Enhancing Reliability of Power Protection Systems Economically in the Post-Restructuring Era

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Abstract: The restructuring of electricity industry has renewed concerns about wide-area disturbances due to their increasing economic and social costs. Power protection systems have played significant roles in propagating these disturbances. In post-restructuring era, smarter relays should be put into service to enhance the overall system reliability. However, it is not economically feasible to replace all the protection devices. Given limited resources, we would like to find an optimal system upgrading solution that can maximally increase the system reliability. In this paper, we analyze the impact of consecutive relaying malfunctions and pinpoint the vulnerable locations in the New York Power Pool (NYPP) 3000-bus system by simulating electrical blackouts using the Cornell Theory Center's supercomputers. We introduce a heuristic random search algorithm for faster search of important blackout paths. The optimal investment plan is given at the end of the paper.

Keywords: Power system reliability; Power system protection; Power system relaying; Search methods; Random Search; Heuristic Search; Vulnerability; Rare events; Hidden failures

I. INTRODUCTION

Power protection systems, as shown in recent studies, have played major roles in spreading electric system disturbances [1]. The redundancy and over-protection in the current protection design, while preventing individual hardware damage, tends to promote hidden failures, propagate long-chain disturbances and as a result compromise global reliability. As we embark on restructuring the power industry, it is crucial to review the current protection philosophy and investigate the feasibility of improving system reliability through an affordable protection system upgrade. Thorp et al [2,3] first studied hidden failures in relays and their impact on the power system reliability. Hidden failures denote the incorrect operations that usually remain undetected until abnormal operating conditions are reached. Bae at al [4] devised a dual-mode relaying concept that allows each individual relay's hidden failure probability to be adaptively adjusted according to the system's operating status. Although the benefit of applying these advanced relays is obvious, the question where to put them cannot be easily answered without a detailed vulnerability analysis of the bulk power system.

Bae et al [5] conducted the earlier simulation work on finding the vulnerable locations by simulating power system blackouts using the importance sampling technique. However, due to the hidden failures' load flow dependent nature and the lack of computational resource, that work was limited to simulating a WSCC 179-bus equivalent system. In this paper, we extended the previous work to simulate the NYPP 3000-bus system utilizing the Cornell Theory Center's supercomputing facility. To speed up the simulation, we introduce a heuristic random search algorithm for faster search of important blackout paths. Our objective is to pinpoint the most vulnerable locations in a real power system, numerically characterize the vulnerability, and find the most economical system upgrading solution.

We describe how we model the power system operations and disturbances in Part II. In Part III, we introduce the heuristic random search algorithm for efficient search of important sample paths. We later analyze the simulation result and study the vulnerability of the NYPP system in Part IV. Part V gives the optimal system upgrade solution.

II. METHODOLOGY

To accurately study the effect of disturbances spreading through the transmission network due to contingencies, we have to first identify the major engaged elements and understand their roles in propagating the disturbances. The example power system shown in Fig. 1 illustrates most elements that we have modeled in our simulation:

1. Generators, loads and transmission lines;
2. Line protective relays;
3. Generator protective relays;
4. Phase-shift transformers;
5. Switch shunt elements;
6. Transmission limits;
7. Generator's VAR limit;
8. Under-frequency load-shedding relays.

While the protective relays operate correctly in most situations, their hidden failures can sometimes be exposed by neighbor faults and lead to further propagation of disturbances. We can model the hidden failure as a stochastic process [5]. The probability of hidden failures depends on the impedance seen by the line protective relays and the VAR limit violation detected by generator protective relays. Fig. 2 shows the probability of hidden failure as a function of impedance seen by the line protective relay. Fig. 3 shows the probability of incorrect generator tripping as a function of reactive power. Let us consider the blackouts in a simple network. In Fig. 4, a legitimate relay operation on line 3 exposes line 2 and line 4. The generator protective relay at bus 2 is exposed due to a VAR limit violation. Now, all the exposed relays are subject to possible false tripping.

