IP	integer programming
OBC	optimal blackstart capability
MILP	mixed integer linear programming
PSR	power system restoration
BSU	blackstart unit
NBSU	non-blackstart unit
BSC	blackstart capability
OPF	optimal power flow
HV	high voltage
EHV	extra-high voltage

System parameters

T	total system restoration time
N_{bus}	number of buses
N_{line}	number of lines
N_{cload}	number of critical loads
N_{BSU}	number of BSUs
N_{NBSU}	number of NBSUs
N_G	number of generators
t_i^C	cranking time of generator i to begin to ramp up and parallel with a system
t_i^{CL}	critical minimum interval constraint of NBSU i
t_i^{CH}	critical maximum interval constraint of NBSU i
K_i	maximum ramping rate of generator i
C_i	capacity of generator i
P_i^{max}	maximum generator output of generator i
P_i^{crk}	cranking power requirement of NBSU i
Q_i^{crk}	cranking reactive power requirement of NBSU i
Q_i^{min}	minimum reactive power output of NBSU i
B_{mn}	susceptance of line mn
V	a user-specified parameter representing the user's estimate of the voltage level along the cranking paths. In this paper, V is set to be 1 p.u.

Sets

Z	set of Integers
$S_t = 1 \ldots t$	set of restoration time up to time t
$S_{NBSU} = 1 \ldots N_{NBSU}$	set of NBSUs
$S_G = 1 \ldots N_G$	set of generators
$S_{bus} = 1 \ldots N_{bus}$	set of buses
$S_{line} = 1 \ldots N_{line}$	set of lines
$S_{cload} = 1 \ldots N_{cload}$	set of critical loads
$S_{line\ mn-bus}$	set of buses connected with line mn
$S_{line\text{-}busi}$	set of lines connected with bus i
$S_{bus\text{-}BSU}$	set of buses connected with a BSU

Decision variables

u_{igen}^t	binary variable of start-up status of generator i at time t, $i \in S_G, t \in S_T$
t_i^{st}	start-up time of generator i, $i \in S_G$
w_{i1}^t	binary variable of ramping up status of generator i at time t, $i \in S_G, t \in S_T$
w_{i2}^t	binary variable of maximum output status of generator i at time t, $i \in S_G, t \in S_T$
$u_{bus\ i}^t$	binary variable of bus i at time t; 1 means energized and 0 means not energized, $i \in S_{bus}, t \in S_T$
$u_{line\ mn}^t$	binary variable of line mn at time t; 1 means energized and 0 means not energized, $mn \in S_{line}, t \in S_T$
u_{kcload}^t	binary variable of critical load k at time t; 1 means critical load i picked up and 0 means not yet picked up, $k \in S_{cload}, t \in S_T$

efficient decision support tool to assist in the development of a feasible restoration plan is important for power systems. Motivated by industry's need for decision support tools, EPRI initialized R&D in 2008 to develop system restoration tools, i.e., System Restoration Navigator (SRN) [7] and Optimal Blackstart Capability (OBC) [35].

In the literature, the problems of generator restarting and transmission path search are handled as separate computational problems. Consequently, technical constraints may be violated and the overall restoration plan may not be feasible. To integrate the two search problems, however, it is computationally challenging to handle the large number of decision variables for a real-world power system. Furthermore, the nonlinear model of generation capability curves adds to the computational complexity for restoration planning. As a result, the state-of-the-art of system restoration has not achieved the computational capability and performance for restoration planning in the practical environment of real-world power systems. To the best of authors' knowledge, no prior work has developed algorithms that can jointly consider generator startup and transmission path search and be applicable for large-scale systems.

To meet these challenges, a new analytical model is proposed in this paper for power system restoration planning; the result is a new algorithm that achieves the global optimality in maximizing the overall MWHr generation capability over a restoration horizon. Notably, the proposed algorithm is scalable and applicable to real-world power systems. It has been implemented and successfully validated with Duke-Energy and New England ISO power system cases. In comparison with the state-of-the-art, including the authors' prior work [36,37], this paper proposes a new computational model for blackstart capability planning. The contributions of the paper include:

(1) By discretizing the continuous restoration horizon into finite time slots, a new restoration model by linear integer programming is proposed for the optimization problem incorporating both nonlinear generation capability functions and transmission constraints. Linearity ensures that the solution is globally optimal.
(2) The proposed transmission path search helps to avoid over-voltage problems by considering the system topology as well as system-wide reactive power balance.
(3) The tasks of cranking NBSUs and picking up critical loads are well coordinated in the proposed model. The coordination results in the reduced outage duration of critical loads without compromising the overall system MWHr generation capability.
(4) Optimal restoration actions over a restoration horizon are identified, and the system BSC is assessed. This enables system restoration planners to determine whether the blackstart resources are sufficient for restoration.

2. Blackstart capability

Depending on whether a unit has blackstart capability, generators are categorized into BSUs and NBSUs. A BSU has self-starting capability while NBSUs rely on cranking power from the system to restart. Thus, only NBSUs require cranking power. After a unit is started and paralleled with the grid, the output of the unit increases subject to the maximum ramping rate until the maximum output is reached. The typical generation capability of a unit is illustrated in Fig. 1. In this paper, a new method is proposed to model this nonlinear curve by four piecewise linear functions. That is,

$$P_{igen}^{t}=\begin{cases}0 & t<t_i^{st}\\ -P_i^{crk} & t_i^{st}\leqslant t<t_i^{ramp}\\ -P_i^{crk}+K_i(t-t_i^{st}) & t_i^{ramp}\leqslant t<t_i^{max}\\ P_i^{max} & t_i^{max}\leqslant t\leqslant T\end{cases} \tag{1}$$

where t_i^{ramp} and t_i^{max} are given by

$$t_i^{ramp}=t_i^{st}+t_i^{c} \tag{2}$$
$$t_i^{max}=t_i^{ramp}+C_i/K_i \tag{3}$$

(1) $t\in[0,t_i^{st})$, the generator is not cranked;
(2) $t\in[t_i^{st},t_i^{ramp})$, the generator is cranked but not paralleled with the system;
(3) $t\in[t_i^{ramp},t_i^{max})$, the generator ramps up subject to the maximum rate;
(4) $t\in[t_i^{max},T)$, the generator reaches the maximum output.

