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Transient Over-Voltage Mitigation and its Prevention in Secondary Distribution Networks with High PV-to-Load Ratio

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1. Abstract

Recent report of utility providers have shown that under certain conditions the integration of renewable energy sources might cause damaging transient over-voltages (TOVs) in the power grid. TOVs are short, rapid rises in voltage along the electric lines of the grid that can occur when the generated power of a distribution circuit exceeds its load while the circuit is isolated. The described scenario can cause permanent damage to utility equipment or personal electric household devices. This report introduces various methodologies that can mitigate TOVs in distribution networks, or reduce the probability of their occurrence.

2. Transient Over-Voltage Mitigation

As the amount of small-scale distributed generation (DG) units within secondary distribution networks, such as photovoltaic power stations or rooftop wind turbines, are on the rise, a lack of proper network protection may cause network instabilities under certain load conditions [1]. Transient over-voltages (TOVs) are impulses and super-synchronous oscillations which last less than a couple of cycles. They will arise when the DG power within a secondary network exceeds its load while the network is isolated, as illustrated in Figure 2.1.

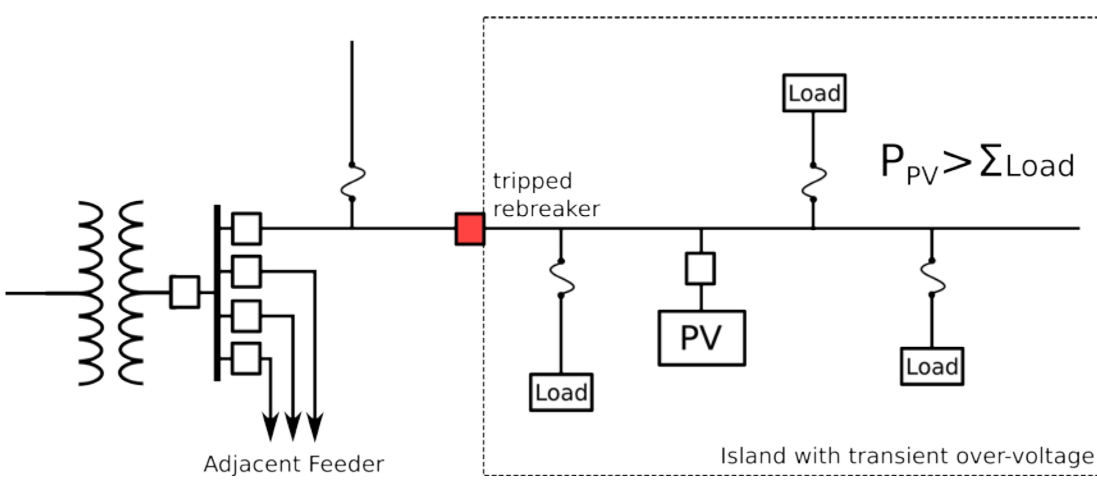

Figure 2.1: Isolated Island with transient over-voltages.

Typical causes of TOVs include switching procedures by the utility provider, failure of protective equipment, or lightning. TOVs are not temporary over-voltages. Temporary over-voltages are oscillatory over-voltages, which persist for many cycles or even seconds. Causes of temporary over-voltages could be load rejections, single-phase faults, or ferroresonance. By comparison, the phenomenon of temporary over-voltages is well studied and solutions to prevent them are available. This is not the case for transient over-voltages (and thus the subject of this report).

TOVs can cause damage to network components and to electric devices of individual consumers. Hence, finding effective mitigation procedures is crucial to guarantee reliability of the grid and minimize compensation claims.

2.1. Fundamentals of Secondary Network Distribution Systems

In order to evaluate the applicability and efficiency of TOV mitigation methods, it is necessary to understand the interconnection of DGs with secondary network systems. This section provides an overview of the characteristics and requirements of interconnected secondary networks based on IEEE and ANSI standards [2,3,4,5].

2.1.1. Electrical Distribution Systems

Ideally, network systems are based on redundancy. Failure of a single component should not result in a power outage of the entire network. Hence, networks should be served by at least two primary feeders [6]. Network units consist of a disconnect- or grounding-switch, a network protector (with master relay, phasing relay and fuses), and a network transformer (typically between 300-2,500kVA). Protector specifications are defined by the standard IEEE C57.12.44. However, their ratings vary depending on manufacturer, type of protector, and the secondary voltage. Continuous current ratings range from 800-6,200A at 216-600V, interrupting current ratings range from 30,000-85,000A, and latch ratings range from 25,000-65,000A.