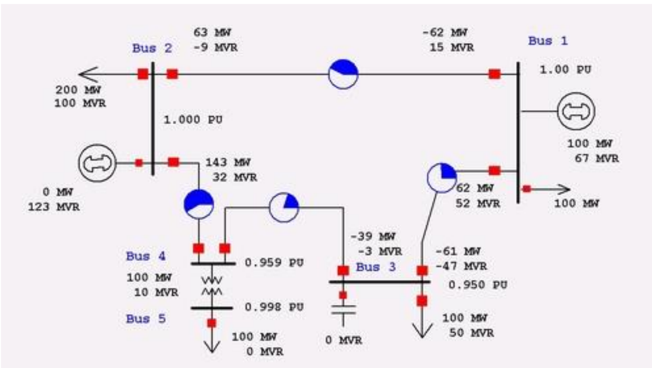

Fig. 1. Illustration of key equipment in a 5-bus system

Suppose the generator at bus 2 is tripped incorrectly. Then line 1 and line 2 are exposed in the next stage. Incorrect tripping of line 1 will expose line 4 and may eventually lead to a system-wide blackout. Many other blackout paths also exist in this simple 5-bus system. The number of blackout paths grows exponentially with the size of the system.

We are interested in both the probabilities of the sample paths and the amount of load lost for that path. Let $U = \{B_1, B_2, \ldots B_M\}$ be the complete set of all possible blackout sequences, and suppose all initiating events in the power system have the same frequency F^0. Let C_i be the load lost associated with the blackout B_i and L be the system overall load lost. Then, the expected overall lost per unit time can be expressed by

$$E(L) = \sum_{i=1}^{M} \left(F^0 C_i \prod_{j=1}^{n_i} p_{ij} \prod_{j=n_i+1}^{N_i} (1 - p_{ij}) \right), \qquad (1)$$

where p_{ij} is the probability of j^{th} exposed hidden failure being triggered in the blackout sequence B_i, n_i is the number of triggered hidden failures and N_i is the total number of exposed hidden failures involved in the B_i sequence.

We define the system reliability as

$$\eta = 1/E(L). \qquad (2)$$

If V is a subset of U containing all the blackout sequences which has protective relay R_k involved, then

$$\upsilon_k = E(L_k) = \sum_{V} \left(F^0 C_i \prod_{j=1}^{n_i} p_{ij} \prod_{j=n_i+1}^{N_i} (1 - p_{ij}) \right) \qquad (3)$$

can characterize the vulnerability of relay R_k.

Since p_{ij} is load flow dependent, the simulation program has to recalculate the system status at each stage of the blackout. For large systems, the work of enumerating all possible blackout sequences in U could be prohibitive. In this case, η and υ_k can be estimated by simulating the most probable sample paths.

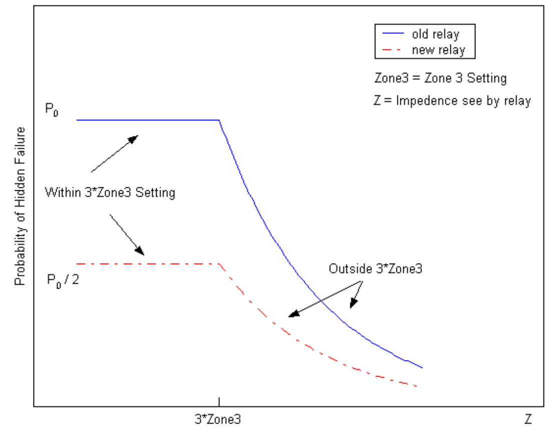

Fig. 2. Probability of hidden failure in line protective relays

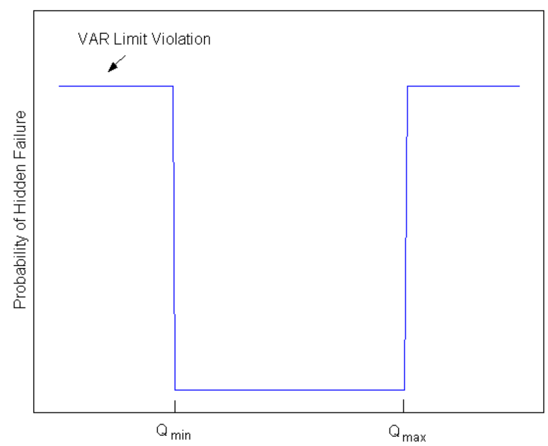

Fig. 3. Probability of hidden failure in generator protective relays

Several special considerations regarding the load flows need to be noted here. In power systems, each transmission line has its maximum transferring capacity. Once the on-line load flow exceeds that limit, the transmission line may be tripped legitimately and promote bigger blackouts. Thus, we have to consider the possible line limit violation in our simulation. Phase-shift transformers and switch shunt elements can also alter the load flows during disturbances.