Different from an NBSU, a BSU does not require cranking power to restart and its starting time is set to be 0. Therefore, P_i^{crk} and t_i^{st} of a BSU are 0. Other characteristics of a BSU and an NBSU are the same. The generation capability parameters in Fig. 1 provide a general model of generator characteristics and apply to both BSUs and NBSUs.

The overall system BSC is defined as the total on-line generation capability (MWHr) to help expedite system restoration [10]. The BSC of unit i can be expressed by subtracting the slash area, S_{1i}, from the back slash area, S_{2i}, as shown in Fig. 1 and (4):

$$BSC_i=S_{2i}-S_{1i} \tag{4}$$

where S_{1i} and S_{2i} are defined as

$$S_{1i}=P_i^{crk}(T-t_i^{st}) \tag{5}$$
$$S_{2i}=C_i(T-t_i^{c}-t_i^{st}-C_i/K_i)+(C_i)^2/(2K_i) \tag{6}$$

By substituting S_{1i} and S_{2i} with (2) and (3), (1) can be reformulated using (4):

$$BSC_i=C_i(T-t_i^{c}-C_i/K_i)+(C_i)^2/(2K_i)-P_i^{crk}T-(C_i-P_i^{crk})t_i^{st} \tag{7}$$

Given the restoration horizon, T, and the unit characteristic parameters, system BSC only depends on the start-up time t_i^{st}. Hence the overall system BSC can be maximized by determining the optimal start-up time of generators.

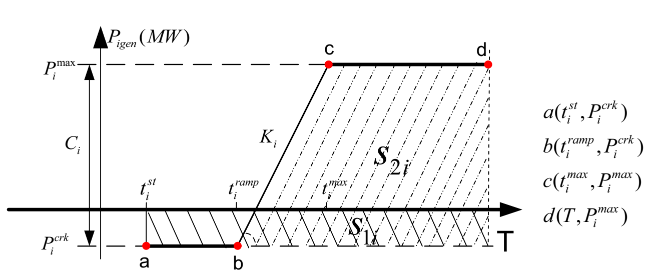

Fig. 1. Nonlinear generation capability curve.

3. Unit modelling based on linear integer programming

As mentioned, the nonlinear generation capability function in (1) adds to the complexity of the optimization problem for system restoration planning. The authors' previous work [13] proposed an MILP formulation by discretizing the continuous restoration horizon into finite time slots, where five sets of continuous decision variables and six sets of binary decision variables are utilized to model the generation capability curve. Over the restoration horizon, T, the size of the decision variable matrix of each generator is 11 by T. It was demonstrated in [13] that the MILP-based optimization model outperforms other search methods, such as enumeration and dynamic programming. However, through extensive evaluations, it was concluded that the MILP formulation is not capable of handling large-scale test cases for restoration planning in the practical environment of power systems. To enhance the computation efficiency without sacrificing the accuracy, this paper provides a new generator model using the unit start-up status as the only decision variables. The consequent size of the decision variable matrix of each generator is then reduced to 1 by T, in contrast to 11 by T by the MILP method. Thus, the computational performance is greatly enhanced.

To formulate the nonlinear generation capability function, the *ceil* and *res* functions are introduced:

$$ceil(x)=\begin{cases}x & x\in Z\\ \text{the least integer larger than } x & x\notin Z\end{cases} \tag{8}$$
$$res(s)=ceil(x)-x \tag{9}$$

Using these functions, some auxiliary parameters are defined below:

$$[t_i^{c}]=ceil(t_i^{c}) \tag{10}$$
$$[t_i^{c}+C_i/K_i]=ceil(t_i^{c}+C_i/K_i) \tag{11}$$
$$res(t_i^{c})=ceil(t_i^{c})-t_i^{c} \tag{12}$$
$$res(t_i^{c}+C_i/K_i)=ceil(t_i^{c}+C_i/K_i)-(t_i^{c}+C_i/K_i) \tag{13}$$

With the auxiliary parameters, three binary decision variables are introduced to convert the nonlinear generation capability curve in (1) into a linear combination of these decision variables.

(1) Introduce a binary decision variable u_{igen}^{t} to represent the start-up status of the ith NBSU at each time slot. $u_{igen}^{t}=1$ means that the ith NBSU is cranked at time t. Otherwise, $u_{igen}^{t}=0$. It is assumed that a generator will not be shut down once it is restarted. The start-up time t_i^{st} of the generator i is expressed as:

$$t_i^{st}=\sum_{t\in S_T}(1-u_{igen}^{t})+1,\quad u_{igen}^{t}\leqslant u_{igen}^{t+1},\ t\in S_{T-1},\ i\in S_G \tag{14}$$

(2) Introduce a binary decision variable w_{i1}^{t} to represent the ramping up status of the ith NBSU at each time slot. $w_{i1}^{t}=1$ indicates that the ith NBSU reaches the ramping up period at time t. Otherwise, $w_{i1}^{t}=0$. w_{i1}^{t} is non-decreasing with regard to t.

$$[t_i^{ramp}]=t_i^{st}+[t_i^{c}]=\sum_{t\in S_T}(1-w_{i1}^{t})+1,\quad w_{i1}^{t}\leqslant w_{i1}^{t+1},\quad t\in S_{T-1},\ i\in S_G \tag{15}$$

(3) Introduce a binary variable w_{i2}^{t} to represent the maximum output status of the ith NBSU at each time slot. $w_{i2}^{t}=1$ means that the ith NBSU reaches the maximum output period at time t; if not, $w_{i2}^{t}=0$. w_{i2}^{t} is non-decreasing with respect to t.