Secondary distribution networks are divided into three types [7]:

- radial distribution
- loop distribution
- network distribution

Radial networks are the cheapest to build due to their simple, tree-like setup. Most often, they are only connected to one power source. Hence, power failures typically affect the entire network connected to the power line. Radial networks are mainly used in rural and sparsely populated areas. Figure 2.2 illustrates a simplified radial distribution system.

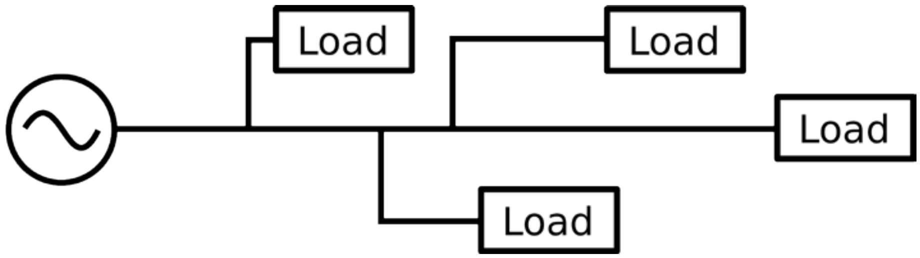

Figure 2.2: Simplified radial distribution system

Loop distribution systems are usually connected to alternate power sources. The power lines loop through the service area and return to the original point. In case of an outage, power can be redirected via switches from other connected power sources. Hence, loop distribution systems offer improved system reliability and are often used for commercial buildings and shopping centers. Figure 2.3 shows a schematic loop distribution network with two power sources.

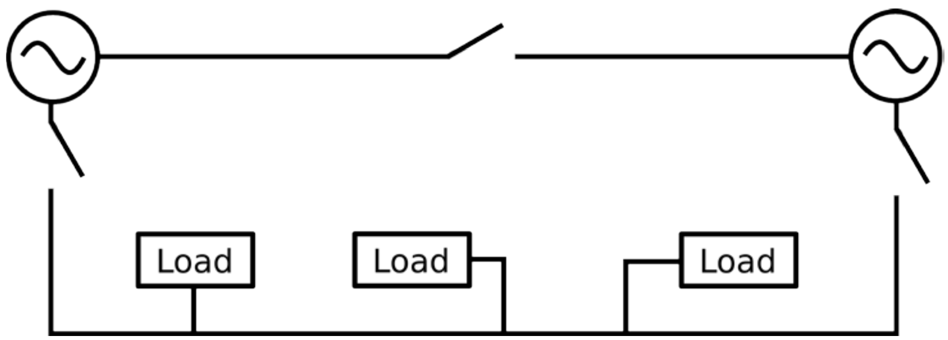

Figure 2.3: Simplified loop distribution system

Network distribution is commonly found in big cities because it is the most reliable of the three. It can be described as a connection of interlocking loop systems operating at utilization voltage. Multiple power supplies feed the network and thereby increase reliability. Numerous cable connections enable multiple current paths from every network unit to every load. In case of failure of a power source, other sources can be utilized without interruption. Most cables are protected by limiters. Secondary voltages typically are 208y/120V, or in some cases 480y/277V.

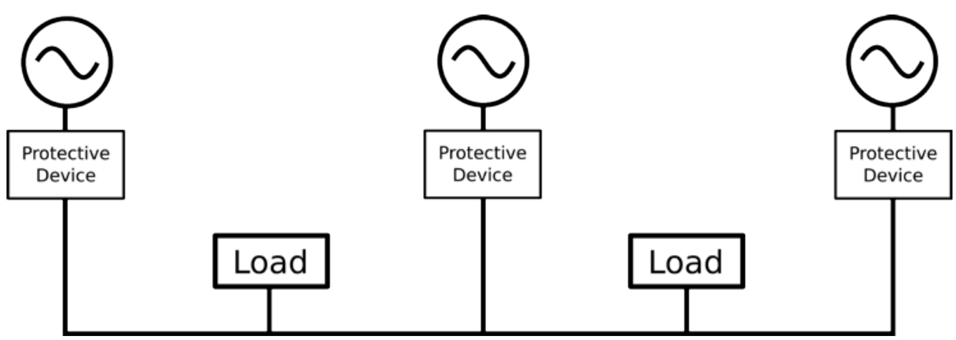

Figure 2.4: Simplified network distribution system

2.1.2. Protection of Secondary Distribution Systems

Network protectors consist of air power breakers, mechanisms to operate the breakers, network relays, and control equipment. They are typically designed for a X/R ratio of 6 to 8. The number of cables per phase within a secondary network depends on the load and ranges anywhere from one to twelve. Cables sizes are typically between 4/0- and 750-kcmil. The cables itself and the cable connections to the buses are protected by cable limiters. However, small 4/0-kcmil cables are often times not protected by limiters, since it is assumed that they are small enough to burn clear. Customer service points are usually protected by a main breaker or by fuses. Isolating a faulty feeder in a network distribution system is achieved by opening the feeder's medium-voltage circuit breaker (MVCB) and all other circuit breakers at the network transformers. The network protection relays are controlled by two power functions:

1. The reverse-power flow function trips if real power flows from the network to the faulty feeder, to its network units, or to supply the core losses of the network transformer.
2. The minimum voltage difference function determines when the re-closing of the network protector is permitted.

