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Power System Restoration using Particle Swarm Optimization

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ABSTRACT
This paper presents an efficient and reliable Particle Swarm Optimization (PSO) algorithm for solving Power System Restoration (PSR). The main objective is that after an incident due to electrical failure, power system restoration becomes a complex process involving decision-making problems of combinatory nature that can be formulated as a multi-stage, non-linear, continuous and binary constrained optimization problem. PSO is a novel optimization method developed by Kennedy & Eberhart. This paper presents an application of the PSO algorithm to Power System Restoration for 9 Bus systems are given to demonstrate that the algorithm can be used in actual, large scale urban distribution system applications. It is found that the Power System Restoration of distribution system can be obtained very efficiently by applying the PSO.

General Terms
Power System, Particle Swarm Optimization.

Keywords
Artificial Intelligence, Distribution System, Particle Swarm Optimization, Power System Restoration.

1. INTRODUCTION
As modern society has become increasingly dependent on electricity, not only is it important to prevent power system failures, but it is also imperative to limit the extent and duration of failures or to restore the power system to an optimal target configuration after the fault. The problem of obtaining a target system is known as a power system restoration [1], many electric utilities develop system restoration plans which allow quick recovery from an outage.

The restoration of a transmission power system from a blackout is a complex real-time control problem. Operators in control centers are, fortunately, not faced with this situation very often because power systems are designed to prevent a total system collapse (e.g., protection devices which isolate a faulted transmission line, shed load, or isolate thermal units). However, a disturbance may cause some cascade events which result in a degradation of frequency and / or voltage conditions in the power system. As the transmission power system is meshed, the consequences of this degradation are spread all over the system. Usually, the system is divided into islands (by protection devices) in order to preserve at least some parts of the system. However, if there is no balance between production and consumption in the islands, they are likely to be blacked-out. Power system Restoration consists of two main sequential steps. First, the optimal system configuration target is obtained from the set of feasible limits. Second, switching operations are performed in order to achieve the optimal target configuration obtained in first step.

Some approaches have been applied to the power system restoration problem such as expert systems, mathematical programming and evolutionary strategy. In radial systems like a distribution system, it is very easy to maintain the network equilibrium at each stage of the switching scenario. The proposed approach in this paper is focused in interconnected power system with multiple generation units and transmission loops.

The approach is concentrated in obtaining a switching scenario or stage where only a load, a transformer, a transmission line, a shunt capacitor bank or a generation unit is switched on one at a time. In each stage all the control and stage variables should be within their limits and the power balance equations should be met.

The main objective of the service restoration problem is to minimize the number of customers faced with the interruption of power delivery by transferring them to support feeders via network reconfiguration, which respects all operational and electrical constraints. Another factor to be considered is the reaction time: outage areas should be restored as quickly as possible, to avoid an impact on the interruption duration indices. In the literature there are several papers [2-12] discussing this problem for utility system. Most of the methods are based on heuristic search techniques. Some of the methods are based on graph theory [9-12]. However, PSR have different configurations when compared to utility systems [13]. In [14] a comparison between PSO and GA in System Restoration Solution is discussed.

2. PROBLEM FORMULATION
The objective function is to minimize the amount of un-served loads at each stage and can be expressed as follows:

$$f_s = min\{-\sum_{L=1}^{N_L}(S_L * M_L * X_L)\} \quad (1)$$

where,

$f_s =$ objective function to be minimized at stage

s = stage index

S_L: $\sqrt{P_L^2 + Q_L^2}$ = capacity of load L

P_L : real power component of load L

Q_L : reactive power component of load L

M_L : percentage of load L being restored

X_L : X_L = 1: load L is restored,

X_L = 0 : otherwise

N_L : number of loads

The following constraint allows a switching scenario or stage where only a load, a transformer, a transmission line, a generation unit or a load is switched on one at a time. Therefore, at each switching operation, a new restoration scenario is obtained containing a new network configuration and a new set of voltages and power balance equations.