$$[t_i^{max}] = t_i^{st} + [t_i^c + C_i/K_i] = \sum_{t \in S_T}(1 - w_{i2}^t) + 1,$$
$$w_{i2}^t \leqslant w_{i2}^{t+1},\ t \in S_{T-1},\ i \in S_G \tag{16}$$

(4) The nonlinear generation capability curve can be modelled using these three decision variables. That is,

(a) when $t \in [0, t_i^{st})$, the decision variables u_{igen}^t, w_{i1}^t, and w_{i2}^t are zero.

$$P_{igen}^t = 0, \quad i \in S_G \tag{17}$$

(b) when $t \in [t_i^{st}, t_i^{ramp})$, the decision variable u_{igen}^t changes to 1 while w_{i1}^t and w_{i2}^t stay at zero.

$$P_{igen}^t = -u_{igen}^t P_i^{crk}, \quad i \in S_G \tag{18}$$

(c) when $t \in [t_i^{ramp}, t_i^{max})$, the decision variable w_{i1}^t changes to 1 while w_{i2}^t is zero.

$$P_{igen}^t = K_i\left\{t - \sum_{j \in S_t}(1 - w_{i1}^j) - w_{i1}^t[1 - res(t_i^c)]\right\} - u_{igen}^t P_i^{crk}, \quad i \in S_G \tag{19}$$

(d) when $t \in [t_i^{max}, T)$, the decision variable w_{i2}^t changes to 1, and all three decision variables are equal to 1.

$$P_{igen}^t = K_i\left\{t - \sum_{j \in S_t}(1 - w_{i1}^j) - w_{i1}^t[1 - res(t_i^c)] - \sum_{j \in S_t} w_{i2}^j + w_{i2}^t[1 - res(t_i^c + C_i/K_i)]\right\} - u_{igen}^t P_i^{crk}, \quad i \in S_G \tag{20}$$

In summary, the generation capability for a unit is evaluated by (21) over the restoration horizon. The generation capability is formulated as a linear combination of the three decision variables u_{igen}^t, w_{i1}^t, and w_{i2}^t.

$$P_{igen}^t = K_i\left\{t - \sum_{j \in S_t}(1 - w_{i1}^j) - w_{i1}^t[1 - res(t_i^c)] - \sum_{j \in S_t} w_{i2}^j + w_{i2}^t[1 - res(t_i^c + C_i/K_i)]\right\} - u_{igen}^t P_i^{crk},$$
$$i \in S_G,\ t \in S_T \tag{21}$$

(5) Represent the decision variables, w_{i1}^t and w_{i2}^t, by a time shift of the generator start-up status variable, u_{igen}^t.

$$w_{i1}^t = u_{igen}^{t-[t_i^c]} \,\&\, w_{i2}^t = u_{igen}^{t-[t_i^c + C_i/K_i]}, \quad i \in S_G,\ t \in S_T \tag{22}$$

Since $t - [t_i^c]$ and $t - [t_i^c + C_i/K_i]$ in (22) may be negative, the generator status in the above formulation is initialized to be zero when $t < 0$. Substituting (22) into (21), the mathematical expression of the generation capability is simplified, i.e.,

$$P_{igen}^t = K_i\left\{t - \sum_{j \in S_t}\left(1 - u_{igen}^{j-[t_i^c]}\right) - u_{igen}^{t-[t_i^c]}[1 - res(t_i^c)] - \sum_{j \in S_t} u_{igen}^{j-[t_i^c + C_i/K_i]} + u_{igen}^{t-[t_i^c + C_i/K_i]}[1 - res(t_i^c + C_i/K_i)]\right\} - u_{igen}^t P_i^{crk}, \quad i \in S_G,\ t \in S_T \tag{23}$$

Note that the goal in this study is to maximize the MWHr generation capability of all units. After a unit is restarted and paralleled with the system, the MW generation increases at its ramping rate until the maximum MW output to maximize its MWHr generation capability. That is, from the perspective of generation capability, a unit would not stay at its minimum MW output level. Hence, the minimum generator MW output is not used in the proposed model.

4. Formulation of the optimization problem

When a blackout occurs, an initial task is to crank NBSUs and pick up critical loads. System operating constraints as well as topology constraints need to be considered: (1) some NBSUs have to restart within a specified time range [5,13]; (2) necessary transmission paths should be established to deliver the cranking power and bus voltages need to be maintained within the prescribed range; (3) picking up critical loads and cranking NBSUs should be well coordinated that system BSC is not compromised.

4.1. Assumption

- The entire restoration horizon is divided into a series of sequential time steps in increments of, say, 10 min, as the per unit value of time. The system restoration state is updated every 10 min.
- Since power flow is light in early stages of power system restoration, power losses and thermal limits of transmission lines are not considered.
- BSUs can be started right after a blackout, and the starting time of a BSU is assumed to be 0. In reality, it takes some time to start the blackstart units. The time 0 here represents the time at which BSUs are started.

4.2. Objective function

As shown in (7), the overall BSC is determined by the start-up time of generators. Since the status of a BSU is initialized to be 1, the BSC of a BSU is constant. Therefore, the objective is to maximize the BSC of all NBSUs over a restoration horizon, i.e.,

$$\max \quad \sum_{i \in S_{NBSU}} BSC_i \tag{24}$$

By substituting BSC_i in (24) with (7) and (14), the objective function is reformulated as:

$$\max \quad \left\{\sum_{i \in S_{NBSU}}\left[C_i(-t_i^c - 1) - (C_i)^2/(2K_i) + P_i^{crk}\right]\right\} + \sum_{i \in S_{NBSU}}\sum_{t \in S_T}(C_i - P_i^{crk})u_{igen}^t \tag{25}$$

