THE BLACKOUT OF 1987 IN TOKYO, JAPAN: PURE VOLTAGE COLLAPSE

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***Abstract*—On July 23 of 1987, voltage collapse caused a large scale blackout to occur in the Tokyo, Japan. Over 2.8 million households serviced by the Tokyo Electric Power Company, Inc. (TEPCO) lost electrical power for a period of over 3 hours. Ultimately, this blackout was caused by severe voltage collapse, and the event has shaped TEPCO's current operational planning and reactive power control methods. This paper serves to introduce and outline the phenomenon of voltage collapse in the context of the Tokyo collapse. The causes of the blackout and its cascading effects are subsequently explained. Finally, the lessons learned by TEPCO through this disaster are analyzed.**

***Index Terms*—Power System Stability, Voltage Collapse, Saddle Node Bifurcation**

I. Introduction

A typical power system is modeled through a series of Differential Algebraic Equations (DAEs), as given by reference [6]. These equations model the power flows, load dynamics, and the dynamics of the voltage regulators, turbine governors, and synchronous machines. Primarily, these equations are functions of both algebraic and differential variables, but they depend on two other important system values too.

$$\begin{bmatrix} \dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} f(x,y,\lambda,p) \\ g(x,y,\lambda,p) \end{bmatrix} \tag{1}$$

In (1), x is a differential variables and y is an algebraic variable. The variable p is not actually a variable but in fact a control setting which grid operators have total authority over. This includes reactive support, regulator set points, and frequency settings. Finally, λ is a slowly varying system parameter, and this is typically chosen to be system load $P_0 + jQ_0$ (and load noise ξ). In any given power system, there is a point called the maximum loadability point, and it corresponds to the maximum value of λ. Once this value of λ is reached, voltage collapse will occur.

True voltage collapse is a relatively uncommon event, as system dynamics often become unstable (in the form of a Hopf bifurcation) long before voltage collapse occurs ([8],[9]). **For this reason, the Tokyo collapse is a fascinating case study on power system stability.** As will be shown, there is no major oscillatory instability, no operator error, no lighting strikes or faults, and no component failure. According to [7], the blackout was due to pure voltage collapse.

II. Paper Body: Voltage Collapse of the TEPCO Network

In this section, the saddle node bifurcation is introduced, as the blackout cannot be understood without it. Next, the causes of the Tokyo collapse are explained. Finally, the lessons learned by TEPCO are given.

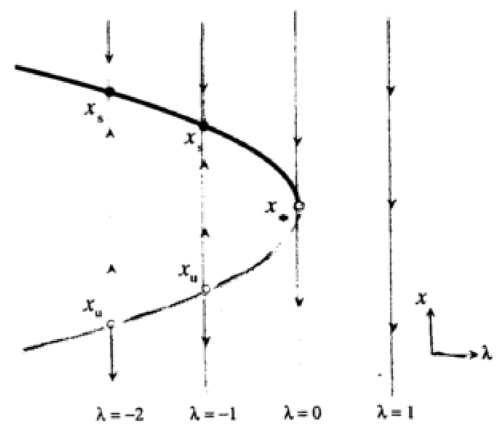

Figure 1. An example of a saddle-node bifurcation is given. The bifurcation occurs once the parameter reaches a value of $\lambda = 0$. This figure is reproduced from reference [2].

A. Voltage Collapse: A Saddle Node Bifurcation

As stated by [7], the 1987 blackout in Tokyo was caused by a phenomenon called voltage collapse. Voltage collapse is a type of saddle node bifurcation. In Ian Dobson's paper *Voltage Collapse in Power Systems*, a visualization of a saddle node bifurcation is given. As indicated, the parameter λ is often considered to be the aggregate system load. Once a system load surpasses a certain value, the Power Flow Equations will no longer converge (via the Newton Raphson Method).