$$\sum_{L=1}^{N_L}(X_L)+\sum_{k=1}^{N_k}(X_k)+ \sum_{g=1}^{N_g}(X_g)) - s=0 \qquad (2)$$

where,

X_k : X_k = 1: branch k is restored,

X_k = 0: otherwise

N_k : number of branches

X_g: X_g = 1: generation unit g is restored

X_g = 0: otherwise

N_g: number of generation units

These following constraints are known as the power balance constraints. They guarantee that the load demand will be met at each restoration stage considering the transmission losses of the system. These constraints are the main objective in a power flow analysis.

$$P_{Gi} – P_{Di} – P_{Li} = 0 \qquad (3)$$

$$Q_{Gi} – Q_{Di} – Q_{Li} = 0 \qquad (4)$$

where,

$$P_{Li} = \sum_{j=1}^{N}[|Y_{ij}| * |V_i| * |V_j| * \cos(\emptyset_{ij} + \delta_j - \delta_i \qquad (5)$$

$$Q_{Li} = \sum_{j=1}^{N}[|Y_{ij}| * |V_i| * |V_j| * \sin(\emptyset_{ij} + \delta_j - \delta_i)] \qquad (6)$$

N: number of buses at each stage

$|V_i|$: voltage magnitude at bus i at each stage

$|V_j|$: voltage magnitude at bus j at each stage

P_{Gi} : real power generation at bus i at each stage

P_{Di} : real power demand at bus i at each stage

P_{Li} : real power loss at bus i at each stage

Q_{Gi} : reactive power generation at bus i at each stage

Q_{Di} : reactive power demand at bus i at each stage

Q_{Li} : reactive power loss at bus i at each stage

$|Y_{ij}|$: admittance magnitude between bus i and j at each stage

Φ_{ij} : admittance angle between bus i and j at each stage

δ_i : voltage angle at bus i at each stage

δ_j : voltage angle at bus j at each stage

These operational constraints guarantee a safe operation of the system at each restoration stage. The limits should be met at all time to avoid damage to the power system components and maintain the system stability.

$$|PF_k| \leq PF_k^{max} \qquad (7)$$

$$P_{Gg}^{min} \leq P_{Gg} \leq P_{Gg}^{max} \qquad (8)$$

$$Q_{Gg}^{min} \leq Q_{Gg} \leq Q_{Gg}^{max} \qquad (9)$$

$$V_i^{min} \leq |V_i| \leq V_i^{max} \qquad (10)$$

where,

PF_k : complex power flow at branch k at each stage

PF_k^{max} : complex power flow limit of branch k

P_{Gg} : real power generation of unit g at each stage

P_{Gg}^{min} : lower real power generation limit of unit g

P_{Gg}^{max} : upper real power generation limit of unit g

Q_{Gg} : reactive power generation of unit g at each stage

Q_{Gg}^{min} : lower reactive power generation limit of unit g

Q_{Gg}^{max} : upper reactive power generation limit of unit g

$|V_i|$: voltage magnitude at bus i at each stage

V_i^{min} : lower voltage magnitude limit at the bus i

V_i^{max} :upper voltage magnitude limit at the bus i

3. POWER SYSTEM RESTORATION PROBLEM FORMULAION FOR PARTICLE SWARM OPTIMIZATION

PSO is a multi-agent search technique that traces its evolution to the emergent motion of a flock of birds searching for food. It was developed by James Kennedy and Russel Eberhart in 1995 [15], [16]. It uses a number of particles that constitute a swarm. Each particle traverses the search space looking for the global minimum or maximum. In a PSO system, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience, and the experience of neighbouring particles, making use of the best position encountered by itself and its neighbours. The swarm direction of a particle is defined by the set of particles neighbouring to the particle and its history experience. The best previous position of a particle is recorded and represented as pBest. The index of the best particle among all the particles in the group is represented as gBest [17].