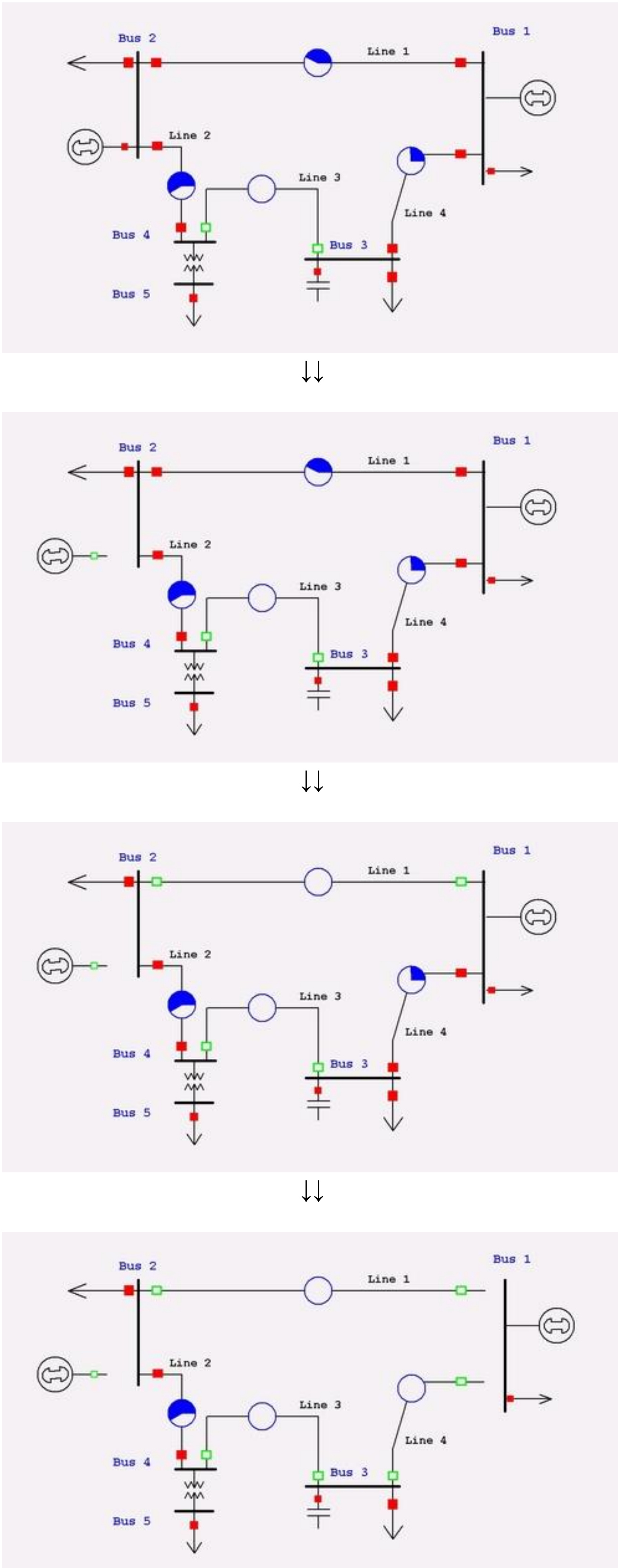

Fig. 4. Evolution of the power system during disturbances

It is possible that during the disturbance the system is separated into two or more islands each of which can independently maintain the balance between generations and loads. In the simulation, different islands should be simulated separately. We employ the BFS-like algorithm to determine the connectivity of the power network and split it whenever necessary.

III. HEURISTIC RANDOM SEARCH ALGORITHM

One obstacle to studying large-scale disturbance is that such events are rare. Importance sampling technique had been applied in earlier works for the rare-event simulation. However, as shown in Part II, we are merely interested in finding the most probable subset of blackout sequences in $\{B_1, B_2, \ldots B_M\}$ and their correspondent probabilities while the importance sampling method usually spends more computing resources in maintaining the original distribution of sample paths. In the case where the underlying stochastic model is given, the heuristic random search algorithm shown below is more appropriate for solving the problems.

