California Public Utilities Commission

THE INTEGRATION OF DISTRIBUTION LEVEL GENERATION & STORAGE INTO THE GRID

PROBLEMS AND SOLUTIONS

GRID PLANNING AND RELIABILITY POLICY PAPER

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ENERGY DIVISION

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Executive Summary

The Governor of California has set a goal of 12,000 MW of localized generation installed in the state at the distribution level by the year 2020[1]. This is an increase of about 8,000 MW over what was installed at the end of 2012. At such a scale, distributed energy resources (DER)[2] will provide significant environmental and financial benefits to California, but will also pose significant challenges. Stated in the broadest terms, the challenge is that the DER will be interconnected to a utility distribution grid that was defined for one-way flow of power – from substations through the grid to serve customer loads. Greater reliance on systems and devices which interact with the grid will fundamentally alter the utility network.

The purpose of this document is to identify technical issues imposed on the distribution grid by the penetration of DER and to offer potential solutions to these problems. If all potential technical problems can be identified and a solution defined for each one, the technical feasibility of DER interconnections will have been proven. This document does not deal with the area-wide problem of balancing generation and load when unscheduled generation ramps up and down as the wind picks up and dies down and as the sun rises and sets and shines or is covered by clouds. Nor does this document deal with the economics of DER interconnection: for instance, a given project could be interconnected to a distribution line by increasing the line's conductor size, but the cost of doing so could outweigh the benefit of the DER.

For the purpose of connecting to the grid, there are two general types of generation: 1) that connected through an inverter, with or without a transformer, and 2) that connected through a transformer alone. Examples of the former are photovoltaic generation whose direct current (DC) power is converted to alternating current (AC) in the inverter, and wind generators whose asynchronous (other than 60 Hz) AC power is converted to 60 Hz power in the inverter. Examples of the latter are small hydro, geothermal and biomass, all of which power synchronous generators which are connected to the grid through transformers. Some wind turbines power induction generators, which are also connected to the grid through transformers. Distribution level storage will be connected to the grid through inverters.

Potential issues associated with the integration of generation and storage into the grid at the distribution level include:

- Threat to safety of utility personnel;
- Line capacity insufficient to accommodate generation and storage;
- Control of voltage on the line;
- Overcurrent Protection of the line under short circuit conditions;
- Overvoltage protection of the line under short circuit conditions;
- Harmonics introduced on the line by inverters;
- Operation of sections of the line separated from the substation but supplied from connected generation (unintended "islanding"[3]);

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[1] "Jobs for California's Future " by Jerry Brown http://www.jerrybrown.org/jobs-california%E2%80%99s-future

[2] Distributed energy resources (DER) are defined in this document as all generation and energy storage devices connected directly or indirectly (behind the customer meter) to the utility's distribution system.

[3] See glossary.

- Limitation on the amount of generation that can be connected to secondary networks used in the downtown areas of certain large cities;
- Impact on the transmission system;
- The connection of microgrids; and
- The interaction of smart VAR generating devices connected to a common line.

There are remedial measures for all problems that may be caused by the connection of generation and storage to distribution circuits, with the exception of connection to secondary networks.

Smart grid innovations can improve system performance in the following ways:

- Voltage data from smart meters can replace the line drop compensation algorithm.
- Power electronics devices, including smart inverters used for connecting generation and storage to the grid, and utility owned equipment, such as shunt static VAR compensators, series power regulators and shunt-series power regulators, can replace mechanical voltage regulators and fixed capacitors to regulate voltage, as well as correct phase imbalance and filter out harmonic voltages.
- Distribution level and customer level storage can even out the fluctuations in generation produced by intermittent generation sources and the associated smart inverter can aid in the control of voltage.
- Enhanced communications can provide the grid operator with the data on the output of generators and, in the case of pondage hydro and storage, the ability to control output.
- Increased application of SCADA, including possible use of microsynchrophasers, can improve reliability and improve voltage control.
- Microgrids may improve reliability.
- Provide coordination of utility owned devices and customer owned generation and storage connected to a common line.
- The application of industry standards now under development may guide the design of reliable circuits and equipment.

The large number of generation facilities proposed to be connected to the grid at the distribution level poses problems to existing circuits which are designed for power flow from the substation to the loads, not from where the generation is located anywhere along the distribution line to the loads and to the substation.

Many distribution circuits may have to be modified to accommodate generation and storage. Which circuits need to be modified can be determined partially through evaluation based on general conditions or "screens": if the considered project meets the established conditions, the circuit does not need to be modified; if it does not, the circuit and/or project need to be modified. The circuit and the project can be simulated on a computer model to determine the effect of the project and to determine remedial measures to mitigate the effects.

Generation connected to a net energy meter[4] (NEM) at utilization voltage (120/240V) does not significantly affect the distribution line (except for cases of clustered generation seen in high

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[4] See glossary.

penetration neighborhoods and some new home developments). To permit expedited connection of larger scale generation and storage connected to the distribution line at line voltage, California's investor owned utilities, in the latest version of their Tariff Rule 21[5], have adopted a set of screens. Projects that pass the screens are approved; projects that do not pass the screens are subject to individual evaluation by computer simulation performed by the host utility. The computer model can also be used to evaluate measures to mitigate the effect of the connected generation.

Taken together, a better understanding of the potential technical impacts of DER, combined with a dedication to resolving those issues in a cost-effective manner before they pose a threat to the reliability and safety of the utility system, provide the framework for understanding the issues addressed in this paper. On a practical level, the California Public Utilities Commission, its regulated utilities, equipment vendors, and customers all have a stake in this effort, as it will guide the investment of billions of dollars in new technologies for the modernization of the electric distribution system over the next several decades.

In 2013, the Legislature passed, and Governor Jerry Brown signed into law AB 327, which among other things, directed the regulated utilities to file distribution resource plans for Commission by July 1, 2015.[6] Each plan will include the following:

- An evaluation of locational benefits and costs of distributed resources, with an assessment based on reductions or increases of local generation capacity, avoided or increased investment in distribution infrastructure, safety benefits, reliability benefits, and other potential savings to ratepayers;
- Proposals for standard tariffs, contracts or other mechanisms for deployment of cost-effective distributed resources;
- Proposals to coordinate existing programs, incentives and tariffs to encourage such deployment;
- Estimates of additional utility spending necessary to integrate cost-effective DER, and
- Identification of barriers to deployment of cost-effective DER.

After consideration, approval or modification of these of these plans by the Commission, the IOUs may propose budgets for new investments to accommodate these resources as part of their subsequent general rate cases.

While AB 327 holds a broader definition of distributed resources – which includes energy efficiency and demand-response technologies along with generation and storage – the Commission believes that identifying and resolving the technical issues raised in this document is a critical first step to implementing the legislative intent of AB 327.

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[5] Ibid.