The protection relays are poly-phase devices responding to the net effect of power flow on all three phases. Unbalanced feeder faults in the presence of load power flow may not result in a net reverse power flow through the relay [6].

Transformer power losses are usually in the range of 0.1-1% of the rated transformer power, which is relatively small. As a result, the reverse-power functions of the master relays are very sensitive. If DGs are incorporated in a secondary network, very small reverse-power flows (less than 3 cycles) may open all network protectors and create an island.

Large DG loads might substantially reduce the real power load of the network for short periods of time. During that time, a temporary reversal of moderate amounts of power flow can occur. To avoid unnecessary tripping of the network circuit breakers, the implementation of a time delay within the power function might be beneficial. However, this time delay should only be effective for low levels of reverse-power flow. For high level reverse-power flows, such as power flows caused during feeder faults, instantaneous tripping is still desirable. This two-level control strategy helps to prevent unwanted islanding of secondary networks with integrated DGs.

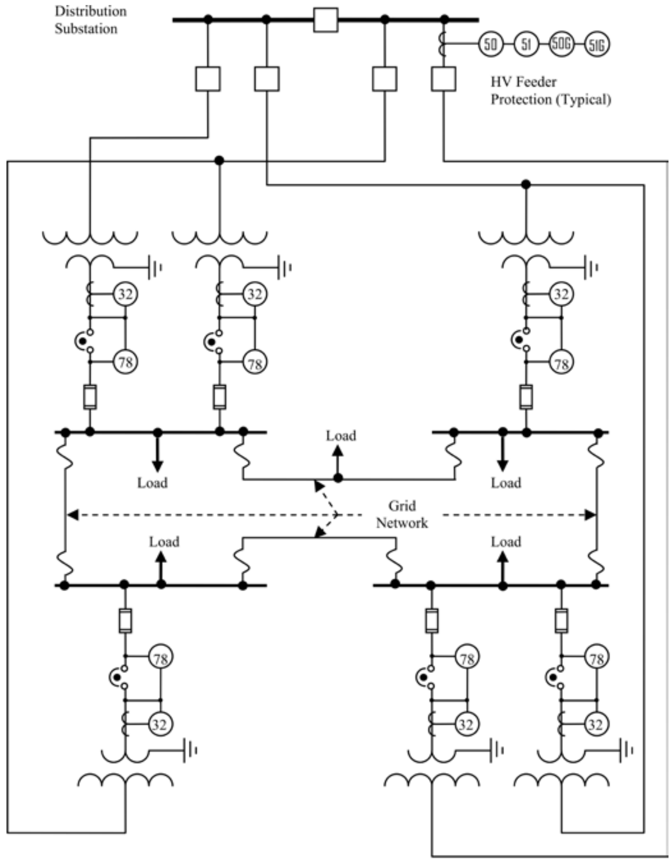

Figure 2.5: Network distribution system fed from a single substation with typical protection setup (source: [6]. Network transformers are served by different primary feeders.

2.2. Prevention of Transient Over-Voltages in Secondary Networks

2.2.1. Inverter Controlled Switch-Off Solutions

DG sources should not energize sections of the distribution system that are isolated from the utility's main supply (islanding) [8]. Hence, DGs should feature islanding detection systems to de-energize or disconnect within a certain period of time. Otherwise, TOVs and frequency fluctuations could cause unsafe and damaging conditions. Even very short duration islands lasting just a few cycles may cause equipment damage.

Hawaiian Electric Company (HECO) has proposed two mitigation options utilizing currently available technology to minimize the potential for TOVs to occur [9]. Both options include switching off the photovoltaic (PV) system instantaneously when TOVs are detected and before voltage spikes can damage utility or customer equipment.

- **Option 1:** Utilization of PV inverters with the ability to switch off the power supply once voltage transients are detected. Many modern inverters already feature this capability.

- **Option 2:** PV inverters that do not have automatic switch-off capabilities can be upgraded with a fast-acting automatic transfer switch (ATS) to operate as described in option 1.