As shown in the figure 1, each value of λ has two solutions: one is stable (x_s) and one is unstable (x_u). Once a power system reaches the bifurcation point, system load cannot increase any more. Small perturbations will cause the system voltages to dynamically fall to very low levels, as the system will be operating in the highly unstable region on the lower side of the nose curve (the region with solutions corresponding to x_u). This is what the Tokyo system experienced in 1987.

B. Causes of the Tokyo Collapse

The following details of the collapse are summarized from references [7] and [5]. Both of these references indicate that on July 23, 1987, Tokyo experienced unusually hot weather. In

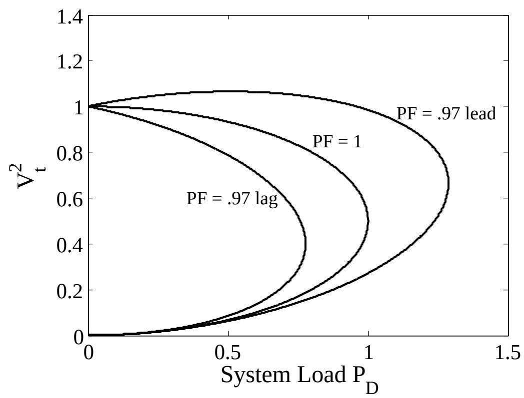

Figure 2. The "To" bus voltage of a small power system is plotted against system load. Loads with three different power factors are plotted.

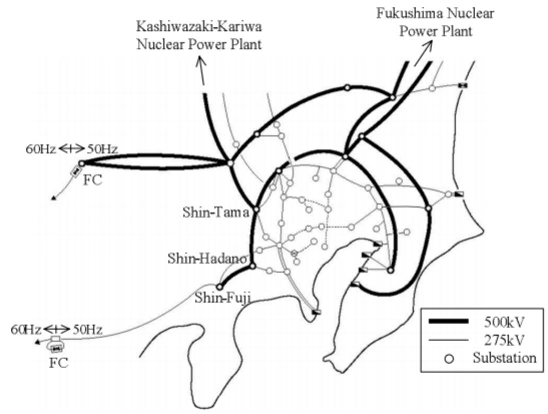

Figure 3. This is the layout of the 1987 TEPCO network. This figure is reproduced from reference [7].

some places of Japan, the temperature exceeded 39° Celsius (102° Fahrenheit). This was the 9^{th} hottest day on record in the region, and so the load began increasing dramatically due to increased air conditioner use. As the day progressed, the load forecast was increased from 38.5 GW to 39 GW, and then around mid-morning it was again increased up to 40 GW. The TEPCO system was nominally rated to handle up to 40 GW of load, but such operating conditions had never been experienced. This peak forecast included 3.8% of operating reserve so that the system could handle all potential increases.

Before the "lunch break" noon hour, the system demand declined dramatically from 39.1 GW to 36.5 GW. When this happened, a large block of shunt capacitors were kicked offline. Shunt capacitors provide reactive support in the form of reactive power. When this support is not needed, it must be removed. The reason why is visualized in figure 2.

In Figure 2, three nose curves are plotted for the same two-bus power system. The "To" (or load) bus voltage is plotted against the load at that particular bus. The maximum loadability point for several types of loads can be seen clearly: this corresponds to the bifurcation point.

If this system is loaded down with say $\mathrm{P_D} = .5$ and a power factor of .97 lagging, the load voltage will be low (just over .8 PU). If, suddenly, reactive support kicks on, and power factor correction occurs (to, say, .97 leading), the load voltage will jump well over 1 PU. Over-voltage spikes are very dangerous and damaging to a power system, so this would be a serious problem. For this reason, reactive support (such as shunt capacitors) must be removed when it is not necessary.

When TEPCO's load dropped before lunch, the reactive support was removed. During the lunch hour, as the system demand increased again, this reactive support should have kicked back online. The demand increase, though, occurred far too rapidly, and the shunt support did not turn back online fast enough. This was an issue caused by the automated response of the Voltage Reactive Power Controller (VQC): the VQC did not respond to the load increase quickly enough.

