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Optimal Restoration Sequence of Parallel Power System Using Genetic Algorithm †

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Abstract: The restoration of power systems is emphasized in the modern electric power system (EPS) due to complex, interconnected networks, and natural catastrophic events. However, large-scale disruptions in the power system result in a partial or complete blackout. Such events have a low probability and high impact, causing significant regional socio-economic losses. Hence, the black start (BS) resource is needed to deliver the cranking power to restart the non-black start (NBS) units, energize the path, load, and restore the complete system with parallel restoration. This paper implemented a novel optimal restoration scheme to restore the power system after partial or complete blackout. A multi-objective genetic algorithm is used to solve each island's optimal generation unit's start-up sequence, priority start of critical load and restoring the maximum load in minimum restoration time using an optimal transmission path with a minimum number of switching actions. A case study based on the IEEE-39 benchmark system validates the effectiveness of the proposed algorithm.

Keywords: power system restoration; black start; optimal transmission path; units start-up; parallel system restoration

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1. Introduction

In the modern world, electric power systems (EPS) are exposed to partial or complete blackout due to human-facilitated or disastrous natural events. The EPS is prone to large-scale disruptions due to interconnection, renewable resource integration, and network complexity, resulting in the interruption of the market environment and significant socio-economic losses. One of the most extensive blackouts in the history of Pakistan halted the power industry, affecting nearly 200 million people in January 2021 [1]. In recent years, natural calamities have also drastically influenced the global power industry, such as blackout in America (2021) and Australia (2021), which threatened the lives of people in America (10 million) and Australia (0.52 million) [2,3], respectively.

To mitigate the repercussions of disruptions in the power system, the world is experiencing a paradigm shift towards a more efficient, adaptable, and flexible approach to restoring the power system. Therefore, various heuristic algorithms are used to optimize the power system restoration. After a blackout, the Tabu Search algorithm is used to restore the cold load pickup (CLPU) to minimize the restoration time and prevent another outage [4]. Discrete particle swarm optimization is used to restore the CLPU by reducing the total power consumption and dividing the system into sections [5]. In [6], topology analysis and genetic algorithm are used to determine intentional islanding, keeping power balance and transmission constraint in bounds. In [7], FICO Xpress Optimizer is used to allocate the BS unit in the grid. Grid parameters are also included, such as generator model, nodal balance, voltage and power limits. A recent literature review is also provided in Table 1.

Table 1. Literature review.

Sr No.	Title	Journal	Conclusion
1	Optimal Black Start Resource Allocation [8]	IEEE Transactions on Power System	Procurement of the right amount of BS resources at the right locations to minimize the restore cost and time
2	Optimal Black Start Allocation for Power System Restoration [7]	IEEE Transactions on Power Systems	Optimally allocate BS units in the grid, simultaneously optimizing system parameters.
3	Strong Mixed-Integer Formulations for Power System Islanding and Restoration [9]	IEEE Transactions on Power Systems	Intentional controlled islanding (ICI) and black start allocation (BSA) have been formulated.
4	A Distributed Black-Start Optimization Method for Global Transmission and Distribution Network [10]	IEEE Transactions on Power Systems	Coordination of transmission and distribution network to minimize the outage cost.

In this paper, the optimal generation start-up sequence is optimized. The critical load is restored on a priority basis. A multi-objective genetic algorithm selects the shortest transmission path to energize the non-black start units and maximize overall generation with minimum restoration time. Maximum load is restored, and islands are synchronized to expedite the whole restoration process.

2. Post Fault Restoration

Power system restoration following a power outage poses many challenges for system planners and engineers as it includes a broad spectrum of independent entities, such as generation, transmission, and distribution owners. After a power outage, a grid-independent source is required to rejuvenate the power system to normal condition. A grid-independent and autonomous generating unit that does not rely on an external source is called a black start unit. Black start units deliver the cranking power to the non-black start unit, and optimal load restored is required to keep the grid parameter within permissible limits.

