Topological Models Underestimate the Impact of Hazards on Coupled Power and Water Distribution Systems

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2024 56th North American Power Symposium (NAPS) | 979-8-3315-2103-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/NAPS61145.2024.10741705

***Abstract*—As the number and severity of low-probability, high-impact weather events increases due to climate change, accurate models are needed to better understand the impact of hazards on critical infrastructure. Many critical systems, such as water and telecommunications, are dependent on the power network. At the distribution level, water and power systems are coupled in that water pumps are driven by three-phase induction motors. These motors require certain levels of power quality; however, hazard simulation literature does not accurately model power flow in distribution systems, opting for topological models to decrease computational burden and data collection. In this paper, we explore several case studies on a test system to show how including power flow both changes and adds to our understanding of distribution system vulnerability. We find that topological models underestimate pump failure in over 50% of single line outage cases. In addition, power flow models can be used to show the impact of other hazard events and failures, such as high impedance faults, voltage regulation failure, and secondary outages. On our test system, almost 50% of single high impedance fault cases result in pump failures. Our results show that topological models can underestimate pump failures, and therefore system vulnerability, in coupled power and water distribution systems.**

***Index Terms*—Hazard modeling, simulation, vulnerability analysis, power flow, power quality, resilience**

I. Introduction

As climate change progresses, the number and severity of hurricanes, tornadoes, and other weather-related hazards is increasing [1]. Our power systems must be able to withstand and adapt to these low-probability, high-impact events. Not only do our communities rely on power directly, other critical infrastructure, such as water and telecommunications, rely on the power network as well. Key to better understanding and preparing for these hazards is being able to accurately model their effects on dependent infrastructure.

Approximately 80% of all power system interruptions occur in the distribution system [2]. However, most of the literature modeling the impacts of hazards on power distribution systems uses simple topological models. This is typically justified by assuming that distribution systems are primarily radial [3], [4]. However, for many critical loads, simply having access to power is not enough; a certain level of power quality is required also. Without power flow calculations, there is no way to assess the power quality experienced at the loads upstream of a line outage.

This work is supported by a National Science Foundation award #2222096.

In this paper, we explore how considering power flow affects the predicted impact of hazards on critical infrastructure. We do this by comparing topological and power flow methods for determining water pump failures in dependent power and water distribution systems. We assess whether or not the pumps are connected to power and, in the power flow case, whether the power quality is sufficient for the pump motors to stay online. We consider hazard events and failures that can be simulated by both methods, as well as certain events and failures that can only be simulated using power flow methods. We conclude by summarizing the impact of including power flow in hazard modeling of distribution systems.

Much literature has been devoted modeling hazard events and failures in critical infrastructure. Hazards were simulated on power transmission networks in [1], [5]–[8], and a coupled power and water transmission network in [9]. Hazards have been simulated on power distribution networks, but rarely, if ever, with power flow, as there are additional challenges when transitioning from the transmission to the distribution level. The first challenge is acquiring detailed data on real networks, given distribution system operators' security concerns over data sharing. To overcome this, hazard simulations on distribution systems typically use a synthetic power network created from public data [3], [4], or, in the case of dependent infrastructure, may consider reliance on power system components probabilistically [10]. The second challenge is computation time. Many hazard models start with fragility curves to determine the probability of component failure [11]. Next, a Monte-Carlo simulation is run to assess system vulnerability/resilience to the hazard – this requires consideration of up to 10,000 different network topologies. Finally, modeling power flow in U.S. distribution networks is challenging, as the systems are unbalanced, and accurately capturing voltage issues requires three-phase unbalanced AC power flow models.

Despite the computational burden, power flow (either DC [1], [5], or AC [6], [8]) is typically calculated when modeling power transmission systems under hazards, as it is well documented that topological methods underestimate transmission system vulnerability [5], [6], [12]. To the authors' knowledge, the superiority of power flow over topological models in distribution system hazard modeling has not yet been assessed in resilience literature.

To address this need, the contributions of this paper are as follows. First, we develop a method for comparing topological and power flow methods in power and water distribution system vulnerability/hazard modeling. Second, we derive new results and insights from case studies showing how considering power flow changes the predicted impact of hazards on critical distribution infrastructure. Our results show that topological methods underestimate failure of critical loads in the system, and that inclusion of power flow could increase our understanding of hazard impacts by providing the ability to simulate more complex hazard events and failures.