During the peak load rise, the demand increase was approximately 400 MW per minute. This was an unprecedented rate of increase, and the switched capacitor banks did not respond quickly enough. Part of the reason for this sluggish response is the fact that voltage collapse is a type of "long term voltage stability". This is explained in reference [4]. Such voltage stability exists on the time frame of 1 to 10 minutes. Therefore, responses often exist on this time frame also. Switched capacitors may take several minutes to respond to voltage sags.

In total, the TEPCO network had 10,570 MVar of switched capacitor reactive support. This is only a nominal rating though. The reason for this can be seen in the equation which computes the reactive power produced by a shunt capacitor: $Q^{\text{inj}} = -\frac{\mathrm{V}^2}{X}$. In this expression, V is the voltage differential magnitude across the capacitor and X is the capacitive reactance. As voltage sags, the reactive power produced by a capacitor bank falls with the square of the voltage. Therefore, if the voltage sags from 1 PU to .8 PU, the reactive power magnitude drops from 1 PU to .64 PU (assuming $X = 1$).

Between 13:00 and 13:15, the 500KV backbone transmission lines were dropping by 4kV per minutes. As the system parameter (load) increased, pushing the system closer to the nose of the nose curve, the 500kV lines began dropping by 18kV per minute. This occurred from 13:15 to 13:19. When these lines dropped below 370kV (.74 PU), lines around the system began to trip and a massive amount of load was shed. Figure 3 shows the physical layout of the system. Most notably are the two inter area tie lines. The Japanese power system has two operating frequencies: one runs at 50Hz while one runs at 60Hz.

Figure 4 shows a fascinating visualization of the saddle-node bifurcation experienced by the network. According to [7], this plot was produced after the blackout using collected real time data as well as time domain simulations. The 500kV backbone voltage is plotted against the increasing system load. As can be seen, the time passage for this plot is not linear. The effects of the implemented reactive support can be seen very clearly: at various times, when $-Q^{inj}$ increases, the voltage spikes back to a higher value (system nominal). At 13:03, the system is momentarily operating on the bottom side of the nose curve, but then more reactive support is added, pushing

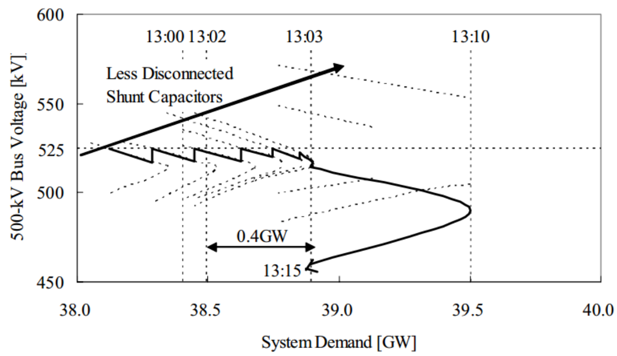

Figure 4. A visualization of TEPCO's Saddle Node bifurcation is plotted. This figure is reproduced from reference [7].

the nose curve father out on the x axis. At 13:10, maximum loadability is reached and a bifurcation occurs. At this point, the system cannot support any more load, and system voltages begin diverging towards very low, unstable values.

It is fascinating to note that the same amount of system load can be served by multiple voltage values. At 13:03 for example, 38.9 GW of load is served with the transmission backbone at 520kV. Later, at 13:15, the same amount of load is served, but the transmission voltage has fallen to 460kV. This is due to the nature of power consumed by a load: $S = \tilde{V}\tilde{I}^*$. Clearly, the same amount of (complex) power can be served with low current and high voltage, or with high current and low voltage.