After a partial or complete power disruption, restoration of EPS is segregated into 3 stages: system preparation, system rejuvenation and load restoration. The system restoration stage consists of black start preparation, system status determination and network determination. The system restoration stage consists of transmission line energization, critical load pickup, cranking power to NBS units and synchronization of the island. The load restoration stage consists of minimizing the unserved load [11]. Black start is necessary to respond to the blackout, to reinvigorate the system to its normal state in minimum restoration time.

3. Problem Formulation and Mathematical Modelling

Efficient and corrective steps need to be considered to avoid cascading power outages. The occurrence of blackouts is rare, but their impact is high. In order to avoid repercussions of power outage, following factors should be taken into account:

- Maximizing the overall generation capability in minimum restoration time;
- Optimal transmission path is selected to rejuvenate the NBSUs;
- Minimum number of transmission switching is performed to restore the system.

These goals are achieved by using a genetic algorithm. The survival of the fittest remained the ultimate goal [12].

3.1. MWH Capability Enhancement

The main focus is to maximize the overall MWh capability of the power system during the restoration process.

$$E_{sys} = \sum_{i=1}^{N} E_{igen} - \sum_{j=1}^{M} E_{jstart} \quad (1)$$

E_{sys} is the total MW capability, E_{igen} is the power of ith generator, E_{jstart} is the starting-up demand of the Non-black start jth generator.

3.2. Constraint Power Requirement

Generation capability of unit i minus the start-up power of NBS must not be equal to zero.

$$\sum_{i=\mathbf{1}}^{N} P_{igen}(t) - \sum_{j=\mathbf{1}}^{M} P_{jstart}(t) \geq \mathbf{0}, t = \mathbf{1}, \mathbf{2}, \ldots, T \tag{2}$$

P_{igen} is the power requirement of unit i, and $P_{jstart(t)}$ is the start-up power requirement of NBS unit j.

3.3. Critical Time Interval Limits

NBSU j will start within the critical minimum and maximum time interval.

$$T_{jc\mathbf{min}} \leq t_{j\text{start}} \leq T_{jc\mathbf{max}},\ j = \mathbf{1}, \mathbf{2}, \ldots, M \tag{3}$$

$T_{jc\mathbf{min}}$ is critical minimum interval constraint of NBSU j, $T_{jc\mathbf{max}}$ is critical maximum interval of NBSU j. $t_{j\text{start}}$ is the starting time of NBSU j.

3.4. Energization of the Connected Bus Will Energize the Line and Vice Versa

If both the connected busses are energized or deenergized the corresponding line is energized or deenergized

$$\begin{gathered} -Mu^{t}_{\text{busm}} \leq u^{t}_{\text{linemn}} \leq Mu^{t}_{\text{busm}} \\ -Mu_{\text{busn}}{}^{t} \leq u^{t}_{\text{linemn}} \leq Mu_{\text{busn}}{}^{t} \\ t \in \Omega_t, mn \in \Omega_{\text{line}}, m\&n \in \Omega_{\text{bus}} \end{gathered} \tag{4}$$

$u_{\text{busn}}{}^{t}$, $u_{\text{linemn}}{}^{t}$ are decision variables of bus and line, Ω_t, Ω_{line} and, Ω_{bus} are set of time, line and buses number.

3.5. If Connected Buses/Line Is Rejuvenated, Then They Will Not Turn-Off Again

At any time interval if the bus or line is energized, that bus or line will not be deenergized again.

$$\begin{gathered} u^{t}_{\text{linemn}} \leq u^{t+\mathbf{1}}_{\text{linemn}}, \quad t \in \Omega_{t-\mathbf{1}}, mn \in \Omega_{\text{line}} \\ u^{t}_{\text{busm}} \leq u_{\text{busm}}t + \mathbf{1}, \quad t \in \Omega_{t-\mathbf{1}}, \boldsymbol{m} \in \Omega_{\text{bus}} \end{gathered} \tag{5}$$

$u_{\text{linemn}}{}^{t}$ is a binary decision variable of line mn at time t. $u_{\text{busm}}{}^{t}$ is decision variable of bus mn at time t. 0 means that line or bus is not energized and 1 means line or bus is energize at time t. Ω_t = 1, ..., T, $\Omega_t - 1$ = 1, . . . , T − 1, and $\Omega_t - 2$ = 2, . . . , T are sets of time.