For a specific unit, the blackstart characteristic is preset and fixed. Thus the BSC of the entire system is determined by the status u_{igen}^t of NBSUs. The objective function is further simplified as:

$$\max \quad \sum_{i \in S_{NBSU}}\sum_{t \in S_T}(C_i - P_i^{crk})u_{igen}^t \tag{26}$$

4.3. Constraints

4.3.1. Constraints for generator start-up

Most NBSUs in the power system are thermal generators. A unit with a drum type boiler has a maximum start-up time [5]. If the generator is not restarted within this time, its start-up has to be delayed by a considerable time period [5].

$$\sum_{i \in S_T}(1 - u_{igen}^t) + 1 \leqslant t_i^{CH}, \quad i \in S_G \tag{27}$$

A unit with a supercritical boiler has a minimum cold-start time [5]. The unit cannot be cranked until the minimum critical time elapses [5].

$$\sum_{i\in S_T}(1-u_{igen}^t)+1 \geqslant t_i^{CL}, \quad i\in S_G \tag{28}$$

At each time step, there should be adequate blackstart resources to meet the cranking power requirement for NBSUs that are to be restarted.

$$\sum_{i\in S_G} P_{igen}^t \geqslant 0, \quad t\in S_T \tag{29}$$

The generator is cranked only after the bus that the generator is connected to is energized. Hence,

$$u_{igen}^{t+1} \leqslant u_{igen-bus}^t, \quad t\in S_{T-1},\ i\in S_{NBSU} \tag{30}$$

4.3.2. Transmission path search constraint

During system restoration, online generators, including BSUs and NBSUs, and appropriate loads are used to control the voltage of a cranking path. In this study, the proposed optimization model includes the constraint of balancing reactive power at each time step for cranking path search. Dispatchable loads are picked up, if needed, in OPF to ensure that the selected cranking path satisfies operational constraints, e.g., bus voltages within 0.9–1.1 p.u. If the voltage deviation of the selected cranking paths exceeds the limit, the strategies of relaxing voltage constraints and postponing energization of long transmission lines are implemented to help find feasible cranking paths.

By searching over the status of each bus and line at each time slot, the optimal transmission path search can be formulated as an IP problem. The proposed formulation is:

(a) If a line is energized at time $t+1$, then at least one of its connected buses is energized at time t.

$$0 \leqslant u_{line\ ij}^{t+1} \leqslant u_{bus\ i}^t + u_{bus\ j}^t, \quad t\in S_{T-1},\ ij\in S_{line} \tag{31}$$

(b) If a bus is energized at time $t+1$, then at least one of its connected lines is energized at time $t+1$.

$$0 \leqslant u_{bus\ i}^{t+1} \leqslant \sum_{ij\in S_{line-bus\ i}} u_{line\ ij}^{t+1}, \quad t\in S_{T-1},\ i\in S_{bus}/S_{bus-BSU} \tag{32}$$

(c) Once a bus or a line is energized, it will not be de-energized.

$$u_{busi}^t \leqslant u_{bus\ i}^{t+1}, \quad u_{line\ ij}^t \leqslant u_{line\ ij}^{t+1},\ i\in S_{bus},\ ij\in S_{line},\ t\in S_{T-1} \tag{33}$$

(d) System wide reactive power should be balanced at each time step. After a unit with reactive power absorbing capability is paralleled with the system, it can be used to adjust voltage profiles. Generators and load with a lagging power factor are able to absorb the reactive power generated by shunt capacitance of transmission lines and help control the voltage.

$$\begin{aligned}&Q_{sys}^t = \sum_{i\in S_G}\left(w_{i1}^t Q_i^{min} - u_{igen}^t Q_i^{crk} - \sum_{k\in S_{cload}} u_{kcload}^t Q_{kcload}\right),\\&Q_{sys}^t + \sum_{ij\in S_{line}} u_{line\ ij}^t B_{line\ ij} V^2 \leqslant 0, \quad t\in S_T\end{aligned} \tag{34}$$

As shown in (34), if the system capability to absorb reactive power is larger than the reactive power generated by shunt capacitance of high voltage transmission lines, the overvoltage problem is alleviated. With $w_{i1}^t = u_{igen}^{t-[t_i^c]}$, (34) can be simplified as:

$$\begin{aligned}&Q_{sys}^t = \sum_{i\in S_G}\left(u_{igen}^{t-[t_i^c]} Q_i^{min} - u_{igen}^t Q_i^{crk} - \sum_{k\in S_{cload}} u_{kcload}^t Q_{kcload}\right),\\&Q_{sys}^t + \sum_{ij\in S_{line}} u_{line\ ij}^t B_{line\ ij} V^2 \leqslant 0, \quad t\in S_T\end{aligned} \tag{35}$$

In addition, all lines and buses are de-energized initially except for buses connected to BSUs and a transformer is modelled as a branch with its branch impedance equal to transformer impedance.

Note that the proposed line model includes both EHV and HV lines. EHV lines differ from HV lines in that the charging capacitance of EHV lines is usually larger than that of HV lines. When both EHV and HV lines are available as candidate cranking paths, the proposed method tends to select a cranking path with minimum switching time on condition that the charging current along the cranking path can be absorbed by online units and loads. In doing so, power can be delivered to NBSUs at the earliest time while reactive power/voltage can be managed. For example, when there is enough reactive power absorbing capability in the system, the proposed method would treat EHV lines and HV lines equally. When limited reactive power absorbing capability is available, the proposed method prefers to crank HV lines because the charging current of HV lines is usually smaller. When EHV lines are unavailable, the proposed method would select HV lines for the cranking path.

4.3.3. Coordination of cranking NBSUs and picking up critical loads

In the optimization model, the pick-up of critical loads is integrated into the real power constraint for generator start-ups. By determining the status of the critical load at each time step, pickup of critical loads and cranking of NBSUs are coordinated.