The remainder of this paper is organized in the following way. In Section II, we briefly review how a wind-based hazard can affect both power and water distribution systems – detailing our motivation for this analysis. In Section III, we present our methodology and calculations used. In Section IV, we present a test system and several case studies analyzing system vulnerability, comparing topological and power flow results. We summarize our conclusions in Section V.

II. Wind-Based Hazard Effects

Many hazards – hurricanes, derechos, etc. – bring with them high velocity winds. The power system components most vulnerable to this phenomenon include overhead lines and poles [2]. The water system, being mostly underground or inside heavily fortified structures, is not considered vulnerable to wind hazards [4].

Wind-based hazards can topple poles and lines directly, or they can cause trees to make contact with or down poles and lines [13]. This, in turn, can cause conductors to make contact with each other, the ground, or something else, creating another path for current to flow. The impedance of this new path is typically much lower, often resulting in a large increase in current – such an event is known as a fault [2]. The nearest overcurrent protection should trip, electrically isolating the fault from the rest of the system. However, sometimes the material the conductor comes into contact with has a high enough impedance that not enough current is generated to trip protection; this is known as a high-impedance fault, or HIF. Today's power distribution systems are not typically protected against HIFs, so downstream lines may remain energized, causing voltage issues in other part of the system [14]. Topological methods assume a pole failure creates a low-impedance fault that trips protection and electrically disconnects the system downstream of the fault; therefore, topological methods cannot simulate the effects of HIFs.

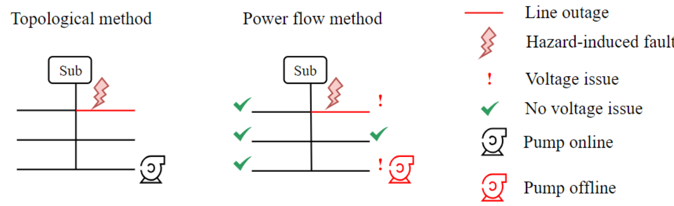

Fig. 1. Comparison of topological and power flow methods on a radial feeder. Voltage issues can only be detected using power flow.

Water and power distribution systems are coupled together at the water pumps, which are typically driven by three-phase induction motors. Water pump power failure is not binary. High currents can damage these motors over time. Power quality events that can generate high currents in induction motors include overvoltage, undervoltage, and voltage/current unbalance [15]. Because of this, National Electrical Manufacturers Association (NEMA) standards recommend that induction motors not be subjected to more than 5% voltage deviation or more than 1% voltage unbalance for extended periods of time [16]. Current water supply plant installations include advanced protection equipment to comply with these standards, based on our recent conversations with a plant operator in the United States.

Fig. 1 shows the difference between the topological and power flow methods. A hazard-induced fault occurs at the same point on a radial feeder. On the left, the topological method assumes that the pump at the end of the feeder is still online. However, the power flow method on the right finds that, in addition to the line outage, there is also a voltage issue at the pump, so the pump is now offline. In hazard situations, power lines can still be energized but not provide quality power to critical loads [6]. Therefore, it is necessary to examine the role power quality plays in hazard scenarios.

III. Methodology

A. Overall Analysis Method

Fig. 2 details our method for comparing the topological and power flow hazard simulation results. First, we determine component failures. In a wind hazard analysis, this involves using wind intensities and locations, along with power pole fragility curves, to determine which poles are damaged directly by the storm [11]. Since we care only about the methods used to analyze the damaged system, we simulate component failures one by one to consider a range of failure scenarios.

The component failures are inputs to both the topological method and the power flow method. For the topological method, we only need the system topology – the lines and buses and how they are all connected together. From this, we can determine which lines and buses will fail when components are damaged by examining what is downstream of the damage. Pumps that are electrically disconnected from the system are determined to be non-functional; all other pumps are determined to be functional. For the power flow method, we need to know the load models and power requirements, as well as the system admittances. With this, we can calculate

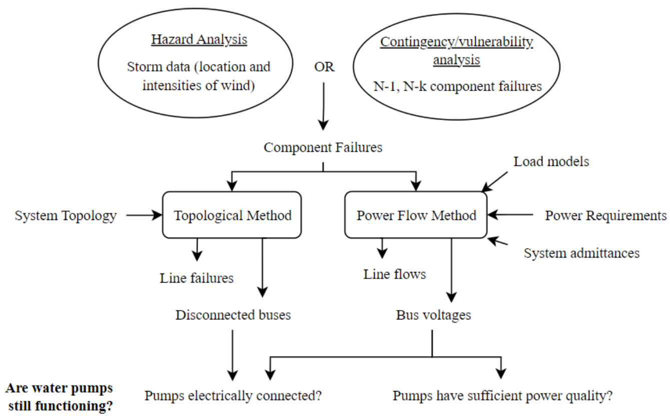

Fig. 2. Method of comparing topological and power flow analyses.

power flow on the system, giving us line flows and bus voltages (magnitudes and angles).