One important part of the voltage collapse in Tokyo which must be considered is the nature of the loads. According to analysis done by [5], there was a certain popular type of air conditioning unit which accounted for much of the increased load. This unit can be approximately modeled as a constant power load, meaning as the voltage sags, the current draw increases. Typically, when the voltage sags in a circuit, the load drops because the power ($\mathrm{P} = \mathrm{IV}$) decreases. For the Tokyo system, the opposite situation occurred. As the voltage sagged, the power remained constant, so the current draw increased. Increased current draw corresponds to larger $\mathrm{I}^2 Z$ losses in the transmission and distribution lines (where $Z = R + jX$). As seen by the network, transmission lines losses and load demand are virtually the same thing.

After 13:19, four 275 kV lines, four 275/66 kV transformers, and four 500 kV lines tripped. Under voltage, over current, and impedance relays worked in conjunction to end the collapse by providing the much needed load shedding of 8.168 GW of load (21% of the total load). The severe voltage drop on the lines caused the apparent impedance of the lines to trigger the impedance relays to trip in some cases, while the voltage and current relays seem to be the causes of the other trips. Interestingly, the impedance relays provided the most relief to the system, even though such devices are not designed to prevent voltage collapse. Once the load was shed, the system rebounded and began operating at stable, nominal voltage once again.

C. How the 1987 Collapse has Influenced Operational Planning of TEPCO

As explained in [5], this failure was not due to network faults, unexpected line trips, scheduled outages or maintenance, or conscious operator error. There are many other root causes behind this particular blackout, and the most apparent, include insufficient system monitoring, lack of strategies to guard against voltage collapse, inadequate control setting and load characterization, and an uneven distribution of power plants. If the reactive support had been turned online sooner (to prevent reactive losses proportional toV^2) or if the operators wouldn't have made assumptions about the speed at which load can ramp up, the situation may have been avoided. The particular lessons learned by TEPCO are separated into seven distinct categories. These are similar to the categories given in [7].

1) Elevating the Voltage Profile: In the Extra High Voltage (EHV) transmission lines, TEPCO has made it a priority to keep the voltage profile "high and flat". This is mainly in order to leverage full usage of all shunt support and transmission capacity (the higher the voltage, the lower the current). Effectively, TEPCO raised all of its nominal set points, allowing more room for error. For example, the nominal operating range for the 500 kV lines was 515~525 kV before the blackout. After the blackout, this range was increased to 525~550 kV. Of course, distribution voltages were not altered. When transmission voltages increase, transformer winding ratios must be altered (in some way) to ensure that consumers see no change in the electricity which serves their home.

Keeping a "flat" voltage profile mean operating far from the bifurcation point (where bus voltage variance is very high for given stochastic perturbations).

2) Increased Installation of Shunt Capacitors: At the time of the blackout, the TEPCO network had 10.6 Gvar of shunt capacitors in the system to support an upper bounded load of 40 GW. Many of these capacitors, though, had to remain disconnected from the system during the collapse because of upper bus voltage limits on the tertiary sides of the transformers. Over voltage is typically a more serious constraint on the system than under voltage is, so these capacitors could not be used. This decreased the effective amount of capacitive support that the system had available. Over the five years after the blackout, TEPCO has installed 11.9 Gvar of additional shunt capacitors.

3) Increased Reactive Support through Dynamic Reactive Power Reserves: Generators use Automatic Voltage Regulators (AVRs) in order to keep generator voltages at a proper level, but Power System Voltage Regulators (PSVR) have the ability to keep the PV bus' "sending end" voltage at a certain prescribed level. TEPCO installed a number of PSVRs as well as SVCs in its network. While shunt capacitors provide long term voltage stability support, SVCs and PSVRs additionally provide short term (quick response) voltage stability support. Both types of stability must be maintained in order to ensure stability of a power system network.

4) Reliance on UVLS in Extreme Situations: Under Voltage Load Shedding (UVLS) can be an extremely effective tool when used properly, and it can be used in such a way that will prevent a large scale blackout. It represents a triage (or utilitarianistic) way of dealing with a looming collapse.