Let us consider a tree composed by all sample paths in $\{B_1, B_2, \ldots B_M\}$ and their connections (Fig. 5). Each node in the tree corresponds to a blackout and has a probability ρ_i and a lost C_i associated with it. Each edge corresponds to a single event during the disturbance, either a hidden failure or a legitimate tripping, with a probability p_{ij}. The root of the tree represents the power system running in the normal operating condition. The problem is to find the nodes having both high probabilities and large amounts of load lost in the tree with least computation.

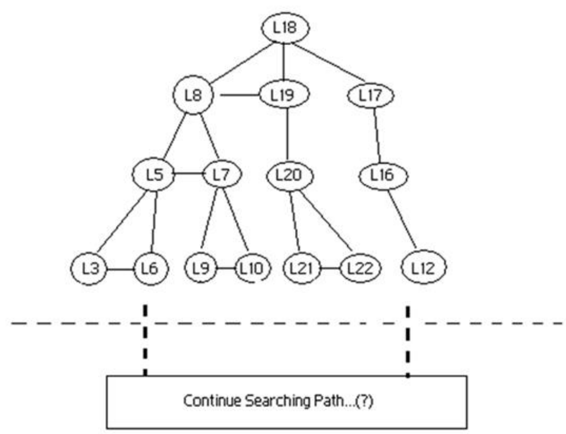

Fig. 5. Illustration of the sample path tree of New England 39-Bus System

Two characteristics differ the above problem from other search and optimization problems. For one thing, each path in the tree starting from the root is a Markov chain. So,

$$\rho_i = \prod_{j=1}^{n_i} p_{ij} \prod_{j=n_i+1}^{N_i} (1 - p_{ij})\,. \tag{4}$$

This implies that the nodes on the top of the tree have higher probabilities. While on the other hand, longer paths have greater amounts of load lost as

$$C_i = \sum_{j=1}^{N_i} c_{ij} \ , \tag{5}$$

where c_{ij} is the loss introduced by j^{th} event in blackout B_i.

Blackouts whose expected loss $E(L_i) = \rho_i \cdot C_i$ are significant contribute more to the vulnerability defined in (3) and therefore deserve more computation resources. Naively, the favorite nodes locate in a range near the top of the tree. The algorithm should focus on expanding nodes with expected lost greater than a minimum value $E_{min}(L_i)$ and within a maximum depth D_{max}. These two values are different from case to case and therefore should be computed on the fly during the simulation. To keep the accuracy, we set $E_{min}(L_i)$ and D_{max} to some safe boundaries at the beginning and dynamically update them during the simulation by analyzing the blackout sequences already generated. The DFS-like algorithm should be applied for searching nodes in the "blackout tree". Otherwise, hundreds of thousands of power system "snapshots" have to be stored to allow the BFS algorithm to recover the search along any blackout sequence in constant time.

Another issue worth noting here is that the loss and probability of each child node cannot be computed in advance. Hence, we cannot choose the next searching direction based on evaluations of the goal functions. Instead, we have to take a random searching approach based on heuristics and the underlying stochastic process of hidden failures. In the power system, two transmission lines are seldom tripped at the same time, i.e. the spread of disturbances is one-dimensional. We can rescale the probabilities of exposed hidden failures to let one and only one event happen at each stage.

The detailed algorithm is list below:

1. Calculate the base load flow and set $E_{min}(L_i)$ and D_{max} to 0 and 50 respectively;
2. Randomly select the initial transmission line to be tripped; If enough significant blackout sequences have been collected, terminate the simulation;
3. Determine all hidden failures exposed by the last event and find the probabilities of false tripping from Fig. 2 and Fig. 3; Check the transmission limits;
4. Trip all lines violating transmission limits; If there is no violation, select one and only one hidden failure from the exposed candidates according to their probabilities and trigger it;
5. Check the connectivity of the network and fork the simulation if the system is separated into multiple islands; Track the frequency of each island and shed the load if necessary;
6. Record the current sequence as a possible blackout; If its expected loss is greater than $E_{min}(L_i)$ and the depth is less than D_{max}, push it into a fixed-size set holding the most significant blackout sequences; Replace the trivial one if necessary; Update D_{max} to two times the average depth of discovered significant paths stored in the set; If current depth is greater than D_{max}, return to step 2 to restart searching from the root;
7. Compute the new load flows using Newton-Raphson method; If it is done successfully, go back to step 3 to continue searching the blackout nodes at deeper depth; Otherwise, if the system become too ill-conditioned to have a mathematical load flow solution, go back to step 2 to restart searching from the root;