We calculated three-phase unbalanced power flow using the Open Distribution System Simulator (OpenDSS), an open-source distribution system modeling platform [17]. OpenDSS solves power flow using the current injection iterative method (unless it does not converge, then Newton-Rhapson is used). After creating the system admittance matrix Y_{s}, the algorithm makes an initial guess of the current injections at each node, then solves the following system of equations to find the nodal voltages V,

$$V = [Y_{\mathrm{s}}]^{-1} I_{\mathrm{inj}}, \tag{1}$$

where I_{inj} represents current injection at each node. I_{inj} is updated iteratively using the new value of V until the new V is within 0.0001 pu of the old V.

Pumps that either have zero voltage (indicating complete electrical disconnect) or voltage issues (in which case the water operator would program safety equipment to trip), are considered non-functional. We then compare the functionality of water pumps as determined by the different methods.

B. Evaluation Metrics

We use a variety of metrics in our evaluation of the two methods. Specifically, we count the number of pump failures found by the two methods in different outage cases, and we define the following voltage metrics.

1) Undervoltage: We define the undervoltage at bus k to be the sum of line-to-neutral voltages less than 0.95 pu at bus k, not including any voltage equal to 0, i.e.,

$$UV_k = \sum_{\phi \in \Phi} \max(0.95 - V_{k,\phi}, 0) \tag{2}$$

where $V_{k,\phi}$ is the voltage magnitude at bus k in phase ϕ and Φ is the set of non-zero voltages at bus k. We also define the total undervoltage in a hazard scenario as

$$UV_{\mathrm{tot}} = \sum_{k \in \mathcal{P}} UV_k \tag{3}$$

where $\mathcal{P}$ is the set of buses with pumps.

2) Voltage Unbalance: We used the NEMA voltage unbalance calculation to assess voltage unbalances at three-phase buses, where voltage unbalance at bus k is defined as

$$VU_k = \frac{|V_{\mathrm{avg},k} - \overline{V}_{\mathrm{dev},k}|}{V_{\mathrm{avg},k}} \cdot 100, \tag{4}$$

where $V_{\mathrm{avg},k}$ is the average of the 3 line-to-line voltages at bus k, and $\overline{V}_{\mathrm{dev},k}$ is the line-to-line voltage at bus k that deviates the most from the average voltage [16]. We note that voltage unbalance factor, or VUF, would be a more accurate measure of voltage unbalance, as it not only considers unbalance in voltage magnitudes, but also in voltage angles [18]. However, we assume the water operator programs the safety equipment according to NEMA standards, and so uses the equation for NEMA voltage unbalance.

We also define the total voltage unbalance as

$$VU_{\mathrm{tot}} = \sum_{k \in \mathcal{P}} \max(VU_k - 1\%, 0), \tag{5}$$

where we subtract 1% because we only consider unbalances greater than the NEMA standard of 1%. There is some voltage unbalance at all buses, but the max function ensures those less than the standard are not counted in the total.

C. Events and Failures

We next describe the events and failures analyzed in our case study.

1) Line Outages: In the topological analysis, any lines or buses that are downstream of the damaged pole are considered to lose power. Any water pumps that are still electrically connected are determined to be functional.

In the power flow analysis, if a line has a damaged pole, we electrically disconnect the line such that no flow occurs on or downstream of the line. We then run power flow on the altered system and check the voltages at the pump buses.

2) High Impedance Faults: High impedance faults (HIFs) cannot be simulated using topological methods. We simulate them using the power flow method, noting where voltage issues occur at the pumps. We simulated faults using the OpenDSS fault object, assuming a fault resistance of 100 Ω.

3) Voltage Regulation Failures: Voltage regulation plays a large role in U.S. power distribution systems [19]. If the voltage regulators at the substation failed completely, electrically disconnecting the entire feeder, power flow cannot be calculated. However, we are able to model what happens if we were suddenly unable to utilize voltage regulation controls by disabling the controls in OpenDSS. Therefore, we are able to model these failures in the power flow method, but not the topological method.