On the Western (weaker) side of the grid, TEPCO has four central units capable of implementing UVLS. When three of the four units detect voltage sags at a specified (alarmingly fast) rate, a signal will be sent to operators at local stations recommending load shedding. Such an action is regrettable and certainly a last resort, but the 1987 blackout itself proved that UVLS is highly effective at stalling and reversing the effects of voltage collapse.

5) Increased System Monitoring: Soon after the collapse, TEPCO installed enhanced on-line voltage security monitoring systems. These system, along with the state estimation tools, give operators the ability to draw PV and QV curves in real time. By doing so, bifurcation proximity estimation can be calculated by tracking the parameter λ. By having access to such curves, operators can make real time control decisions about how power should be dispatched, when and how reactive support should be implemented, and how much more loading the system can take.

Such data can also allow operators to see long term trends. Operators might see, for instance, that the system is often operating close to a collapse, or that the system is often having over-voltage spikes. Increasing the system monitoring will make long term systemic issues much more visible.

For instance, reference [1] outlines the causes of the 2011 US Southwest blackout. In the official report, the authors sight poor situational awareness (along with poor operational planning) as one of the primary causes of the failure. Situational awareness will only be enhanced through elevated system monitoring.

6) Enhanced Simulation Tools: In response to the blackout, TECPO developed a software package entitled VQC Simulation. This simulator models the dynamic reactive power units in the system: these include SVC, PSVR, and VQC technology. This software serves to help grid operators and planners study "slow" grid stability. More specifically, the software helps the operators understand how the different control settings of these reactive devices influence the stability of the overall grid. In this way, the control settings can be chosen in an optimized fashion without having to rely on intuition or the guess and check methods.

TEPCO also developed a slimilar program called the Voltage Stability Contained Optimal Power Flow (VSCOPF) program. In this program, users can study voltage stability margins and voltage sensitivity in the context of OPF using the gradient of the PV Curve.

7) Altered Control Settings for Tap-Changing Transformers: When a system is tending towards voltage collapse, shunt reactors will be switched off and shunt capacitors will be switched on. Additionally, tap-changing transformers will begin to affect the system also. An on-load tap-changing transformer has the ability to change its winding ratio (while the load is in service) in order to raise or lower the secondary side voltage. Such devices are incredibly useful at keeping consumer voltages constant when system voltages are sagging.

When voltage collapse is looming, though, a tap changing transformer is effectively keeping the entire load in a constant power configuration. This is because even though transmission voltages are falling, distribution voltages are not, and therefore the loads are consuming the same amount of power. If the load voltages are allowed to sag, power demand will begin to drop accordingly (in most cases).

In order to combat this problem, TEPCO implemented an interesting protocol after the 1987 blackout. When the controller sees that all shunt capacitors are in service, and primary side voltage falls lower than a certain value, the tap controller locks itself. This prevents the tap-changing transformers from elevating secondary voltages. In effect, the aggregate load shift from constant power to constant impedance (at a very high level).

III. Conclusion

This paper outlines the causes, the consequences, and the outcomes of the voltage collapse in Tokyo in 1987. The results are primarily pulled from two interesting case studies done on this blackout ([5], [7]). As part of the conclusion, six insightful questions concerning the failure shall be addressed explicitly.

A. Was the cause of failure known a priori or was it an unknown unknown?

Certainly, the cause of the blackout was known a priori, as voltage collapse is a well known and thoroughly understood phenomenon. Extremely high load levels coupled with limited reactive support will clearly lead to extreme sagging, if not total collapse. The situation was unique and unprecedented, but given all system information, a modeling platform could have predicted the collapse.

B. Was the failure due to a random act or human error?

Primarily, this collapse was due to poor long term operational planning. Reactive support was not high enough, the maximum loading point was over estimated, VQC controls were not properly tuned, and the operators were not thoroughly trained on how voltage collapse should be responded to. In [5], the Tokyo region on July 23 is said to have experienced "high temperatures caused by a stagnant atmosphere and strong daylight due to a Pacific anticyclone." This can certainly be seen as a random event, but it is one which is not outside the scope of imagination.