The power system Restoration approach consists of maximising the served loads subject to the power balance and power flow constraints, control and state variable limit and the condition of switching operation. In the formulation the following variables are the control variables:

- ✓ Transmission lines, transformers and generation units states (ON or OFF): Binary variables (0 or1).
- ✓ Load restored (Yes or No): Binary variables (0 or 1).
- ✓ Load percent (0%, 25%, 50%, 75% or 100%) : Discrete variables
- ✓ Voltage magnitude at PV buses including the slack bus: Continuous variables
- ✓ Real power at PV buses excluding the slack bus: Continuous variables

The following variables are the state variables:

- ✓ Real power balance from power flow.
- ✓ Reactive power balance from power flow.
- ✓ Voltage magnitude at PQ buses.
- ✓ Power flow through transmission lines and transformers.
- ✓ Reactive Power generation at PV buses including the slack bus.
- ✓ Real Power generation at the slack bus.

In this approach there are twenty-three control variables for the WSCC Nine Bus Test Systems. The first three position of the control variables vector are the states of the three generation units, one if the generation unit is turned on or zero otherwise. The next three control variables are the states of the loads, one if the load is in the restoration path or zero otherwise. From the position seventh to the fifteenth, there are the control variables of the ninth transmission lines and transformers, one if it is in the restoration path or zero otherwise. These fifteen control variables are discrete binary variables and were handled using the PSO model for binary variables. The control variables in the position sixteen, seventeen and eighteen are the voltage magnitudes of the generation units G_1, G_2 and G_3 respectively. These control variables were adjusted in the limit range specified (0.9 to 1.1) p.u. The position nineteen and twenty are the real power generation in MW of generation units G_1 and G_2 respectively. These control variables were adjusted in the limit ranges specified for each generation unit. The last three position of the control variables vector are the load percentage of each load. These variables were adjusted in the discrete range [0%, 25%, 50%, 75% and 100%]. The last eight control variables were handled using the PSO model for continuous variable. The following table shows a control variable vector or particle:

Table1: Control Variables Vector or Particle for the Power System Restoration Problem

Control Variables Vector or Particle																						
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
G_1	G_2	G_3	L_5	L_6	L_8	T_{1-4}	T_{2-7}	T_{3-9}	L_{4-5}	L_{4-6}	L_{5-7}	L_{6-9}	L_{7-8}	L_{8-9}	V_1	V_2	V_3	P_{G2}	P_{G3}	M_{L5}	M_{L6}	M_{L8}

At each stage s, the objective fitness function is expressed in terms of penalty functions as follows;

$$f_s = \min\{-A_L \sum_{L=1}^{N_L} (S_L \times M_L \times X_L) + A_s * \Delta S^2 + \sum_{g=1}^{N_c} (A_{P_{Gg}} * \Delta P_{Gg^2}) +$$

$\sum_{g=1}^{N_g} \left(A_{Q_{Gg}} * \Delta Q_g^2\right) + \sum_{i=1}^{N} \left(A_{V1} * \Delta V_i^2\right) + \sum_{k=1}^{N_K} (A_{PF_K} * \Delta PF_k^2)\}$

(11)

Subject to:

$$P_{G_i} - P_{D_i} - \sum_{j=1}^{N} [|Y_{ij}| \times |V_i| \times |V_j| \times \cos(\emptyset_{ij} + \delta_j - \delta_i)] = 0 \quad (12)$$

$$Q_{G_i} - Q_{D_i} - \sum_{j=1}^{N} [|Y_{ij}| \times |V_i| \times |V_j| \times \sin(\emptyset_{ij} + \delta_j - \delta_i)] = 0 \quad (13)$$

where,

$$\Delta S = \left(\sum_{L=1}^{N_L} (X_L) + \sum_{K=1}^{N_K} (X_k) + \sum_{G=1}^{N_G} (X_G) \right) - s$$

$$\Delta P_g = P_{Gg} - P_{Gg}^{lim}$$

$$\Delta Q_g = Q - Q_{Gg}^{lim}$$

$$\Delta V_i = |V_i| - V_i^{lim}$$

$$\Delta PF_K = PF_K - PF_K^{lim}$$

A_L : Load weight factor.