4) Secondary Outages: In the power distribution system, the secondaries refer to the lines connected to or on the low voltage side of distribution transformers. Synthetic systems created for topological hazard analysis typically only include the primaries [3]. Random secondary outages are more rare, but secondaries can still be vulnerable to wind hazards if they include overhead lines [2]. To simulate secondary outages,

TABLE I

NOMINAL VOLTAGE UNBALANCE AT ALL THREE-PHASE BUSES

Bus	VU_k (%)
Source Bus	0.00188
650	0.002465
RG60	0.2927
633	0.3986
634	0.3427
671	0.7695
692	0.7695
675	0.9551
670	0.4548
680	0.7342
632	0.4033

we disconnect the loads from their respective buses. Here, we assume topology models do not include secondaries, and therefore can not be modeled by the topological method, only the power flow method.

IV. CASE STUDIES AND DISCUSSION

In this section, we compare the topological and power flow methods through several case studies. We first directly compare them by simulating all line outages and exploring differences in the results. We then simulate other failures in the system that can only be simulated using power flow. We examine the voltage issues that arise from these types of failures; the resulting pump failures would not be captured through topological methods. These include high-impedance faults, voltage regulation failures, and secondary outages.

A. Test System Setup

We perform the case studies on a coupled power-water network consisting of the IEEE 13-Bus feeder [20] and a simple water network with 3 pumps [21]. Ref. [21] considered a single-phase equivalent model of the feeder. In this work, we use the full three-phase model and relocate the three-phase pumps to the three-phase buses 633, 675, and 680. In addition, we model the pumps as induction motor loads (using the Ind-Mach012 object in OpenDSS [22]), a more accurate model than the typical constant power or ZIP model. The power ratings of the motors are derived from the needs of the water network, as simulated using [23].

For the power network, we assume the protection system outlined in [24]. We modify the loads in the IEEE 13-Bus system so that voltage unbalance is less than 1% at every bus – the full coupled system with the modified loads is detailed in Fig. 3. This way, the pumps experience acceptable voltage unbalance in the nominal case. The NEMA voltage unbalances at each bus in the nominal case is shown in Table I.

We note that the test system itself is unbalanced and highly loaded. For example, bus 675 (where pump 2 is located) is the most unbalanced bus in the system. This is realistic, as most U.S. distribution system are unbalanced [19]. Also, most distribution systems and critical loads are constrained to a narrow window of acceptable voltages (e.g., 0.95-1.05 pu); so much so that line flows are not even considered here, as a stressed system is more likely to meet voltage issues before exceeding line capacities.

TABLE II

NUMBER OF PUMP FAILURES FOR EACH LINE OUTAGE DETECTED BY THE TOPOLOGICAL AND POWER FLOW METHODS

From Bus	To Bus	Topological	Power Flow
650	632	3	3
632	670	2	2
670	671	2	2
671	680	1	2
632	633	1	1
632	645	0	2
645	646	0	1
692	675	1	2
671	684	0	1
684	611	0	2
684	652	0	0
Computation Time (s)		0.0575	0.1469

TABLE III

VOLTAGE ISSUES ASSOCIATED WITH LINE OUTAGES

From Bus	To Bus	VU_{tot} (%)	UV_{tot} (pu)	Locations
671	680	0.064	0	Pump 2
632	645	0.443	0	Pumps 2 & 3
645	646	0.124	0	Pump 2
692	675	0.209	0	Pump 3
671	684	0	0.00546	Pump 2
684	611	0	0.00874	Pumps 2 & 3

B. Direct Comparison

First, we directly compare topological and power flow results for $N-1$ line outages. Table II shows the number of pumps that fail for each line outage. The first and second column list the buses to which the line is connected. The third column shows how many pumps fail in the topological analysis, and the final column shows how many pumps fail in the power flow analysis. Though both methods sometimes get the same results, in 6 out of 11 cases (54.5%), the topological method underestimates the number of pump failures. However, the computation time of the power flow method was about 250% greater than that of the topological one.

C. Line Outages

To understand the discrepancies between the power flow and topological results in the previous subsection, we next examine the voltage issues that arise from line outages. Six out of 11 cases resulted in voltage issues at the pumps – these are the same cases where the topological method underestimated pump failure. Of these cases, most involved voltage unbalance at one or more pumps; a couple resulted in undervoltage on one of the phases.

Table III shows the voltage issues in detail for the six cases with issues. The third column shows VU_{tot} and the fourth column shows UV_{tot}. The final column shows the locations of the voltage issues. It is clear that pump 2 is the most vulnerable to power quality issues in the case of line outages.