Furthermore, HECO requires that both solutions trip the equipment within the duration of one cycle or when the voltage exceeds 120% of the nominal voltage. However, the IEEE 1547 and the UL-1741 islanding protection requirements require a 2 second response time [10,11]. Hence, they are not compatible with high speed utility re-closing practices. HECO also demands a time delay of 30 seconds or more before resetting an ATS, and 5 minutes or more for inverter-based solutions to avoid exacerbating any lingering line voltage issues and prevent short-cycling.

2.2.2. DG Regulation

The addition of DG, such as PV solar inverters, to a distribution system may have significant impacts on the power quality, reliability, and equipment safety [8]. The amount of installed DG within the distribution system is often times correlated to the occurrence of excessive fault currents, voltage and frequency excursions, and TOVs during uncontrolled islanding. Hence, preventing unintentional islanding of DGs within an isolated secondary network is crucial. Inverter-based switch-off mechanisms might not be fully sufficient, since failures within the inverter's anti-islanding protection system have been reported to occur [12].

However, if islanding does occur, the risks of TOVs become smaller the larger the Minimum Load to Generation Ratio (MLGR) is. MLGR is the annual minimum load on the relevant power system section divided by the aggregate DG capacity on the power system section as illustrated in Figure 2.6. If the DG penetration cannot fully support the system load, many DGs will shut down based on their inherent protection systems.

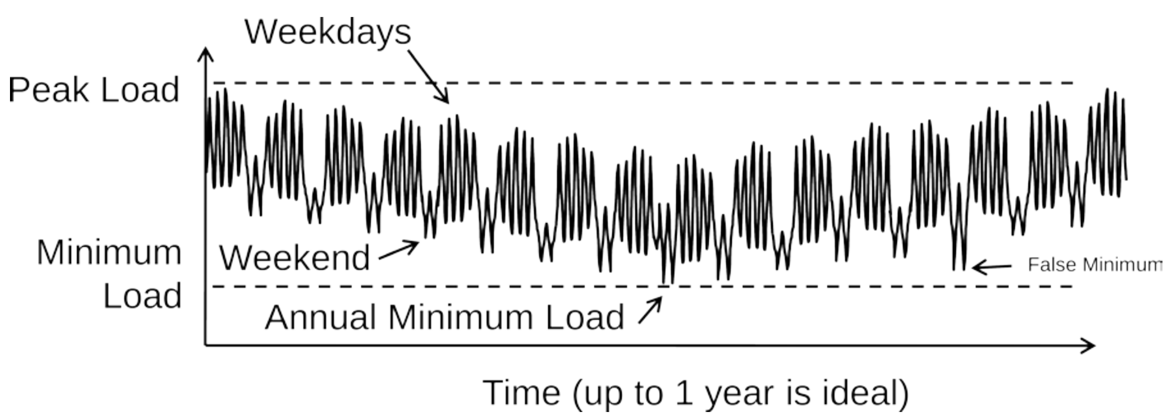

Figure 2.6: Calculation of Minimum Load to Generation Ratio (MLGR), source: [11].

Table 2.1 shows suggested penetration level ratios and their respective risks. Utility providers can regulate the MLGRs accordingly under consideration of network topology, the DG Stiffness Factor (available utility fault current divided by DG rated output current), and the Fault Ratio Factor (available utility fault current divided by DG fault contribution).

Table 2.1: Penetration risk levels depending on MLGR. The minimum load is the lowest annual load on the line section of interest. Power factor is assumed to be 0.9 inductive. In cases with high power factor, a slightly higher ratio may be needed [13].

Penetration / Risk Level	Very Low	Moderate	High
Minimum Load to Generation Ratio (MLGR)	>4	4 to 2	<2

2.2.3. Reactive Power Control

The main purpose of solar inverters is to output real power from the solar irradiance on the PV panels (DC source) [14]. However, solar inverters can also be controlled to output reactive power to regulate the voltage. Hence, it is possible to lower the power factor and temporarily reduce the MLGR if needed. Small changes in power factor can significantly decrease the voltage in the network. The impact of power factor control on the distribution system has been discussed in the literature [15,16,17].

Various options to control the Var output of the inverter exist:

- A maximum Var threshold can be set to limit the ratio of minimum load to active power.
- A schedule can be defined to vary the Var output by time of the day according to past solar irradiance and network load data.
- The Var output can be significantly reduced when critical network conditions are detected.