[6] PUC Sec. 769

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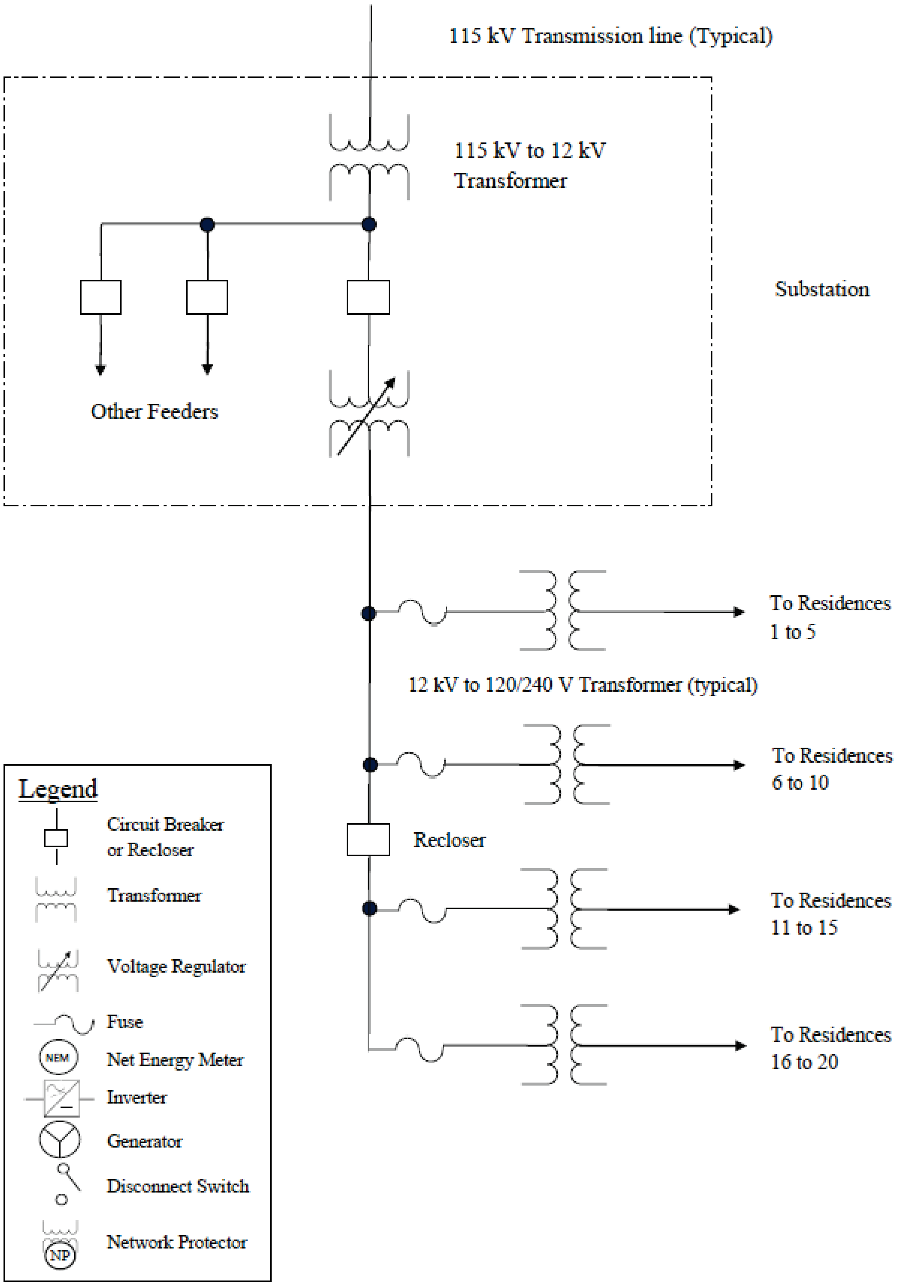
1 Technical Background

1.1 Distribution Lines

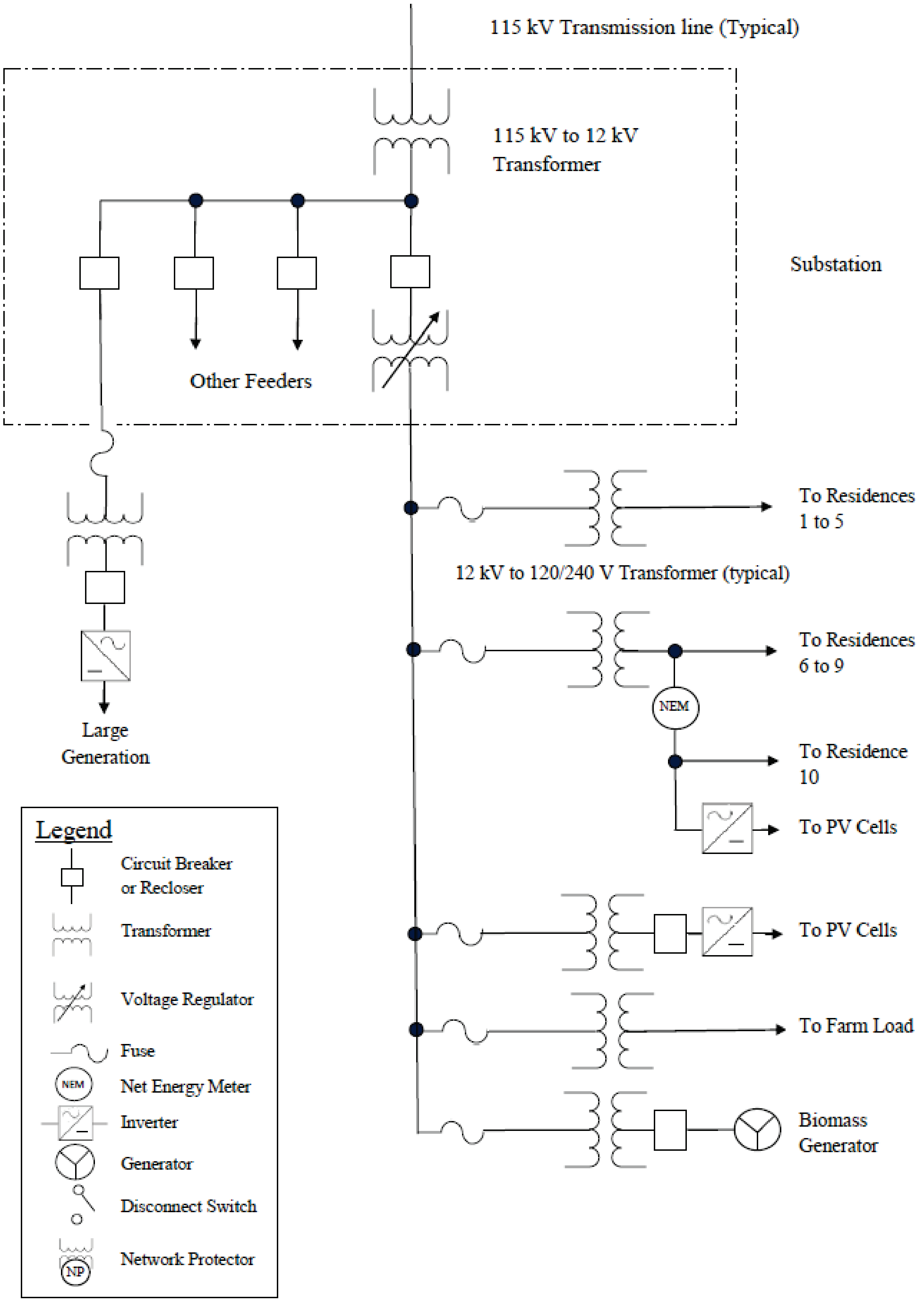
Distribution lines are typically electricity conducting, uninsulated wires supported on the top of wood poles that run along city, suburban and rural streets. The same poles may support a multitude of cables, including telephone, television cable and the low voltage service lines that connect to residences. The distribution voltage is usually 4 to 30 kilovolts (kV) and pole top transformers are connected to the wires at intervals to reduce the voltage to 240 and 120 volts, safe values for use in the home. The distribution lines originate at distribution substations where transformers reduce transmission voltages of 60kV, 115kV and 230kV to the distribution voltage. The problems discussed herein with regard to overhead distribution generally also apply to underground distribution used in cities and residential subdivisions. A symbolic representation, known as a single line diagram, of a distribution line is shown in Figure 1, below.

Figure 1



The integration of distribution level generation and storage into the grid usually involves connection to a distribution line, although larger scale generation (typically, 5 to 20 MW) can be connected directly to the substation. Examples of the connection of two photovoltaic generation sources and a biomass generator to the distribution line are shown on Figure 2. These examples illustrate the two primary types of interconnection: a) net energy metering and b) distribution connected generation.

Figure 2



1.2 Net Energy Metering

The photovoltaic generation consists of photovoltaic (PV) cells connected to an inverter[7] which transforms the direct current output of the cells to alternating current. The inverter

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[7] See glossary

of a small source, typically PV cells on the roof of a house, is connected in parallel with the residence load to a net energy meter. Larger PV generation is connected to the distribution line through the inverter, a circuit breaker and a dedicated transformer.