C. Could it have been prevented by some kind of monitoring system?

Indeed, the disaster could have certainly been prevented by an enhanced monitoring system. In 1987, TEPCO had three power system control centers. These centers knew most system voltages, but the 500 kV lines voltage outside of their respective territories were not known. This greatly inhibited operator situational awareness, and it prevented them from taking early mitigating control actions (such as minor load shedding or blocking the actions of the on-load tap changing transformers). Today, Phasor Measurement Units (PMUs) are becoming extremely widespread. These units measure instantaneous voltage phase and magnitude and can provide this

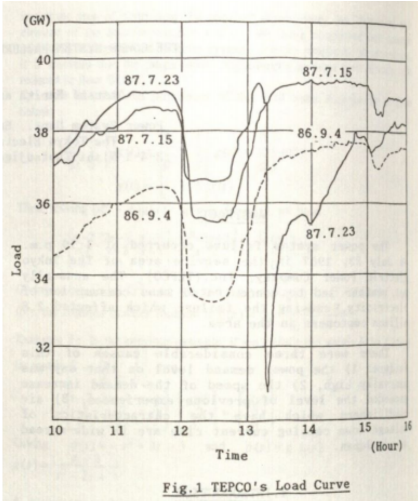

Figure 5. A visualization of load during several days. This figure is reproduced from reference [5].

data to grid operators in real time. This data can also be used to compute current flows and power flows very quickly. If the TEPCO operators had access to such data, these control actions could have been taken.

D. Did this failure have an effect on the future design of similar systems?

Yes indeed, this failure has been a well studied example of voltage collapse, and much work has been done to understand how systems might be updated to avoid such a collapse. Because of the collapse, TEPCO began to plan out a 1000 kV transmission system to be constructed in the 1990's. TEPCO also made many operational changes, as outlined in Section 2.3.

E. Can the general public learn something from this?

In general, the general public did not learn very much from this disaster. Although costly, blackouts typically do not cause the sort of death and destruction associated with a bridge collapse or a transportation system which cataclysmicly fails. The general takeaway is this: an overloaded system, when not properly supported, will fail. The public does not have very much control over such things. TEPCO, on the other hand, learned several very valuable lessons from this disaster.

Figure 5 shows a plot of the aggregate load seen by generators in the TEPCO network. Clearly, the event on 7/23/87 experiences a load level and load increase which, cumulatively, cause the system to collapse. The massive load shedding which occurs at 13:19 is interesting to note. Of course, the general public cannot be held accountable for such a disaster, and their usage habits probably did not change after this blackout. TEPCO learned, though, that its system must be robust enough to handle such system demands.

F. What were the consequences for society and the engineering profession?

The direct consequences of the failure are obvious: several million people in an urban area of Japan lost electrical power for three to four hours. The indirect consequences are, in fact, far more reaching than the direct ones, and society can learn some very important lessons from this disaster. In order to optimize constrained grid infrastructure, power systems are often operated close to their limits (maximum loadability). When unprecedented load levels are reached, though, this paradigm is challenged, and cost of upgrading infrastructure versus the cost of an unstable grid (i.e. a brownout or a blackout) must be weighed.

Even when investments are made to upgrade a system, though, reference [3] makes an important observation: large investments do not always lead to a more stable grid. This is primarily due to how the power is dispatched. Grid operators (or in the US, Independent System Operators (ISOs)) will dispatch the power flows in the most economical ways possible which still maintain N-1 security. If new transmission lines are added, and power dispatch does not drastically change, then stability will certainly be enhanced. If the power flows are totally redirected in order to re-optimize the system, then in terms of stability, the system is more or less right where it started: right on the brink of collapse. This insight is reflective of human nature: constant dissatisfaction.

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