3.6. Initially, the Line and Bus of the Black Start Unit Are Just Connected

Intially. All the line and buses are de-energized except the line and bus connected with the black start unit.

$$\begin{gathered} u_{\text{linemn}}{}^{t} = \mathbf{0},\ t = \mathbf{1}, mn \in \Omega_{\text{line}} \\ u^{t}_{\text{busm}} = \mathbf{1},\ t = \mathbf{1}, m \in \Omega_{\text{bus-BSU}} \\ u^{t}_{\text{bus } m} = \mathbf{0},\ t = \mathbf{1}, m \in \Omega_{\text{bus}}/\Omega_{\text{bus-BSU}} \end{gathered} \tag{6}$$

Ω_{line} is set of line numbers, equal to 1 . . . . . N_{line}. $\Omega_{\text{bus-BSU}}$ is the set of busses connected with black start unit. Ω_{bus} is the set of bus number that is equal to 1 . . . N_{Bus}. u^{t}_{busm} is the binary decision variable of bus m at time t. $u_{\text{linemn}}{}^{t}$ is the set of binary decision variable of line mn at time t. $u^{t}_{\text{bus } m}$ is the binary decision variable of bus m at time t.

3.7. Non-Black Start Unit Is Energized after the Energization of Its Connected Bus

The NBSU will start after the connected bus is energized.

$$u^t_{\text{busm}} \geq u^t_j,\ m \in \Omega_{\text{bus-NBSUj}}, j \in \Omega_{\text{NBSU}}, t \in \Omega_t \tag{7}$$

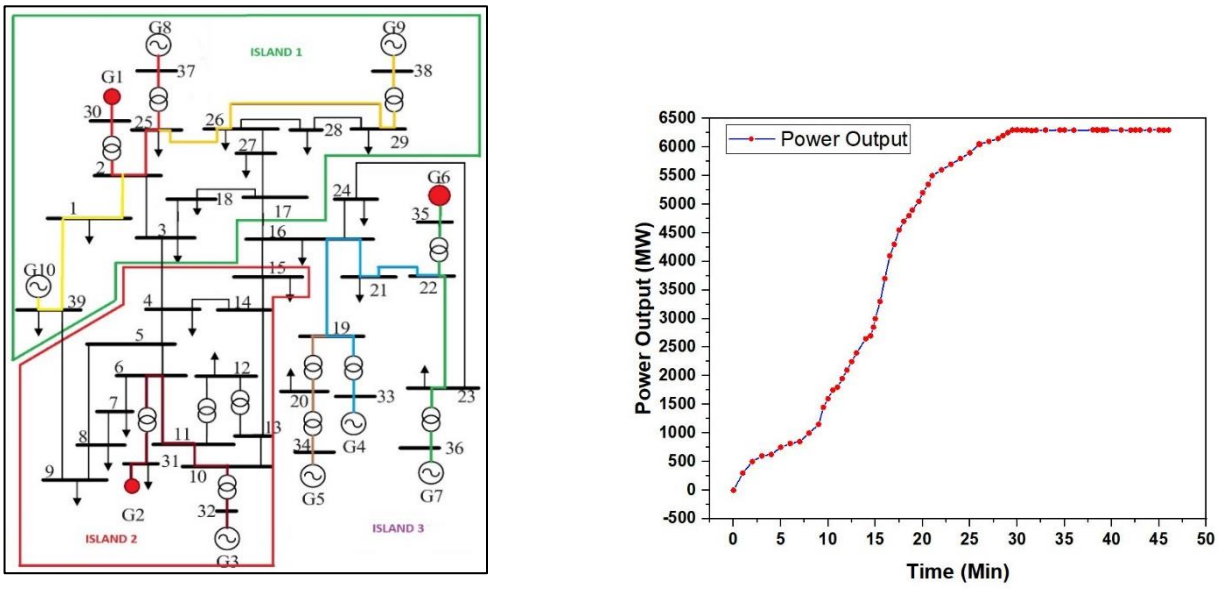
$u^t_{\text{bus } m}$ is the binary decision variable of bus m at time t. $\Omega_{\text{bus-BSU}}$ is the set of busses connected with non-black start unit. Ω_{NBSU} is the set of non-black start unit that is equal to $1 \ldots N_{\text{BSU}}$ Ω_t is the set of time that is equal to $1 \ldots T$.