1.3 Distribution Connected Generation

The biomass generator at a farm is also connected to the distribution line through a circuit breaker and a dedicated transformer, as shown on Figure 2. The circuit breaker trips to protect the generator in the event of a short circuit on the line and to protect the line and the loads connected to it in the event of a short circuit or other problem in the generator. The farm load is not at the same voltage as the generator and is connected to the line through a separate transformer.

1.4 Dispatchable Resources

An important characteristic of generation is dispatchability, or the absence thereof. Dispatchability is desirable because it enables the generation to be used to match the load profile when it is most economical to do so. In particular, it can be applied during peak loads, when generation is most expensive. Wind and solar power are not dispatchable: wind power is available when the wind blows; concentrated solar power is available only when the sun shines; photovoltaic cells produce their maximum output under sunny skies, reduced output under cloud cover and no output at night. However, wind and solar can be combined with storage, so that the storage can be accessed in times when the wind is not blowing or the sun is not shining. But in the case of storage combined with wind and solar, it is the storage and not the generation that is dispatched; the wind generator would not want his generation interrupted when a strong wind was blowing.

Geothermal and biomass generation operate continuously and therefore are not dispatchable. Pondage hydroelectric power, that is hydro whose source is a reservoir, is dispatchable and can be turned on and off almost instantaneously. However, small scale hydropower, the hydro most likely to be connected at the distribution level, is more probably run-of-the-river, which produces power as long as the river flows and is therefore not dispatchable. In spite of not being dispatchable, solar power has the advantage of producing power when the sun shines, which in areas with heavy air conditioning loads is the time high power demand.

Although storage at the distribution level is more expensive on a dollar per kilowatt basis than large scale storage, such as pumped storage, distribution level storage can reduce the load on a distribution line when renewable generation, wind and solar, is not available, thereby reducing the required distribution circuit capacity in terms of conductor size and substation transformer rating.

2 Conditions Imposed on Potential Generators for Connection to the Distribution Grid in California

With tens of thousands of low voltage connected NEM and thousands of distribution level renewable generation projects awaiting connection to the grid, an expedited process for approval by the local utilities is very desirable.

2.1 Tariff Rule 21

The recent revision of Tariff Rule 21 provides a basis for quick approval by means of standard conditions or "screens", by which projects which have applied for connection are evaluated. The purpose of the screens is to determine if the project will have a significant effect on the grid: if the project meets the conditions (passes the screens), its effect would be minimal. Therefore, if it passes the screens, the application is approved. If the project does not pass the screens, the applicant must request a detailed study, for which it has to pay, in addition to providing any mitigating measures found to be necessary as a result of the study.

2.2 Rule 21 Interconnection Screens

Among the screens specified in Rule 21 are:

- Does the project inject power into the grid?
- Is it a net energy metering project whose rating is greater than 500kW?
- Is the total generation connected to the line section less than 15% of the line section's peak load?

If the answers to these questions and others are negative, the project passes the screens and is approved.

2.3 Other Rule 21 Considerations

Once connected to a distribution line, the project has to meet requirements to ensure that it does not disrupt the service to customers on the line or to the utility's operation of the line and the substation. These include automatic disconnection from a de-energized line (so as not to feed into a short circuit), automatic shutdown in the event of islanding[8], not influencing the voltage on the line, and a host of very detailed requirements concerning harmonics, conditions for disconnection, reconnection, etc.

The present version of Tariff Rule 21 does not address intentional islanding.

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[8] See glossary

3. Problems Associated with the Connection of Generation and Storage to the Grid and Possible Remedial Measures

This section describes the problems imposed on the distribution grid by the connection of generation and storage to it; and it describes potential solutions to these problems. It does not deal with the area-wide problem of balancing generation and load as renewable, unscheduled generation ramps up and down as the wind picks up and dies down and as the sun rises and sets and shines or is covered by clouds. Nor does it deal with the economics of DER interconnection: for instance, a given project could be interconnected by increasing the conductor size of the distribution line, but the cost of doing so could outweigh the benefit of the DER.

3.1 Safety of Utility Personnel

When the line is shut down due to a short circuit or other problem, all connected generation must also be shut down or disconnected from the line so that the line can be inspected and repaired without endangering the linemen. In cases where the generation does not shut down automatically on low line voltage and the generation is connected to the line through a circuit breaker or through a remotely controllable inverter, the circuit breaker or inverter could be opened from the utility dispatch center by transfer trip[9], which would require a communication channel between the utility dispatch center and the generator, usually in the form of a leased telephone line.

3.2 High Penetration

"Penetration" is the term used for the ratio of the connected generation on a distribution line to the connected load. As stated in Section 2.2, above, a screen in Rule 21 allows a potential project to pass if the total generation on the line never exceeds 15% of the peak load on the line. Another and probably stricter criterion is that the output of the connected generation is at all times less than the load on the line, in which case there will not be a flow of power from the line into the substation, and the influence on voltage regulating and overcurrent devices will be small. On the other hand, if the generation exceeds the load at any time, the operation of the circuit may be affected and problems described in Sections 3.3 to 3.5, below, may be encountered.

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[9] See glossary.

3.3 Thermal Overload

The distribution line conductor may be of insufficient capacity to transmit the output of the generator. For instance, if the farm load were 200kW, which draws about 11amperes at 12.5kV, the conductor to the farm could be the utility's minimum standard size, which could be AWG (American Wire Gage) #4 aluminum[10], whose rating is 138 amperes, which is 3 MW at 12.5 kV. But if subsequent to installation of the load, the farmer were to install a biomass generator whose capacity was 4 MW (or a neighboring farmer were to install another generator so that the total generation was 4 MW), the thermal rating of the line conductor would be exceeded. The only remedy for this is to increase the conductor size; if the conductor on this line were AWG #4 all the way to the substation, the conductor on the full length of the line would have to be replaced. Note that the standard ratings of reclosers, switches and fuses are generally sufficiently in excess of the conductor capacity so that, although the conductor is upgraded, the switches, reclosers and fuses may not have to be replaced.

3.4 Voltage Regulation

3.4.1 Case 1

The distribution line source has a regulator with line drop compensation[11] *and the distribution level generator is connected near the substation.*

An increase in the load on a line due to daily and seasonal variations will cause a voltage drop along the line (the magnitude of this voltage drop depends on the impedance of the line and the size of the increase in load) possibly resulting in an undervoltage at the end of the line. To offset this drop, a voltage regulator on the line at the substation can sense the increase in load and increase the voltage at the sending end (line drop compensation), thereby maintaining the voltage at the end of the line more or less constant.

However, a significant input of generation near the substation would diminish the load delivered from the substation and consequently the load (current) sensed by the regulator, causing the regulator not to function as intended, resulting in undervoltage at the end of the line. This condition could be remedied by inserting a signal in the regulator control circuit proportional to the output of the generator, though this solution is simpler in theory than in practice[12].

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[10] Distribution line conductor sizes vary with the utility; this is the minimum on the PG&E network.

[11] See glossary

[12] The signal to the voltage regulator is the output of a current transformer in the transformer's secondary (distribution line) circuit. It is not feasible to add to or subtract from the output of a current transformer. A second sensing circuit would have to be added to the voltage regulator. Field modification of standard equipment is difficult and subject to malfunction, though if the demand for the modification were sufficient, the equipment manufacturer might be able to furnish a retrofit kit, to which a separate current

If customers at the end of the line had smart meters, the voltage reading from one of them could be sent to the substation and used instead of the line drop compensation algorithm. The signal from the meter would indicate the drop in voltage as the load increases when people turn on their lights and coffee makers in the morning and when clouds diminish the PV generation on the line (and likewise the rise in voltage as the load decreases and the clouds dissipate).

3.4.2 Case 2

The distribution line source has a regulator with line drop compensation and the generation is connected at a distance from the substation.

In this case, the effect is beneficial: the load current along the line will be reduced, thereby lessening the need for regulator control at the substation and at other locations on the source side of the line from the generator. However, if the generation is intermittent, the number of operations of the mechanical regulator will increase; and in some cases the rate of intermittency will exceed the operating speed of the regulator. In these cases what is needed is voltage control based on power electronics, such as smart inverters functioning independently of the generation connected to them, or utility owned static VAR compensators, series regulators and shunt-series regulators.