(a) Sufficient generation is available to pick up critical loads.

$$\sum_{i\in S_G} P_{igen}^t - \sum_{j\in S_{cload}} u_{jcload}^t P_{jcload}^t \geqslant 0, \quad t\in S_T \tag{36}$$

(b) Once the load is picked up, it will not be curtailed.

$$u_{jcload}^t \leqslant u_{jcload}^{t+1}, \quad t\in S_{T-1},\ j\in S_{cload} \tag{37}$$

(c) The bus connected with the load is energized before the load is picked up.

$$u_{jcload}^{t+1} \leqslant u_{jcload-bus}^t, \quad t\in S_{T-1},\ j\in S_{cload} \tag{38}$$

Both the objective function and constraints are a linear combination of generator status, bus status, transmission line status, and critical load status at each time slot. The status indicators are represented by binary decision variables. Hence a global optimal solution is achieved by solving this linear IP optimization problem for system restoration planning.

4.4. OBC tool

The OBC tool [4], based on the proposed model, has been developed as a decision support tool for system restoration planners. The flowchart of OBC is shown in Fig. 2.

The OBC tool consists of five modules: Island detection, Preprocessing, Run CPLEX, Apply OPF, and Post-processing. The functionality of each module is summarized as follows:

(1) Island detection: designed to check the connectivity of a system. Isolated islands, such as isolated NBSUs, buses, and lines disconnected to blackstart resources, are identified.

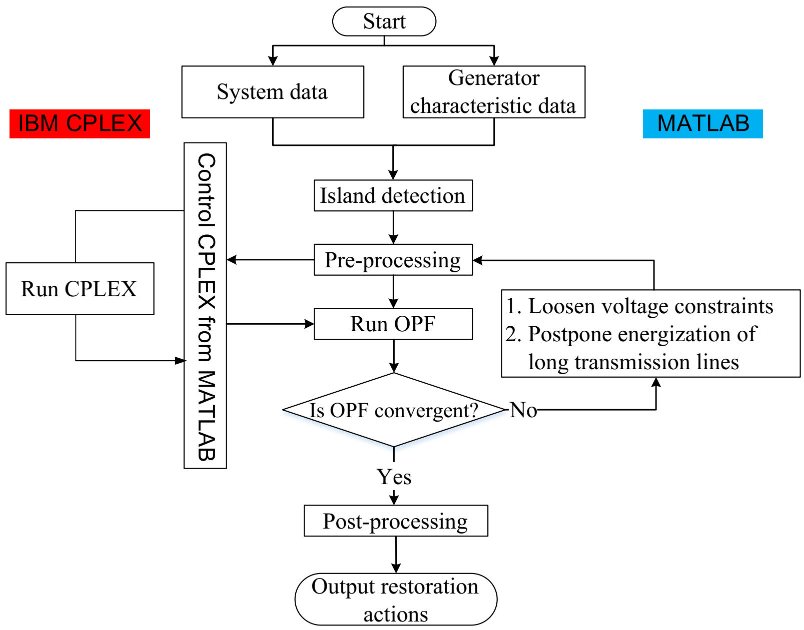

Fig. 2. Flowchart of the OBC tool.

(2) Pre-processing module: used to convert system data and generator characteristics into a format suitable for the optimization model in CPLEX.
(3) Run CPLEX: designed to implement the proposed optimization model to identify sequential actions over the time horizon for system restoration planning.
(4) Apply OPF: the OPF is applied to examine the feasibility of each restoration action. Picking up dis-patchable loads is included in OPF to help maintain bus voltages within the allowable range. The strategies of relaxing voltage constraints and postponing energization of some buses connected with long transmission lines are implemented to obtain feasible planned restoration actions.
(5) Post-processing: used to calculate the overall system BSC and output sequential restoration actions, such as cranking times of NBSUs as well as energizing times of buses and lines.

The restoration planning tool, OBC, helps restoration planners to develop a feasible and efficient system restoration plan. The overall system MWHr generation capability is assessed to determine if blackstart resources are sufficient for system restoration. OBC can also be a decision support tool to evaluate locations and capacity levels for installation of (a) new BSU(s).

5. Simulation results

The OBC tool is applied to test cases from the IEEE 39-bus system, ISO New England system, and Duke-Indiana system. In power system restoration, nuclear units usually rely on its own emergency generators to restart and are paralleled with the power grid for load restoration (not picking up NBSUs) [38]. As a result, in this study, nuclear power plants are not considered in determination of the NBSU startup sequence.

5.1. IEEE 39-bus system

The IEEE 39-bus system includes 10 generators, 39 buses, 12 transformers, and 34 lines. The parameters of the system can be found in [39] Q_i^{min} is set to be $-0.3 * P_i^{max}$. G10 serves as a BSU providing power to crank the other nine NBSUs. The planned energizing sequences for NBSUs, transmission lines, buses, transformers, and critical loads are shown in Fig. 3 and Table 1. By t = 15 p.u., all units are cranked and restarted.

Under the optimal start-up sequence of all units, two MW generation capability curves are shown in Fig. 4 for cases with and without considering the constraint of transmission path search. Clearly, if only the constraints associated with the generators are considered, NBSUs can be restarted earlier. However, necessary transmission lines may not be available between blackstart resources and the NBSUs to be cranked. By combining the generator start-up constraints and transmission path search constraints, necessary transmission paths are established for cranking of NBSUs, making the restoration procedure feasible.

5.2. ISO New England system

The study case on ISO New England system includes 14 generators, 139 buses, 172 branches, and 26 loads (3 critical loads and 23 non-critical loads). G14 is a BSU, and the other thirteen generators, G1-G13, are NBSUs. OBC is employed to identify the sequential actions for system restoration. The generator starting sequence is shown in Table 2. The MW generation capability curve is shown in Fig. 5. Within 4 h, all the generators are cranked and paralleled with the system. By coordinating start-ups of NBSUs with picking up critical loads, the three critical loads are restored at time step 10, 13, and 14, respectively. The outage duration of critical loads is significantly reduced.