A_S : Penalty factor associated with the violation of the current stage.

$A_{Q_{Gg}}$: Penalty factor associated with the violation in the reactive power limit of the available generation unit g at the current stage.

A_{V_i}:Penalty factor associated with the violation in the voltage limit of active bus i at the current stage.

A_{PF_K}: Penalty factor associated with the violation in the power flow limit of active branch k at the current stage

$A_{P_{Gg}}$: Penalty factor associated with the violation in the active power limit of the available generation unit g at the current stage.

Variables values were forced to be within their limits using penalty functions. If a variable was out of a limit, a penalty factor (i.e. relative large number) is multiplied by the difference between the value and the limit violated, and then added to the fitness function. Discrete variables, like the load percent, were forced rounding them to their discrete values. In addition a large penalty factor is added to the fitness function when the power flow does not converge. This allows to particles to move away from this scenario. In general, the penalty function methods can be seen as penalizing infeasible solutions.

Once the algorithm converges in an optimal solution for the stage s, the devices switched on so far are fixed for the rest of the restoration process. That means that each generation unit, transformer, transmission line or load that have been switched on at or previous stage s will remains switched on for the stage s+1. The approach allowed the load percent to then at any stage.In order to demonstrate the robustness of the approach, it was performed in a blackout situation that may be considered as the worth case scenario for the power system restoration. In a blackout scenario all system components are disconnected. The approach also can be adapted to the situation where only a part of the system is collapsed. In this case, the initial stage is the current system configuration after the fault or disturbance.

The program code was developed using MATLAB 6.0 R12 on a Pentium 4 PC. The power flow equations were solved using the Full-Newton load flow method with a tolerance of 10^{-4} for each feasible network configuration. After several trials, the particle swarm optimization parameters were selected. The inertia weight was set to 0.9. The constants c1 and c2 were set to 1. These values were selected based on the results of several trials. The size of the swarm was 75 particles. As converged criteria, the algorithm stop looking for a solution if the global best solution does not change after 15 consecutives iteration and the iteration have reached 10% of the maximum iterations specified. The maximum iteration was set to 500.

4. POWER SYSTEM RESTORATION SOLUTION

In order to test the proposed approach and demonstrate its effectiveness, it has applied to the 9 bus test system and described in Table 1, table 2, Table 3. The restoration process proposed was applied to a completely collapsed system. Therefore, all system devices were switched off expect the generation unit G_1 as a reference. Due to that the generation unit G_1 was set as the reference, the bus 1 was the slack bus. The generation unit G_1 and the transformer 1-4 were active previous the first stage, because transformer 1-4 is the step-up transformer of G_1 and it is obvious that G_1 and transformer 1-4 need to be restored simultaneously. This situation also applies to G_2 with transformer 2-7, and G_3 with transformer 3-9.

The following tables show the results obtained in each stage.

Table 1: Switching Operations for the Power System Restoration Problem

Stage	Restoration Path											
	Generation Units and Transformers			Transmission Lines						Loads		
	G1 & T1-4	G2 & T2-7	G2 & T2-7	L4-5	L4-6	L5-7	L6-9	L7-8	L8-9	L5	L6	L8
0	X											
1	X				X							
2	X				X						X	
3	X			X	X						X	
4	X			X	X					X	X	
5	X			X	X	X				X	X	
6	X	X		X	X	X				X	X	
7	X	X		X	X	X		X		X	X	
8	X	X		X	X	X		X		X	X	X
9	X	X		X	X	X		X	X	X	X	X
10	X	X	X	X	X	X		X	X	X	X	X
11	X	X	X	X	X	X	X	X	X	X	X	X