3.5 Overcurrent Protection under Short Circuit Conditions

3.5.1 Case 1

All short circuits

Short circuits on the distribution line are detected by relays at the substation which measure current and cause the line circuit breaker to trip when the current exceeds a set value above maximum load. As with the operation of line drop compensation, the output of generation connected close to the substation will decrease the current contribution coming from the substation, thereby slowing or preventing altogether the operation of the relay and circuit breaker. This is a far worse problem if the generator is a synchronous or even an induction generator, which may, under short circuit conditions, produce currents six times as high as rated current; it is of lesser significance for generation connected through an inverter whose output current is not significantly increased under short circuit conditions.

A possible remedy to the effect of the short circuit contribution of the generator is to cause the relay to pick up at a lower value of current; but the downside to this solution is possible pick up of the relay under heavy load when the generator is off line. A better solution is rapid operation of the generator circuit breaker, thereby removing the generator short circuit contribution and enabling normal but sequential operation of the line circuit breaker.

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signal from the generator would be applied, either by direct wiring or some other communication circuit. This process would be complicated and expensive.

3.5.2 Case 2

Single Line-to-Ground Short Circuits

Another problem is presented by a three phase generator transformer connected delta on the generator side and grounded wye on the line side[13]. In the event of a short circuit to ground, this transformer would produce ground fault current which would decrease or eliminate the ground fault current from the substation, thereby interfering with the operation of the ground fault relay. This problem can be overcome with the use of a generator transformer connected delta-delta or delta-ungrounded wye. However this solution to the operation of the substation circuit breaker would interfere with the operation of the generator circuit breaker on ground faults. A better solution would be provided by a utility-approved ground overcurrent relay at the generator circuit breaker to provide rapid opening of this circuit breaker followed by normal but sequential opening of the line circuit breaker, as indicated above.

3.6 Overvoltage Protection under Short Circuit Conditions

A large penetration of generation through inverters which do not immediately drop off line on a line-to-ground fault after the substation circuit breaker has tripped, may result in overvoltage in the non-faulted phases, which can damage equipment connected to the line[14]. This overvoltage can be prevented with the installation of a grounding transformer, that is, a zigzag transformer or a transformer connected grounded wye on the line side and delta on the load side. With both types of transformer, with a single-line-to-ground fault there is sufficient ground current to prevent overvoltage in the non-faulted phases. Note, the current through the grounding transformer subtracts from that through the substation transformer, so that the operation of the substation ground overcurrent relay is slowed, allowing the fault to persist for a longer time. Nonetheless, the tradeoff may be worthwhile to protect equipment connected to the line from overvoltage.

3.7 Voltage Quality

Harmonics produced by inverters can affect sensitive loads on nearby circuits, particularly in the case of loads on the secondary of the same distribution transformer as the inverter: the high impedance of these transformers prevents the dissipation of the harmonics into the distribution line and confines them to loads connected to the same secondary. The solution to this problem is to impose limits on harmonics emissions by the inverters, as required by Tariff Rule 21.

3.8 Islanding

In the event of a short circuit on a distribution line which has provision for sectionalizing, a portion of the circuit may be isolated (“islanded”), see Figure 3. On the figure the line

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[13] Certain combinations of connections of the high and low side windings of the transformer will enable or prevent the flow of short circuit current across the transformer.

[14] The overvoltage due to the inverters which remain connected is exacerbated by induction motor loads: the induction motors supply VARs to the system for several cycles after the main power source has turned off.

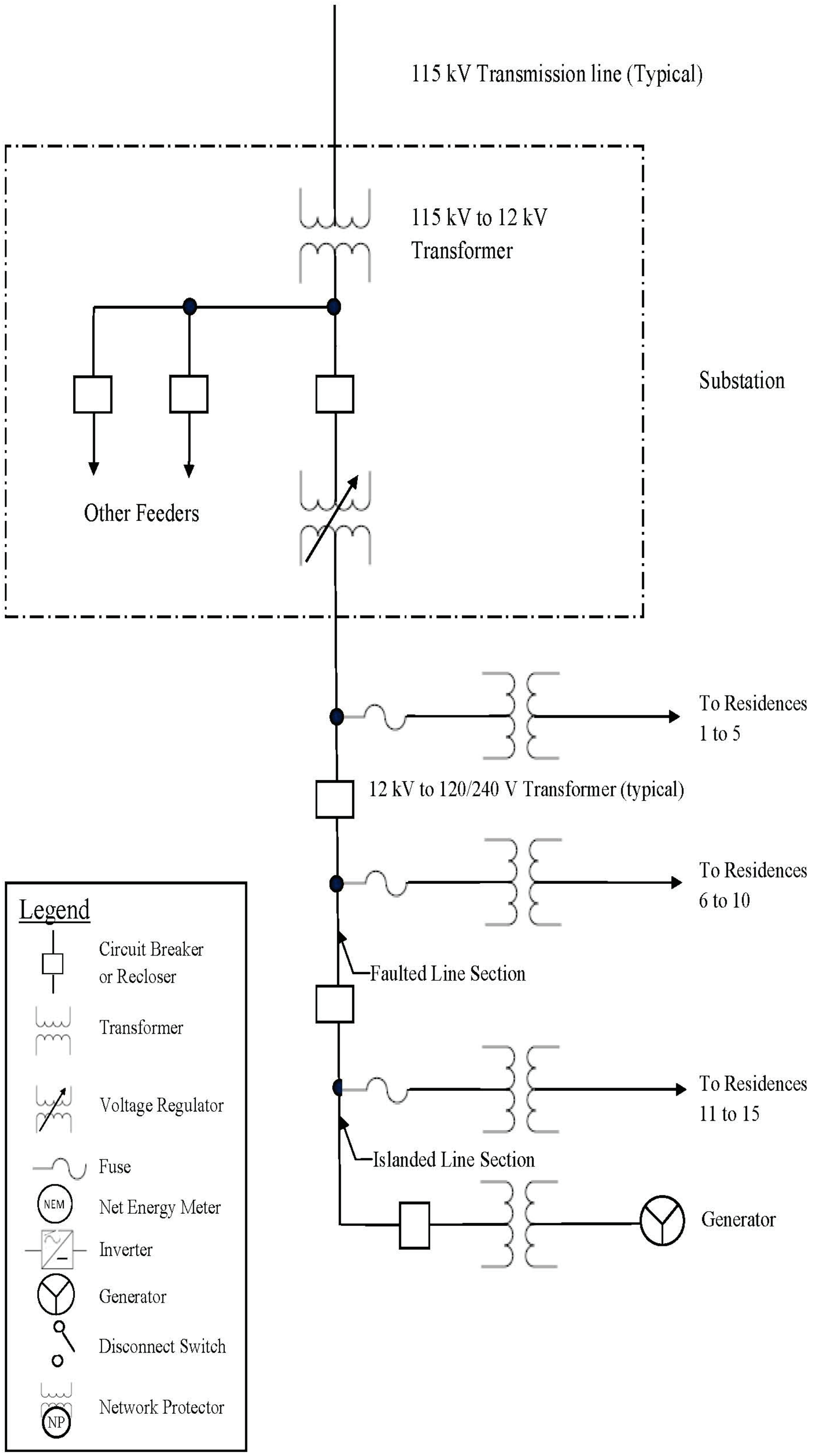
section downstream from the second recloser becomes the island. If the isolated section has generation connected to it, this generation can serve the loads on the section provided:

- The generation is equal to or greater than the loads (including the VAR requirement) on the island
- The generator has the capability of regulating voltage and frequency to acceptable standards.

If the generation does not meet these criteria, the generator circuit breaker must trip or, if the generator is connected to the line through an inverter, the inverter must shut down. This action could be the result of short circuit detection by the devices themselves or of transfer trip from the substation. The dispatch center should be aware of the islanded line section and coordinate with the generator operator the synchronization of the generator for reconnection to the line after the fault has been cleared.