2.2.4. EV Charging Stations

As the number of EVs connected to secondary networks via private and commercial charging stations is rapidly rising, grid-connected EV batteries can potentially be utilized to temporarily increase the load within the network. TOVs occur when the integrated DG power exceeds the network load while being isolated. If islanding or TOVs are detected, EV batteries can quickly be connected to the distribution system to act as additional loads. Furthermore, if the power flux of all available EV batteries within the secondary network is larger than the difference between DG power and network load, TOVs can be mitigated. Even if this condition is not met, small additional loads will reduce TOVs and their associated risks. This concept is illustrated in Figure 2.7.

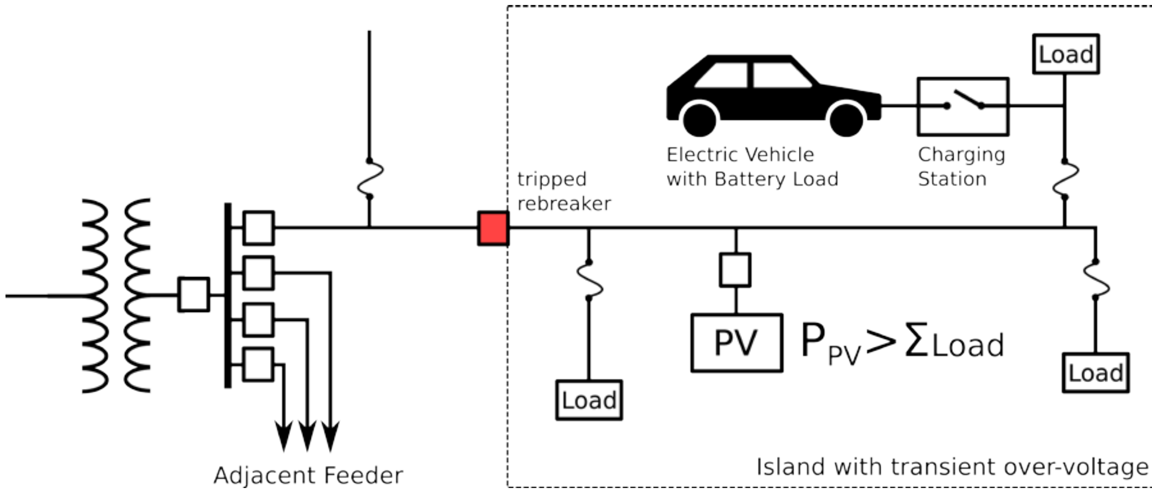

Figure 2.7: EV batteries can potentially be utilized to temporarily increase the load within an isolated network to mitigate TOVs. EV charging stations need to include fast-switch capabilities. The power flux of the available batteries should be larger than the difference between DG power and the network load.

EV charging stations need to fulfill several technical requirements to enable TOV mitigation:

- fast TOV and islanding detection, or constant communication with external detection system
- established secure connection to EV including acquisition of current charging state and maximum charging capabilities of the battery pack
- fast-switch capabilities within 1 cycle
- specific communication protocol for TOV mitigation in addition to existing charging protocols

It must be noted that the availability of interconnected EV batteries within secondary networks is unstable. It is solely dependent on the operator of the vehicle and his schedule. Even multiple charging stations within a distribution system cannot guarantee the availability of an interconnected EV at all times. Furthermore, connected EVs could already be charging at maximum rate when islanding occurs and therefore might not be able to act as an additional load when needed.

Hence, EV charging stations should not be used as the primary TOV mitigation option for a distribution system if 100% reliability is required, but rather as a secondary backup. Inverter failures that interfere with anti-islanding protections have been reported [12]. EV charging stations could then serve as a secondary layer of protection for critical distribution systems.

Furthermore, during normal network operations, EV charging stations can function to reduce the risk of TOVs by optimized scheduling of the EV charging process. This methodology is similar to peak load leveling in V2G systems. The charging station schedules the entire charging process or parts of it during periods of the day with typically high DG levels and low load levels, which is when TOVs are most likely to occur. It thereby increases the generation to load ratio and reduces the risks of TOVs during potential islanding. The scheduling of the charging process is based on past load and generation data. However, it would be conceivable to re-adjust the charging schedule in real-time when unexpected DG or load levels occur.

3. Conclusion

Due to quickly increasing PV-to-load-ratios in power grids, TOVs might become a more prevalent phenomena in the near future. Hence, the development and evaluation of efficient strategies for TOV detection, mitigation, and prevention must be facilitated. While basic strategies such as inverter controlled switch-off solution do exists, it might be beneficial to investigate the TOV mitigation potential of other smart grid components, such as EV charging stations. The existing processing architecture might be co-used for grid monitoring, stabilization and advanced control. Thus, more stable network operations can be achieved compared to simple switch-off solutions.

4. Acknowledgements

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