Fig. 4 shows the voltage issues spatially. If the pumps experience undervoltages from a line outage, the line is dashed according to which pump or pumps fail. If the pumps experience voltage unbalance from a line outage, the line is colored according to which pump or pumps fail. For example, if the line between bus 650 and bus 632 fails, no undervoltages or voltage unbalance is experienced at the pumps. Therefore,

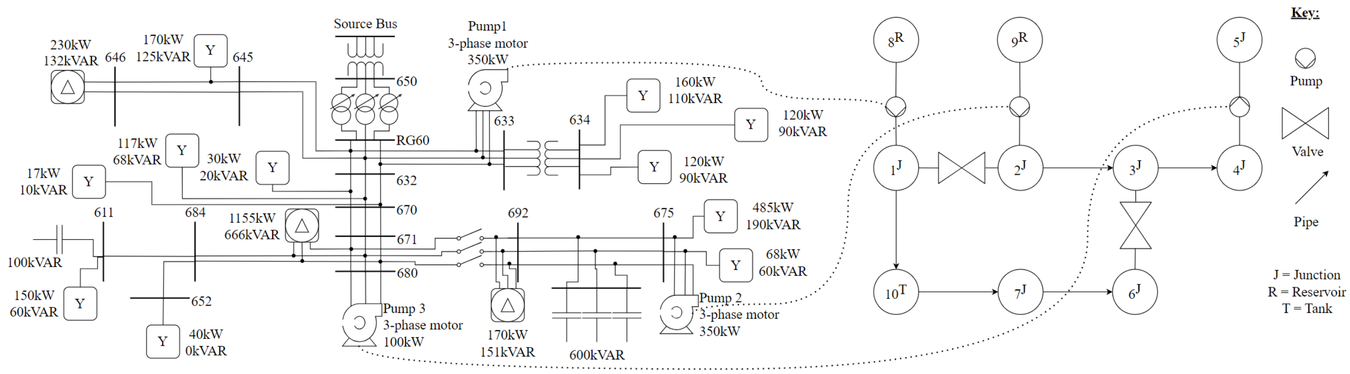

Fig. 3. IEEE 13-bus feeder with modified loads coupled to a water network with 3 pumps.

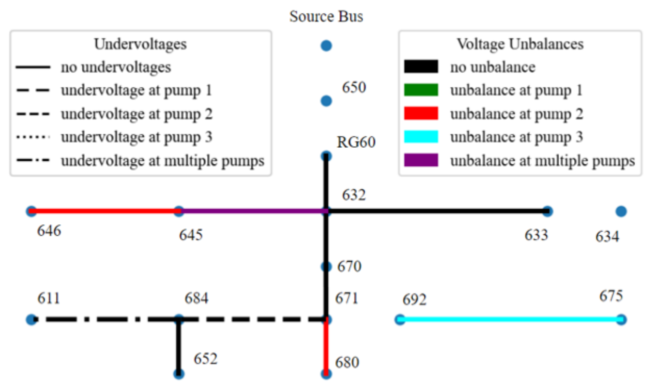

Fig. 4. Spatial depiction of voltage issues caused by line outages. Lines are drawn according to which voltage issues they cause if they fail.

this line is drawn solid and black. However, if the line between buses 692 and 675 fails, pump 3 experiences voltage unbalance, but no pumps experience undervoltage. Therefore, this line is drawn solid and colored cyan. These results show how and where voltage issues (and thus, pump failures) can arise that are not captured by topological methods. An outage on any two-phase line may cause voltage issues at the pumps.

We have seen that the topological method underestimates pump failures by not accounting for voltage issues. We have also seen that the topological method sometimes gets the same result as the power flow method. To understand why, we conducted an $N-k$ line contingency analysis - we simulated outages of every possible combination of lines. Out of the 2046 possibilities, 85 cases, or 4.15%, resulted in voltage issues other than complete loss of power (the topological method accounts for complete loss of power, but not loss of power quality). We note that as more lines fail, the less power is able to flow, and the impact of power quality on failure diminishes. For example, any scenario in which the line connecting bus 650 to bus 632 fails will result in complete loss of power for all the pumps; this failure will be captured by both methods. We also observe that in the case of 7 or more line outages, the pumps do not experience power quality-specific issues, as they are more likely to be completely electrically disconnected.