As described in Section 2.3, the connection of generation to the distribution lines of utilities regulated by the CPUC is governed by Tariff Rule 21, the present version of which does not address intentional islanding.

Figure 3


115 kV Transmission line (Typical)
115 kV to 12 kV
Transformer
Substation
Other Feeders
To Residences
1 to 5
12 kV to 120/240 V Transformer (typical)
To Residences
6 to 10
Faulted Line Section
To Residences
11 to 15
Islanded Line Section
Generator
Legend
Circuit Breaker
or Recloser
Transformer
Voltage Regulator
Fuse
NEM
Net Energy Meter
Inverter
Generator
Disconnect Switch
NP
Network Protector

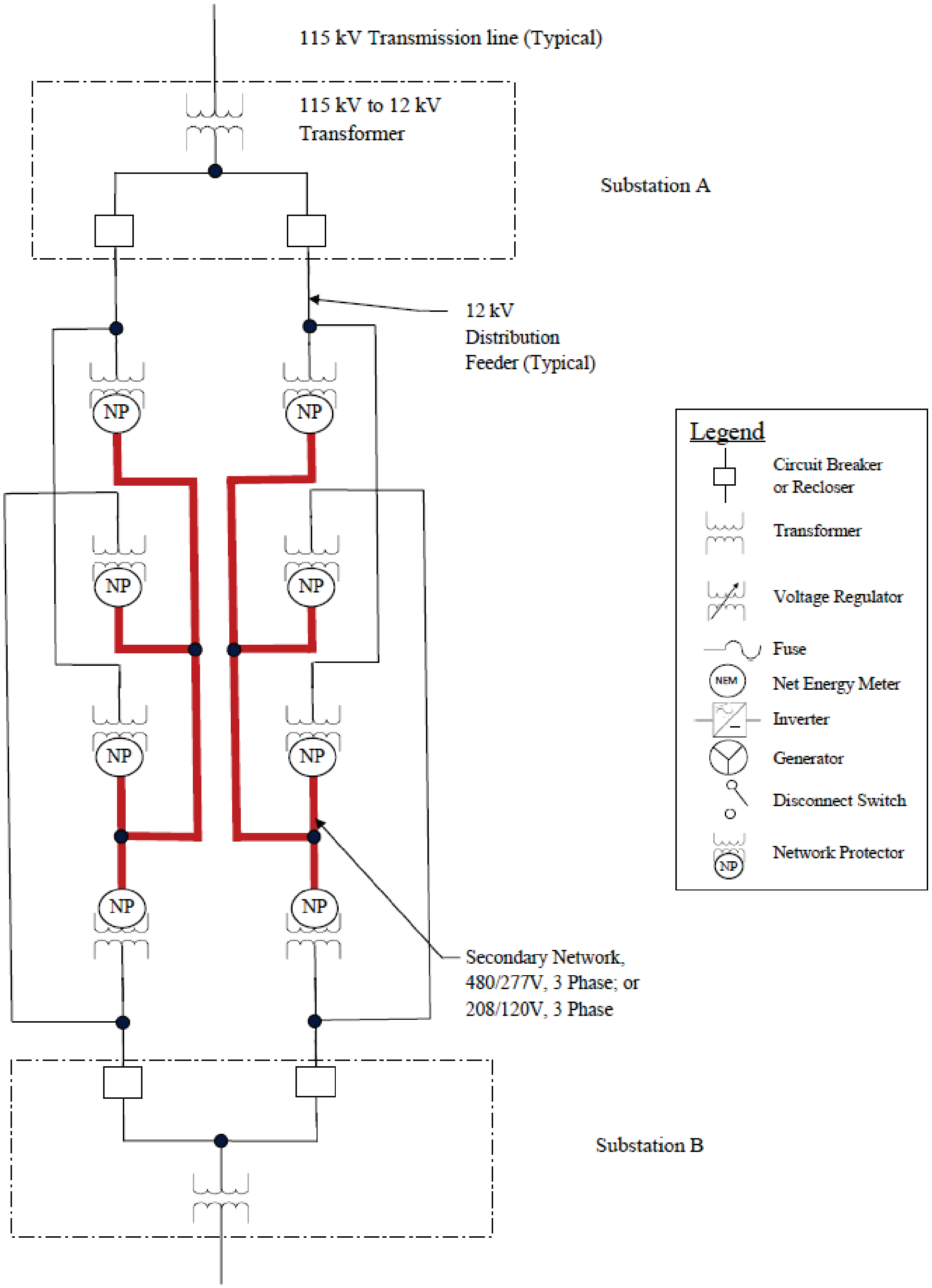
3.9 Impact on Secondary Networks

Some cities, including San Francisco, have secondary networks for the purpose of providing reliability in high load density areas. Typically several distribution feeders supply a number of network transformers that reduce the distribution voltage to what can be used in buildings: 480/277 and 208/120 volts. The circuits at this voltage are interconnected so that any given location on the network is served from multiple sources.

An example of a secondary network is shown on Figure 4: the loads are connected to the lines shown in red. A problem for these networks is that a short circuit on a network transformer, on a feeder or on the substation bus causes a current to flow from the other feeders through the network into the short circuit. To get around this problem, network protectors are installed on the secondary of the network transformers.

These devices detect reverse power flow, that is, power going from the network into the feeder, and in the event open the circuit to interrupt the flow. This feature limits the capacity of generation that can be installed on the network: the total connected generation cannot exceed the value at which the network protectors operate to prevent reverse flow under minimum load conditions. That is, to prevent power flow from the network into the feeders, the generation must always be less than the sum of the loads. This limits the capacity of the DER: large scale generation in the area served by the network has to be connected to a feeder or directly to the substation, as shown on Figure 2.

Figure 4



3.10 Impact on the Transmission System

The transmission system transfers power from power plants and transmission substations to distribution substations by means of transmission lines. Generation at the distribution level will reduce the load on these lines and thereby delay or eliminate the need for upgrading this infrastructure. Only in the event of a very large volume of connected generation, or generation that is not coincident with the load such that the flow on the transmission line is not only reversed but then exceeds the capacity of the line, would any action, i.e., transmission line upgrade, be required.

3.11 Microgrids

Microgrids[15] are self-contained distribution voltage networks which may be connected to the utility grid for reliability or economic power interchange (Figure 5 below). The concept can make sense for military installations, research centers and universities where maximum reliability by means of self-generation is a requirement, but connection to the utility is desirable for the purchase of economical power. A Sandia report[16] says "Microgrids can offer advantages over the conventional power system such as lower environmental impact, higher efficiency, higher reliability, and more flexibility to meet changing or unique loads." Nonetheless, there are presently few existing microgrids other than those built for stringent reliability or experimental purposes.

The problem for the utility with a microgrid connected to it is the same as with any large generator connected to a distribution line: the maintenance of correct voltage at the substation with competing voltage controls from the microgrid generators and the requirement for fast separation of the microgrid in the event of short circuit, either in the microgrid or in the substation.