Due to the expected retirement of a BSU, ISO New England considers the installation of a new BSU with the same capacity as the existing one. Different locations need to be investigated to determine the effectiveness on system restoration. Table 3 shows that as the new BSU is installed at different locations, the generator starting sequences are very different. The location of the new BSU has a significant impact on the power system restoration actions. Taking the installation of the new BSU at Bus 8 as an example, the overall system BSC reaches 5889 MWHr with a restoration horizon of 4 h. Compared to the scenario that the BSU is installed at

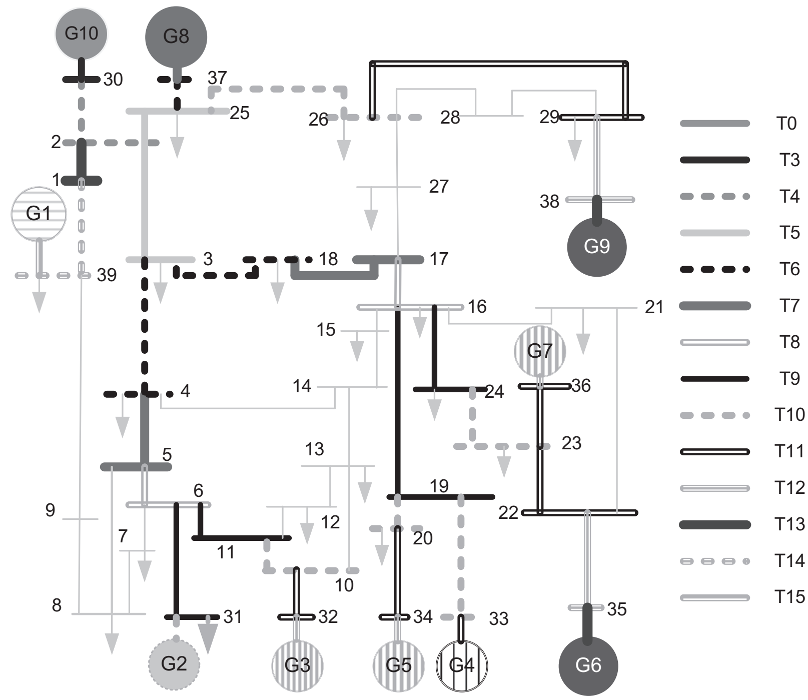

Fig. 3. Sequential restoration actions.

Table 1
Start-up sequence for IEEE 39-bus system.

Start-up time (p.u.)	0	3	4	5	6
Elements energized	G10	B30*	B2	B3 B25	B37 B4 B18
Start-up time (p.u.)	7	8	9	10	11
Elements energized	G8* B17 B5	B6 B16	B11 B31 B19 B24	G2 B26 B10 B20 B33 B23	B29 B32 B34 G4 B22 B36
Start-up time (p.u.)	12	13	14	15	
Elements energized	G3 G5 G7 B35 B38	G9 G6	B39	G1	

*B30 means bus 30, and so forth.
*G8 means generator 8, and so forth.

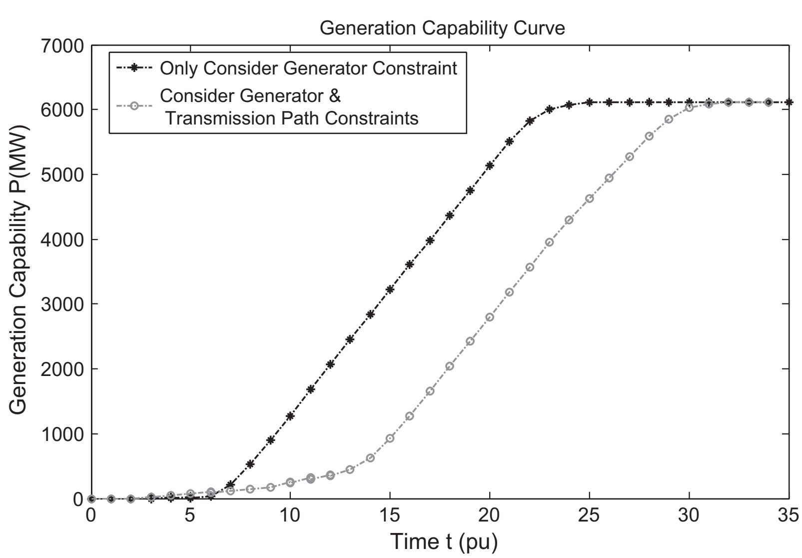

Fig. 4. MW generation capability curve of IEEE 39-bus system.

Bus 91, the BSC increases by 23%. This study case indicates how the proposed tool for blackstart capability evaluation can be used to identify new BSU locations. The optimal installation of BSUs is beyond the scope of this paper.

5.3. Duke-Indiana system

The OBC tool was applied to the Duke Energy-Indiana system. The objectives were to assess the effectiveness of the existing

Table 2
Generator starting sequence for ISO New England system.

Generator No.	G1	G2	G3	G4	G5	G6	G7
Start-up time (p.u.)	7	13	13	13	13	6	12
Generator No.	G8	G9	G10	G11	G12	G13	G14
Start-up time (p.u.)	12	12	12	12	10	10	0