Table 2: Voltage Profile for the Power system Restoration Problem

Stage	Bus Voltage Magnitudes(p.u)								
	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9
0	0			0					
1	0.926			0.935		0.942			
2	1.027			1.026		1.011			
3	0.966			0.974	0.981	0.958			
4	1.028			1.026	1.005	1.023			
5	0.899			0.907	0.906	0.902	0.929		
6	1.047	1.99		1.046	1.033	1.032	1.093		

7	0.994	1.070		0.993	0.986	0.978	1.066	1.071	
8	1.99	1.99		1.087	1.060	1.075	1.092	1.073	
9	0.960	1.091		0.965	0.968	0.949	1.070	1.068	1.079
10	1.99	1.055	1.99	1.081	1.045	1.068	1.067	1.607	1.092
11	1.052	1.037	1.99	1.046	1.017	1.047	1.050	1.054	1.089

Table 3: Power Generation for the Power System Restoration Problem

Stage	Generation Unit (P-MW and Q-MVAR)					
	P_{G1}	Q_{G1}	P_{G2}	Q_{G2}	P_{G3}	Q_{G3}
0	0	0				
1	0.008	-13.762				
2	45.343	1.547				
3	45.393	-13.113				
4	85.493	5.640				
5	85.650	-10.456				
6	76.613	4.791	96.507	13.566		
7	65.538	2.160	108.627	11.074		
8	59.379	23.115	189.000	21.161		
9	60.331	-7.328	189.000	45.379		
10	53.300	34.719	189.000	-10.154	31.791	12.628
11	48.819	11.163	189.000	-10.286	81.859	20.113

Table 4: Load Restored for the Power system Restoration Problem

Stage	Loads (P-MW and Q-MVAR)								
	P_5	Q_5	M_5	P_6	Q_6	M_6	P_8	Q_8	M_8
0									
1									

2				44.9	15.00	50%			
3				44.9	15.00	50%			
4	62.49	25.00	50%	22.4	7.50	25%			
5	62.549	25.00	50%	22.4	7.50	25%			
6	124.99	50.00	100%	44.9	15.00	50%			
7	124.99	50.00	100%	44.9	15.00	50%			
8	124.99	50.00	100%	44.9	15.00	50%	75.00	26.245	75%
9	124.99	50.00	100%	44.9	15.00	50%	75.00	26.245	75%
10	124.99	50.00	100%	44.9	15.00	50%	100.00	34.99	100%
11	124.99	50.00	100%	89.9	30.00	100%	100.00	34.99	100%

Table 5: Branch Power Flow for the Power System Restoration Problem

Stage	Branch Power flow(Maximum MVA)								
0	0								
1	13.9				13.9				
2	45.4				47.4				
3	47.6			16.8	47.4				
4	85.7			67.3	24.2				
5	87.1			64.0	23.7	25.5			
6	76.8	97.5		37.1	47.4	98.4			
7	65.6	109.2		25.1	47.4	110.7		17.0	
8	63.7	191.2		44.7	47.4	115.0		79.5	
9	61.1	195.3		19.3	47.4	120.3		79.3	24.0
10	63.7	192.4	34.2	53.4	47.4	122.4		70.2	47.3
11	50.1	192.6	84.3	48.7	25.7	101.6	73.1	91.6	48.1

5. CONCLUSION

The sequence of the restoration path shows in Table 1. Only one switching operation was performed for each stage. The voltage profile during the restoration process shows in Table 2. No voltage was out of its limits. The power generated by the generation units at each stage shows in Table 3. No generation unit was out of its generation limits. According to the objective, our main aim is to minimize the unserved loads. The total load served increases with the stages shows in Table 4. The power flows through the transmission lines and transformer at each stage shows in table 5. All power flows are within their limits. After finished the restoration, all loads were served at 100%. All the generation units, transformers and transmission lines were switched on. Some control variables i.e. voltage magnitudes and real power generation scarcely change. These changes do not affect the objective function. In each stage all the control and stage variables were within their limits and the power balance equations were met. The restoration path was established, all loads were served, and the restoration switching process was confirmed fulfilling all the problem constraints.

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