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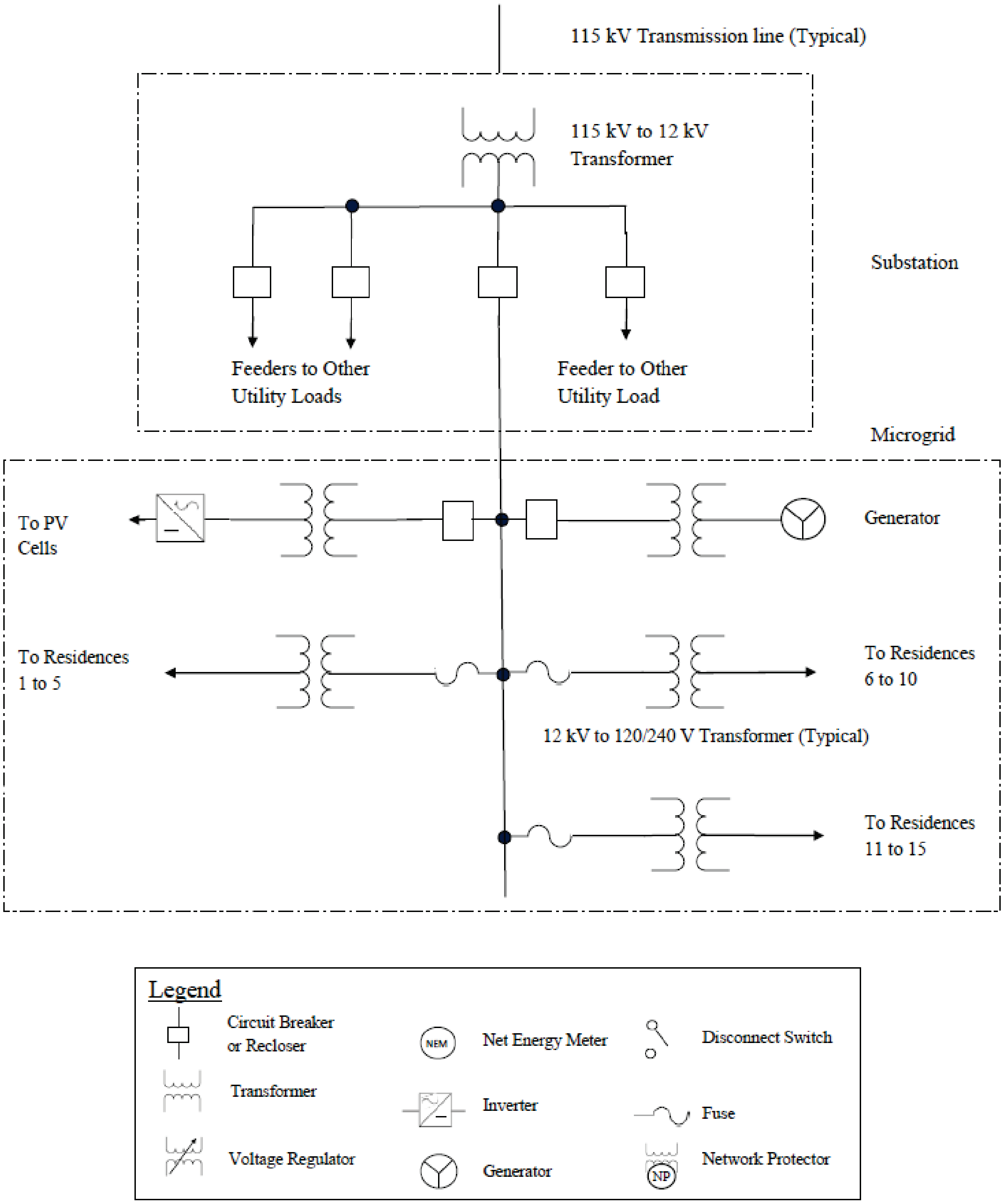
[15] See glossary

[16] "Renewable Systems Interconnection Study: Advanced Grid Planning and Operations," February 2008

Figure 5


115 kV Transmission line (Typical)
115 kV to 12 kV
Transformer
Substation
Feeders to Other
Utility Loads
Feeder to Other
Utility Load
Microgrid
To PV
Cells
Generator
To Residences
1 to 5
To Residences
6 to 10
12 kV to 120/240 V Transformer (Typical)
To Residences
11 to 15
Legend
Circuit Breaker
or Recloser
Transformer
Voltage Regulator
NEM
Net Energy Meter
Inverter
Generator
Disconnect Switch
Fuse
NP
Network Protector

3.12 Interaction of Multiple VAR generating Devices Connected to a Common Line

With multiple VAR generating devices, such as smart inverters and static VAR compensators, connected to a common line there may be interaction between them with some generating VARs and others absorbing VARS, resulting in unnecessary and loss-inducing flow of reactive power. This interaction may be overcome by slowing reaction times and widening dead band settings, but these measures limit the potential to manage voltage changes that occur at rates as fast as 10 seconds. An electronic series power regulator, operating with shunt VAR devices and/or generator inverters set for fixed VAR output or fixed power factor could maintain the voltage at its downstream terminals with speeds faster than expected voltage variations due to changing loads or intermittent generation.

4 The Connection of 12,000 MW of Localized Generation to the Grid

As stated above, California has the goal of integrating 12,000 MW of renewable power into the distribution grid by the year 2020. The problems and potential solutions to this high penetration of distribution level power are described in Section 3, above. In a survey of the principal investor-owned utilities in the state, PG&E, SCE, SDG&E, plus the Los Angeles Department of Water and Power and the Sacramento Municipal Utility District, the present and projected levels of distribution level renewables was obtained. The results are given on the table below.

YEAR	2012		2020	
	NEM	Direct Connection	NEM	Direct Connection
	(MW)	(MW)	(MW)	(MW)
UTILITY				
PG&E	880	410	2,400	3,400
SCE	575	479	1,900	1,300
SDG&E	159	384	291	715
LADWP	64	282	340	830
SMUD	47	125	160	250
SUBTOTALS	1,725	1,680	5,091	6,495
TOTALS: NEM + DIRECT		3,405		11,586

The sum total of projected local renewable generation in 2020 is 11,586 MW. Since the five utilities listed on the table cover 86.8% of the load in California[17], assuming the remaining utilities have a proportionate amount of renewables, the total projected for the state would be 11,586/0.86.8 = 13,348 MW. The governor's goal is met.

But this value may be an underestimate: according to SCE, the values it reported for direct connected generation consist of only the amount declared for export, the amount a customer keeps for its own use but which could be counted as local renewable generation, is not included. Furthermore, generation connected at 60kV and at 115kV, but which could also be counted as local renewable generation, is not included.

5 Smart Grid[18] Innovations that Can Improve the Performance of Distribution Circuits

5.1 Smart Meter Voltage Signal Replaces the Voltage Drop Compensation Algorithm

Line drop compensation for under-voltage at the end of the distribution feeder is provided by a voltage regulator at the substation terminals of the feeder. However, if there is generation connected to the feeder, particularly near the substation, the current flow through the voltage regulator would be less than that on which the line drop had been calculated, resulting in a smaller voltage rise by the regulator and consequently insufficient voltage at the end of the line. If the actual voltage at the end of the line were available from a smart meter connected at that location, this signal could be used to control the regulator instead of the current flow from the substation, rendered unreliable by the generation on the line, see Section 3.4.1.Case 1, above. Note that the mechanical voltage regulator at the substation does not provide the speed response of an electronic device (see Section 3.12, above).

5.2 Power Electronic Devices Replace Fixed Capacitors and Voltage Regulators

Power electronic devices, including smart inverters, static VAR compensators, series power regulators and shunt-series power regulators, have the potential to regulate voltage (provide VARs), filter harmonics, balance the power across phases and control power flow along the distribution line. Three possible applications are shown on Figure 6, below: a shunt device which supplies VARs to be used in place of shunt capacitors; a series device to be used in place of a voltage regulator; and a combination shunt and series device which can take the place of capacitors and a voltage regulator. Smart

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[17] Percent of peak load in 2013, per e-mail from Chris Kavalec of the Energy Commission, dated October 3, 2013.