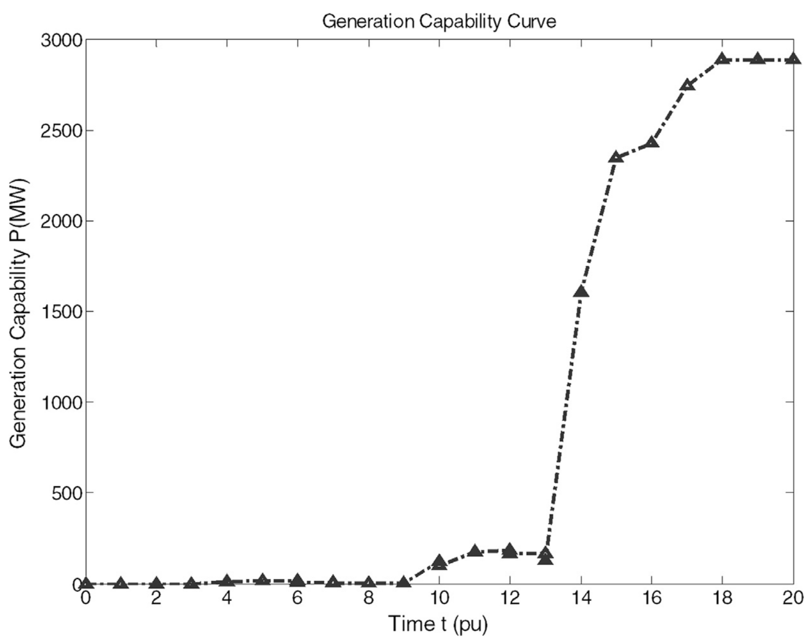

Fig. 5. MW generation capability curve of the ISO New England system.

Table 3
Blackstart capability with the BSU at different locations.

BSU location	BSU Cap (MW)	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	Cap. (MWHr)
Bus 91	16	7	13	13	13	13	6	12	12	12	12	12	10	10	4801
Bus 37	16	8	13	13	13	13	6	12	12	12	12	13	10	10	4798
Bus 47	16	5	13	13	13	13	8	16	16	16	16	15	10	10	4617
Bus 100	16	20	15	15	15	15	15	7	7	11	11	8	11	11	4302
Bus 13	16	17	8	8	4	5	12	11	11	11	11	13	12	12	4071
Bus 34	16	9	13	13	13	13	6	12	12	12	12	13	10	10	4794
Bus 44	16	19	16	16	16	16	14	6	6	10	10	8	11	11	4320
Bus 65	16	19	10	10	10	10	14	8	8	5	4	9	12	12	4125
Bus 60	16	18	14	14	14	14	13	9	9	9	9	4	9	9	5286
Bus 8	16	14	14	14	14	14	9	16	16	16	16	11	9	5	5889

BSU on the system, and to identify locations and corresponding MW sizes for new BSUs.

The area of interest in the Duke Energy-Indiana system territory included 1 BSU with the capacity of 90 MW, 37 NBSUs, 348 transmission buses (with the voltage levels above 100 kV), and 397 transmission lines. The OBC case study results indicate that with the current BSU, the system can be restored in 14 h and the total online generation capability will be 55,054 MWHr. The MW generation capability curve, as well as the sample interface of the OBC tool, is shown in Fig. 6.

At each time step, the OPF is applied to examine the feasibility of restoration actions identified from the proposed optimization model. The maximum and minimum voltage at each time step is presented in Fig. 7. At the early stage of restoration, limited dispatchable loads are available for voltage control, resulting in temporary voltage violations by around 2%. As the restoration process proceeds and more resources are available, bus voltages are maintained within the allowable range.

Duke Energy is exploring options to replace or increase its blackstart capability. As part of this study case, three candidate locations were tested and compared. Fig. 8 shows the MWHr generation capability for these three locations, and the variation of total MWHr generation capability with respect to the MW capacity of the new BSU. It is observed that Location 3 is superior to Locations 1 and 2 (Location 1 is where the current BSU is located), if the capacity of the new BSU to be installed is at least 30 MW. Moreover, the total MWHr generation capability does not increase significantly as the capacity of the new BSU increases within the range of 30–90 MW. This increment of the overall system generation capability is attributable to the capacity increase of the new BSU, rather than starting up other NBSUs earlier. This implies that installing a BSU with a capacity lower than 90 MW at Location 3 is a cost-effective choice.

5.4. Incorporating different blackstart resources into OBC

As defined by NERC, a blackstart resource is "a generating unit and its associated set of equipment which has the ability to be started without support from the system..." [3]. This definition of blackstart resources includes load rejection (LR), low frequency isolation scheme (LFIS), and a blackstart unit such as a gas turbine.

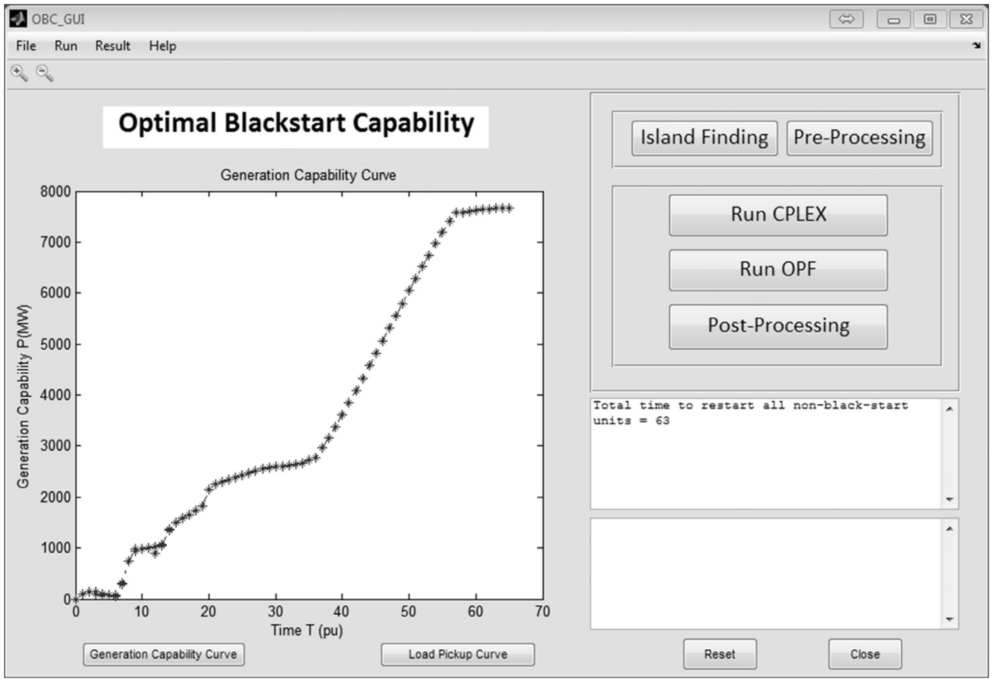

Fig. 6. MW generation capability curve of Duke Energy system.