IV. VULNERABILITY ANALYSIS OF NYPP 3000-BUS SYSTEM

The NYPP 3000-bus equivalent system contains 2935 buses, 1304 generators, 6571 transmission lines and 457 transformers. Using a 256-Processor Intel cluster, we simulated 41,053 NYPP blackouts that have lost greater than 10MW. Let us now analyze the system vulnerability. From the simulation result, the vulnerability of each relay is calculated. Fig. 6 illustrates the distribution of the most vulnerable locations in NYPP. Relative vulnerability of relay k is defined as $\upsilon_k / \max_{\forall i}(\upsilon_i)$.

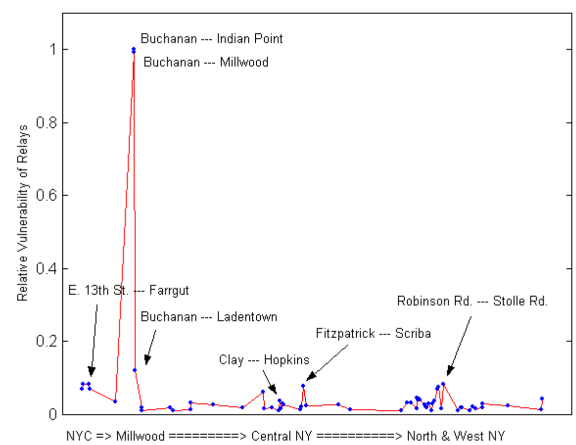

Fig. 6. Locations of most vulnerable relays in NYPP

As we can see in Fig. 6, the top three most vulnerable relays locate around the Indian Point Power Plant at Buchanan while the rest distribute around NYC, Oswego and Niagara regions respectively. We shall keep in mind that this result does not necessarily reflect each relay's actual vulnerability since we have assumed in Part II that all relays exhibit the identical hidden failure characteristics and the frequency of initiating events (flashovers, human faults, etc.) does not change with locations. However, the NERC Disturbance Analysis Working Group (DAWG) Database [6] does indirectly support our assumptions and analysis. For instance, the following documented disturbance is a typical one having hidden failures involved and matches well with our simulation result.

"On Apr. 26, 1995, some shorting bars inadvertently left on a test block caused a relay to operate as if there was a breaker failure. The breaker failure scheme caused several breakers to open at the Volney Station (NYPP), and it sent a direct transfer trip signal to the Scriba Station (shown in Fig. 6, NYPP) to open other breakers at Scriba removing the line connecting the two stations. A phase-to-phase fault occurred at the Volney Station and it was seen correctly as a line fault by relays at Volney, and the relays opened breakers at Volney and Oswego Stations. Then a phase distance directional relay at the Clay Station misoperated and caused a breaker to open at Clay and a direct transfer trip signal was sent to Nine Mile Point No. 1 (NYPP) to open, removing the Clay-Nine Mile Point No. 1 line from service."

Relays with highest vulnerabilities are good candidates to be upgraded to increase the system reliability. Table 1 lists the twenty most vulnerable relays in NYPP and their relative vulnerabilities. They should gain more attentions than other relays when planning a protection system upgrade.

V. OPTIMAL SYSTEM UPGRADING SOLUTION

System reliability can be increased by using reliable relays with lower hidden failure probabilities. In Part IV, we have pinpointed the most vulnerable locations in the NYPP protection system. Upgrading relays at those locations can of course increase the reliability. However, to find the most economical solution, we shall optimize the reliability defined in (2) as

$$\max_{Cost \le H} \eta = \min_{Cost \le H} \sum_{i=1}^{M} \left(F^0 C_i \prod_{j=1}^{n_i} p_{ij} \prod_{j=n_i+1}^{N_i} (1 - p_{ij}) \right), \quad (6)$$

where H is the budget.