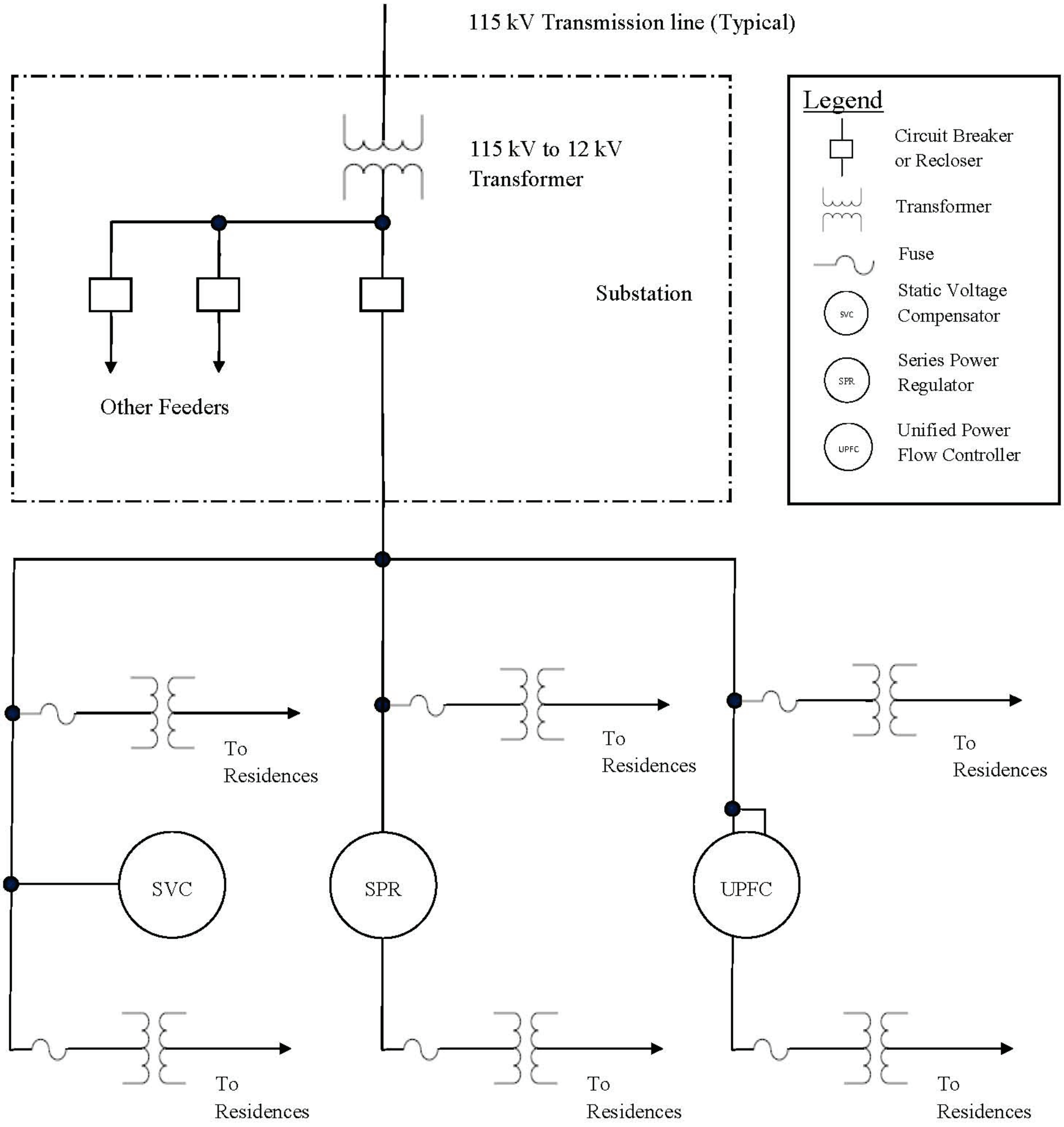
[18] See glossary.

inverters or static VAR compensators with the capability of detecting the voltage at their output terminals could generate or absorb VARs to maintain the desired voltage much more closely than the switching in and out of fixed capacitor banks, as well as filter harmonics, which capacitors cannot do. Likewise, an electronic series power regulator with voltage sensing capability could maintain the voltage at its downstream terminals much more closely than a mechanical voltage regulator (with speed on the order of cycles), as well as correct phase imbalance and filter harmonics, which a voltage regulator cannot do.

In the case of a merchant generator or storage developer connected to the grid through an inverter, the utility could, as a condition for connection, require the installation of a smart inverter whose VAR output could be either controlled from the substation or programmed for autonomous operation to provide one of the following: a fixed value of VARS, power delivered at a fixed power factor, or maintain a fixed voltage at the point of common coupling. But there are potential problems with the use of merchant generator supplied inverters to control voltage: the inverter would have to stay on line even though the power it was intended to deliver was absent (the wind wasn't blowing) and it would have to be under utility control, either directly or by means of autonomous mode programming. Also no market currently exists for compensating the generator for supplied VARs.

Electronic power devices owned and installed by the utility would obviate these limitations. From an economic perspective this is a more likely possibility for new feeders than for retrofitting existing feeders, unless the retrofitting is required to accommodate the installation of generation or storage. The technical and economic feasibility of the application of electronic power devices and their type and rating can be determined by a study of each individual application. Because distribution lines and the devices connected to them can be modeled on a computer, studies of this type should not impose an excessive burden on the host utility.

Figure 6


115 kV Transmission line (Typical)
115 kV to 12 kV Transformer
Substation
Other Feeders
Legend
Circuit Breaker or Recloser
Transformer
Fuse
SVC
Static Voltage Compensator
SPR
Series Power Regulator
UPFC
Unified Power Flow Controller
To Residences
To Residences
To Residences
SVC
SPR
UPFC
To Residences
To Residences
To Residences

5.3 Distribution Level Storage

Energy storage connected either to the distribution line or behind the customer's meter could produce power when the wind isn't blowing or the sun isn't shining and its output could be controlled by the utility to offset the load on the distribution line, or for use at the time of greatest need. In so doing, it could reduce the capacity required of the line and the transformer at the substation.

The Holy Grail of distributed energy resources is storage connected to the grid through an inverter that operates in four quadrants[19], the combination of which can generate power, generate VARs; generate power, absorb VARs; absorb power (store energy), generate VARs; absorb power, absorb VARs. Such a resource would even out the fluctuations of intermittent resources by storing energy when the sun is shining, generating power when clouds cover the sun, generating VARs when there is an excess of lagging power factor load and absorbing VARs when other generation sources or fixed capacitors produce leading volt-amperes in excess of the lagging power factor of the connected load.

A recent decision by the CPUC[20] provides a target for the three large utilities in California to have installed by the year 2024 625MW of storage at the distribution level and behind the customers' meters. This powerful incentive is expected to jump start the development of storage just as the California Solar Initiative led to the widespread development of rooftop photovoltaic generation. This incentive will also help the industry address the present high cost and short maintenance windows of battery-based storage technologies.

5.4 Enhanced Communications

Enhanced communications can provide the grid operator with data on the output of generators and, in the case of pondage hydro and storage, the ability to control output.

5.5 Dispatch Center Control or Automatic Control of Tie Line Switches, VAR and Storage

With more extensive application of legacy SCADA and remotely controlled switches, voltage control devices and storage, short circuits on distribution feeders could be quickly isolated and the voltage could be closely controlled from the substation or utility dispatch center. Alternatively, the operation of these devices could be automatic, in response to conditions sensed by the devices themselves. In either case, the reliability of the distribution line and the loads and generation connected to it would be enhanced and close voltage control would provide savings from excessive usage due to overvoltage at

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[19] With the real power output of a generator plotted along the horizontal axis and the reactive power on the vertical axis, the total output can be plotted as a vector with positive real generation and absorbed VARs (underexcited generation) in the first quadrant, and, going counterclockwise, the second quadrant represents negative real and reactive power, the third quadrant, negative real power and positive reactive power (overexcited generation) ; the fourth quadrant positive real and reactive power.

[20] CPUC Decision 13-10-040

the loads. PG&E is working on a pilot project[21] to (among other things) test the effectiveness of fast isolation of short circuits and closer control of voltage.

5.6 Industry Standards for Equipment and Practices

For many years industry standards have guided the design and manufacture of electrical equipment: the IEEE 37 series covers switches, circuit breakers and protective relays; IEEE series 57 covers power and instrument transformers. A new series, IEEE 1547, first issued in 2003 and currently under revision, covers "interconnecting distributed resources with electric power systems", essentially the same ground as Rule 21. In addition Underwriters Laboratories Standard 1741 covers the testing of inverters. When specifying equipment the distribution engineer can require compliance with these standards to obtain a minimum functionality.