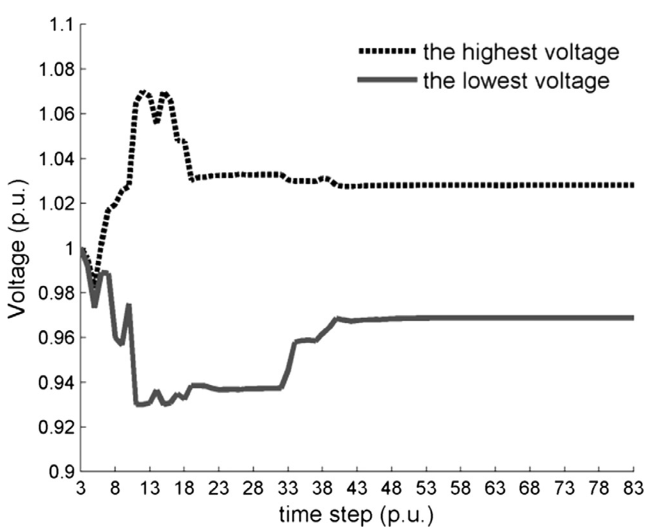

Fig. 7. Bus voltage profile at each time step.

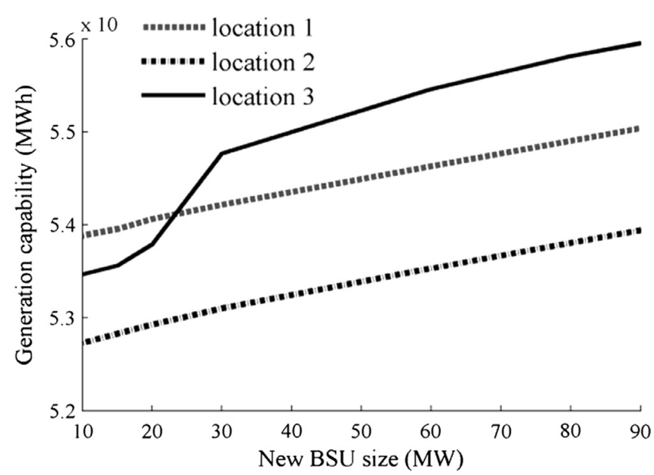

Fig. 8. MWHr generation capability curves for different BSU locations.

Following a major disturbance, a power station may experience a load rejection by suddenly removing loads from the generator or isolation of generation with matching local loads through relay schemes. These schemes are designed to avoid start-up of the generator from a complete shutdown and consequently would speed up the restoration process.

LR, LFIS, and a blackstart unit as blackstart resources can be incorporated in the proposed optimization model. A generator surviving a blackout by LR or LFIS is modelled as a BSU by initializing u^t_{igen} to be 1. Therefore, these generators, which survive a blackout by LR and LFIS, or a blackstart unit, provide blackstart resources for system restoration.

5.5. Computational complexity analysis of IP-based and MILP-based generator model

To solve an MILP or IP problem, two major issues are the computational speed and needed computer memory [40], which are critical for large-scale system applications. Using the ISO New England system above as the test case, Table 4 compares the computational performance of the IP-based and MILP-based generator models in [13]. The simulation is performed using IBM CPLEX Version 12.4 on a computer with the configuration of Intel Core i5-3360M 2.80 GHz and 8 GB RAM.

According to the simulation result, the memory needed and computation time of the IP formulation are 592.94 M and 4.76 s, respectively, which are significantly reduced compared with those of the MILP model. Note that the transmission path search increases the computation time and occupies memory for OBC, but both simulation cases have the same data input and transmission path search strategy except the generator model.

By enlarging the RAM to 48G, OBC is successfully applied for the Duke-Indiana system to identify the sequential actions for restoration planning. The performance is summarized in Table 5.

Note that the searching space of a binary optimization problem is 2^N, where N is the number of binary decision variables. Decreasing the number of binary decision variables can significantly enhance computation performance in terms of needed computer

Table 4
Performance analysis based on ISO New England system.

Generator model	No. of binary decision variables of a generator	No. of continuous decision variables of a generator	Computation time	Memory
MILP	6 by T	5 by T	18.59 s	956.32 M
IP	1 by T	0	4.76 s	592.94 M

Table 5
Performance analysis based on Duke-Indiana system.

Generator model	No. of binary decision variable (T = 72 pu)	No. of continuous decision variables (T = 72 pu)	Computation time	Memory
MILP	70,056	13,680	Not feasible	Not feasible
IP	56,376	0	192 s	41.5G

memory and computation speed. From Tables 4 and 5, it is concluded that the proposed IP-based optimization model outperforms the MILP-based model in terms of computer memory utilization and computational speed. This makes the proposed algorithm desirable for solving large-scale power systems.

6. Conclusions and future work

This paper presents a novel model for decision support in power system restoration planning. The optimization model is designed to maximize the overall system MWHr generation capability of NBSUs. A path search algorithm is proposed and integrated to find the optimal path through which the cranking power from BSUs to NBSUs is delivered. A concise generator model is proposed to enhance the computational performance of the optimization model. The developed OBC tool based on the proposed approach provides a feasible restoration plan for bulk power system restoration planning.

In this study, the system restoration state is updated every 10 min, which corresponds to a default value of restoration time for each line. Flexibility to allow different restoration times for different transmission lines needs to be incorporated. Moreover, the optimization of blackstart capabilities and their locations for restoration planning of large-scale power systems remain unsolved. Future research should address these issues as well as power system dynamics during system restoration, e.g., frequency and voltage stability.

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