We have recorded p_{ij}'s for hidden failures in all significant blackout paths during the simulation. Suppose the probabilities of hidden failures in the new relays are reduced by a half as shown in Fig. 2. Then, all p_{ij}'s associated with the new relays in (6) will also be reduce by a half. In the case that H can be used to upgrade relays at ten locations in the NYPP system, solving the equation (6) yields the optimal solution listed in Table 2. The ten locations in Table 2 are quite different from the top ten in Table 1 where records are sorted by vulnerabilities. Their improvements over the original system are compared in Fig. 7. In both cases, the major improvement comes from the new relays around Indian Point. However, their difference is still significant. In general cases where many relays have similar vulnerabilities, the optimal solution is expected to yield a much better improvement.

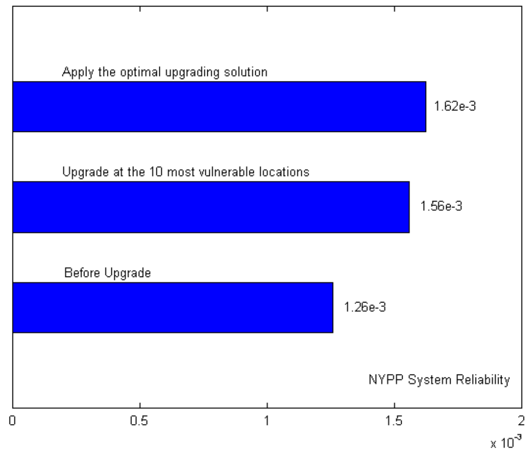

Fig. 7. A comparison of different upgrading solutions

An even better solution exists if the hidden failures can be reduced more than a half by spending more resources. For example, in the NYPP system, it will be better if the hidden failures around Indian Point can be reduced to one quarter, instead of one half.

VI. CONCLUSION

It is not our intention to simulate every aspect of the running power system. Instead, we focus on studying key elements relevant to transmission line protection, generator protection and system stabilities. Our goal is to illustrate the basic methodology for planning system upgrades and to show the feasibility of studying rare events of power systems precisely using modern powerful parallel computing facility.

System reliability and vulnerability are defined in this paper. They are then used to pinpoint vulnerable relays. By solving the equivalent optimization problem based on blackout records collected in our simulation, we found the optimal upgrading solution for the NYPP system.

We characterized the blackout simulation as a tree-searching problem and devised a random search algorithm based some power system heuristics for faster rare-event simulation.

VII. ACKNOWLEDGMENTS

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Table 1. List of most vulnerable relays in NYPP (locations & relative vulnerabilities)

Line No.	Bus from	Bus to	Zone	Relative Vulnerability
0127	Buchanan	Indian Point	Millwood	1.000
0126	Buchanan	Millwood	Millwood	0.993
0128	Buchanan	Ladentown	Millwood	0.122
0047	E. 13th St.	Farragut	N.Y.C.	0.084
0036	Hellgate	W. 179th St.	N.Y.C.	0.084
0673	Robinson Rd.	Stolle Rd.	West	0.082
0426	Fitzpatrick	Scriba	Central	0.078
0664	Davis Rd.	Stolle Rd.	West	0.074
0663	Harrison Radiator	Hinman	West	0.071
0048	W. 179th St.	Dunwoodie	N.Y.C.	0.070
0035	Poletti	E. 13th St.	N.Y.C.	0.070
0354	Mountain	Swann Rd.	West	0.063
0627	Cedars	Rosemont	North	0.045
0848	Beebee	Beebee	Genesee	0.043
0630	Dennison	Rosemont	North	0.042
0631	Malone	Willis	North	0.041
0628	Cedars	Rosemont	North	0.041
0629	Dennison	Rosemont	North	0.040
0658	Plattsburch	Ashley Rd.	North	0.038
0384	Clay	Hopkins	Central	0.036

Table 2. List of ten locations in NYPP where the relays should be upgraded first (under limited budget)

Line No.	Bus from	Bus to	Zone	Vulnerability Rank
0127	Buchanan	Indian Point	Millwood	1st
0126	Buchanan	Millwood	Millwood	2nd
0047	E. 13th St.	Farragut	N.Y.C.	4th
0663	Harrison Radiator	Hinman	West	9th
0035	Poletti	E. 13th St.	N.Y.C.	11th
0627	Cedars	Rosemont	North	13th
0630	Dennison	Rosemont	North	15th
0628	Cedars	Rosemont	North	17th
0629	Dennison	Rosemont	North	18th
0384	Clay	Hopkins	Central	20th

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IX. BIOGRAPHIES

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