4. Case Study

The IEEE-39 benchmark system is utilized to validate the effectiveness of the proposed algorithm. IEEE 39 bus system data is taken from [8]. It includes 46 branches, 39 buses and ten generators. Among ten generators, there are 3 BS units and 8 NBS units. The scenario of complete blackout is considered. The BSU (G1) is located at bus 30 in Island 1. The BSU (G2) is located at bus 31 in Island 2. The BSU (G6) is located at bus 35 in Island 1. Non-black start units in Island 1 are G8, G9, and G10. NBSU in Island 2 is G3. NBSUs in Island 3 are G4, G5, and G7. The proposed model is solved in MATLAB R2018a on a laptop with an Intel i7-10510U processor and 8 GB RAM.

5. Results and Discussion

In this paper, each island has at least one black start unit; three islands were created [13]. Loads on each bus were restored in minimum time. The status of each generator is shown in Table 2. In Island 1, the black start unit (G1) is placed at bus 30, G2 is placed at bus 31 in Island 2 and G6 is placed at bus 35 in Island 3. Each black start unit restore other's NBSUs in their vicinity, as shown in Table 3. Loads are gradually connected to avoid the voltage dip or frequency drop. Total restoration time is 36 min, and prioritized load is energized at first. G5 is restored on priority basis in Island 3. The optimal transmission path from BSU to NBSUs in each island is shown in Figure 1a. After 36 min of restoration process, total the MW capability restored is shown in Figure 1b. The total restoration time is minimized because of the optimal generator start-up sequence, the optimal transmission path search and the resynchronization of three islands.



(**a**) (**b**)

Figure 1. (**a**) Optimal transmission path with generator and load restoration (**b**) Total Generation curve of IEEE 39 bus system.

Table 2. Generator location and status.

Generator Number	Generator Status	Bus Location
1	Black-Start	30
2	Black-Start	31
3	Non-Black Start	32
4	Non-Black Start	33
5	Non-Black Start	34
6	Black-Start	35
7	Non-Black Start	36
8	Non-Black Start	37
9	Non-Black Start	38
10	Non-Black Start	39

Table 3. Cranking path from BSU to NBSU.

Island	BS Gen	NBS Gen	Cranking Path (Bus Number)
Island 1	G1	G8	30→2→25→37
		G9	30→2→25→26→29→38
		G10	30→2→1→39
Island 2	G2	G3	31→6→11→10→32
Island 3	G6	G5 (prioritized)	35→22→21→16→19→20→34
		G4	35→22→21→16→19→33
		G7	35→22→23→36

6. Conclusions

Parallel power system restoration using the multi-objective Genetic algorithm is proposed. The optimal start-up sequence of generating units has further minimized the overall restoration time. The path that requires the minimum switching actions is considered the optimal transmission path. Three islands are created, and each island has one black-start unit that transfers the cranking power to other NBSU. The shortest transmission line path using a genetic algorithm has enhanced the restoration time. The overall combination of the optimal start-up sequence of the generating unit, the optimal transmission line path search and synchronization of the island has improved the efficiency of the proposed algorithm.

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