The first row of Table IV summarizes the voltage issues associated with line outages; specifically, we present the number (#) of simulations with issues out of the total number conducted, along with the mean, standard deviation, and the

TABLE IV
SUMMARY OF VOLTAGE ISSUES DUE TO HAZARD EVENTS/FAILURES

		VU_k (%)		UV_k (pu)	
Type	**#**	**mean(std)**	**max**	**mean(std)**	**max**
Line	6/11	1.17 (0.11)	1.34	0.0047 (0.0031)	0.0074
HIF	20/41	1.03 (0.03)	1.12	0.0010 (0.0005)	0.0019
VReg	5/6	1.84 (0.54)	2.71	0.0303 (0.0290)	0.0714
Secondary	1/14	1.11 (-)	1.11	- (-)	-

maximum of the voltage unbalance and undervoltage across all cases with issues and buses (each VU_k and UV_k is considered separately and not combined into one metric as they were in Table III with VU_{tot} and UV_{tot}). We also use this table to summarize the results of other events/failures, as described in the next subsections. A single line outage may cause up to 1.34% voltage unbalance and up to 0.0074 pu undervoltage (i.e., 0.9426 pu) at a single pump bus. Though these deviations are small, if they persist for many minutes and even hours, they could damage the pump motors.

D. High Impedance Faults

We next consider the vulnerability of the network to HIFs by simulating 100-Ω impedance single-line-to-ground faults at every node in the system. Out of the 41 faults, 20 (48.8%) resulted in voltage issues at pump 2 (pumps 1 and 3 did not experience any voltage issues). Roughly one-third of issues were voltage unbalance, one-third were undervoltage, and the final third were a combination of both.

The second row of Table IV summarizes the voltage issues experienced with HIFs. The voltage unbalances and undervoltages are not as large as those experienced from line outages, but they are still enough to trip off the pumps. These results show that even the occurrence of 1 HIF can cause power quality issues during a hazard, causing pump failures that the topological method would not predict.

E. Voltage Regulation Failure

The IEEE 13-bus feeder is equipped with voltage regulators at the substation, as well as capacitor banks located at buses 692 and 611. Table V displays results for each voltage regulation failure possibility. In every case except for capacitor bank 2 failure, the topological method would have underestimated pump failure. The third row of Table IV summarizes the voltage issues experienced with voltage regulation failure.

TABLE V
VOLTAGE REGULATION FAILURES

Failure	VU_{tot} (%)	UV_{tot} (pu)	Locations
VReg phase a	4.052	0.124976	Pumps 1, 2, & 3
VReg phase b	0.399	0.000058	Pumps 1 & 2
VReg phase c	2.157	0.015366	Pumps 1, 2, & 3
Cap Bank 1	0	0.005481	Pump 2
Cap Bank 2	0	0	None
All Controls	0.082	0.157012	Pumps 1, 2, & 3

Out of all the hazard events and failures, we found that voltage regulation failure resulted in the largest and most widespread voltage issues. Power flow analysis would almost certainly be needed to accurately predict the effects on critical infrastructure should voltage regulation fail.

F. Secondary Outages

The loss of load 646 results in voltage unbalance at pump 2 of 1.11%; however, no other single load outages presented voltage issues at the pumps. This, along with the fact that secondary outages are more rare, suggests that it might be possible to leave this failure type out of a hazard analysis if computation time is an issue; although, other test systems may not exhibit this same result, so more work is needed to explore this. The fourth row of Table IV summarizes the voltage issues experienced with secondary outages.

V. CONCLUSION

The case studies analyzed in this paper clearly illustrate how voltage issues resulting from a contingency can affect critical loads such as water pumps. Topological methods do not accurately predict all pump failures from line outages, and cannot predict failure from HIFs or loss of voltage regulation control. The results presented in this paper suggest that a simple topological analysis could underestimate the effect any hazard has on critical infrastructure by not taking power quality into account. However, if the damage to the system is extensive enough, power flow does not add any additional insight into the analysis from the perspective of the water network. Voltage issues may be observed at other buses and loads, but that is not relevant to the water network.

Future work should explore power flow and quality in a typical hazard analysis on a more complex and realistic coupled water-power distribution system. One drawback is the added complexity and computation time with the inclusion of power flow. Future work should examine the impact of power flow on computation time and find ways to simplify and decrease this burden.

ACKNOWLEDGEMENTS

The authors thank Seth Guikema, Zaira Pagan Cajigas, Mike Ropp, and Eric Witt (Brookings Municipal Utilities, SD).

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