These standards, while helpful, do not replace the engineer's judgment in regard to the specific needs for a given application. For instance, the design engineer, in specifying a piece of equipment, should refer to the applicable standard, but may need to list additional characteristics required for the specific application, e.g., operating temperature between -20 and +100°C, withstand voltage capability 150% of rated, maximum harmonic distortion of output voltage 10%, etc. Likewise, the maximum voltage deviations at the customer's meter listed in Tariff Rule 2 provide outer limits, but smart grids should do better, as PG&E proposes to do in its smart grid pilot project.

6 Conclusions

General conclusions to be drawn from this report are:

- The large quantity of generation scheduled to be connected to the grid at the distribution level poses problems to existing circuits which are designed for power flow from the substation to the loads, not from where the loads are located to the loads and to the substation. Many lines will have to be modified to accommodate this generation.
- Which lines need to be modified can be determined partially through standard screens: if the considered project passes the screens, the circuit does not need to be modified; if it does not pass, the circuit and the project must be simulated on a computer model to determine the effect of the project on the distribution system and what modifications are required to the distribution system and/or project to accommodate the project.
- Tariff Rule 21 defines the conditions under which distribution level generation and storage can be connected to the grid and the conditions under which it can be operated once connected to the grid.
- Connecting generation and storage to the distribution grid will cause a number of problems, all of which can be mitigated with the exception of generation connected to secondary networks.

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[21] CPUC Decision 13-03-032

- The governor's goal for the connection of 12,000 MW of localized generation at the distribution level by the year 2020 will be met.
- Smart grid technology, consisting of enhanced communications, smart inverters, power electronic devices, data from smart meters and distribution level storage, can facilitate the connection of renewable generation to the distribution grid and improve power system reliability and economics.

Taken together, a better understanding of the potential technical impacts of DER, combined with a dedication to resolving those issues in a cost-effective manner before they pose a threat to the reliability and safety of the utility system provides the framework for understanding the issues addressed in this paper. On a practical level, the California Public Utilities Commission, its regulated utilities, equipment vendors, and customers all have a stake in this effort, as it will guide the investment of billions of dollars in new technologies and for the modernization of the electric distribution system over the next several decades.

Glossary

Automatic Reclosing: Short circuits on overhead transmission and distribution lines are sometimes transient and self-correcting, such as those caused by the branch of a tree falling onto a line and momentarily spanning two or more conductors. To maintain the line energized after the short circuit has cleared itself, the circuit breaker at the substation may have the capability open the line and then after lengthening periods of time (the longest a minute or more) reclose four times. If the short circuit persists after the fourth reclosure, the circuit breaker opens and remains open until reset by the operator.

Capacitor or capacitor bank: Device for increasing voltage by means of producing VARs; can be applied at any voltage level from 230kV to 12kv to 120V. A capacitor bank is several capacitors used together. See VAR below.

Capacity: As used herein this term designates the rated capability of a device or system. For instance, an electrical conductor has a capacity rated in amperes; if current in excess of capacity is applied, the conductor will overheat. A generator has a capacity rating which represents its maximum output, but the actual output at any given time may be less than the capacity (a gentle breeze is blowing across the wind turbine). Likewise, an inverter has a capacity in volt-amperes, but its output may never reach the capacity because the connected generation is less.

Grid: As used herein, grid denotes the physical infrastructure that provides electricity. It comprises all the devices from generators, transformers, transmission and distribution lines and utility meters used to supply the consumer with electricity; synonymous with "network".

Inverter: Device for changing direct current to alternating current. When used with photoelectric cells, it converts the 100 to 600 volts of direct current generated by the cells connected in series to 120 or 240 of alternating current volts used in the home, or 480 volts for larger scale generation connected to distribution feeders through transformers.

Islanding: It is possible under certain conditions that a line section with generation connected to it is separated from the source at the substation, creating an electrical "island". In this case the generation will try to supply the load, but if it is less than the load or if it does not have voltage and frequency regulating capabilities, both these parameters may deviate from the normal, possibly damaging load equipment. On the other hand, if the generation is equal to or greater than the load and has frequency and voltage regulating capability, the island can survive as a microgrid, see below.

Line Drop Compensation: An algorithm used in conjunction with a voltage regulator to maintain the voltage at the end of the feeder as the load on the feeder increases. The amount of voltage increase per unit of load increase is based on a calculation of the voltage drop at the end of the feeder, which is a function of the impedance of the feeder and the current flowing through it.

Line Section: A portion of a distribution feeder between one end of the feeder and a recloser or disconnect switch or between any combination of reclosers and disconnect switches.

Localized Generation: Term used to categorize the 12,000MW called for in the governor's message. Presumably means generation close to the load as distinguished from generation in some far off desert.

Microgrid: A self-contained electrical network (generation sufficient to serve load and capable of regulating voltage and frequency) which may be connected to the utility for reliability and/or economic exchange of energy.

Net Energy Meter: A meter used where there is generation as well as load. Because in most cases the generation, such as PV, and the load vary over time, the generation may sometimes exceed the load, in which case the excess is fed into the grid. The net energy meter measures the difference between the generated energy and the load energy. When the load exceeds the generation, the customer is billed at the standard rate. When the generation exceeds the load over the course of a year, the value of the excess generation is paid to the customer at the rolling 12-month average of the CAISO spot market energy price, which is currently about 3.5 cents per been subject kWh and averages about 40% of the total retail energy charge.

Network: As used herein, network denotes the physical infrastructure that provides electricity. It comprises all the devices from generators, transformers, transmission and distribution lines and utility meters used to supply the consumer with electricity; synonymous with "grid".

Primary: The supply (usually high voltage) side of a transformer, as opposed to the secondary, load side of the transformer.

Recloser: An automatic switch which detects a short circuit on a line or section of a line, opens in response to the short circuit then recloses several times so as to maintain the operation of the line in the case of transient, self-clearing short circuits. If the short circuit persists after 3 or 4 reclosures, the recloser stays open.

SCADA: This acronym stands for Supervisory Control and Data Acquisition. It is a concept which dates from the seventies and consists of control and monitoring from a substation of field devices, such as switches and capacitor banks.

Secondary: The load (usually low voltage) side of a transformer, as opposed to the primary, supply side of the transformer.

Smart Grid: The electrical power system has been subject to continuous incremental improvements since its inception in the 1880s, though by 1940 the American home was much as it is today: a switch (or a pair of buttons) on the wall turned on and off the lights and receptacles above the floor provided 60Hz, 120 volt power for appliances. Since then the major changes have been nuclear power generation starting in the 50s, extra high voltage transmission and combustion turbine generation in the 60s, supervisory control and data acquisition (SCADA) and combined cycle generation in the 70s and microprocessor relaying and renewable generation in the 90s. This steady progression has continued into the 21st century and is now given the name "Smart Grid" (smart being a popular adjective to denote new and enhanced capabilities, such as "Smart Phone", "Smart Meter"). It includes synchrophasers for accurate state estimation, enabling the grid to be operated closer to its limit, automated distribution lines for quick isolation of short circuits and close voltage control, and smart meters with home area networks (HAN) which enable consumer control over power usage. Smart grid is driven by a pair of technological advances, namely enhanced communications and controls, which make possible synchrophasers, automated distribution and HAN.

Storage: As used herein this term refers to the storage of electricity, either as electrical energy or as mechanical or potential energy, which can be readily, in fact almost instantaneously, converted into electricity. Large scale storage is in the form of water behind hydroelectric dams, hydroelectric pumped storage, experimental compressed air storage and hot salt; smaller scale storage, which could be connected to distribution lines, is in the form of batteries, energized electrical coils and capacitors, flywheels and maybe hot salt. As stated in Section 5.3, storage in California was given a hefty boost in CPUC Decision 3-10-040, which provides a target for the installation of 1325 MW of storage by the year 2024, 625 MW of which is to be at distribution and utilization level voltage.

Tariff Rule 21

The CPUC establishes rules for the utilities it regulates by means of tariffs and general orders. Tariff Rule 21 establishes the conditions under which prospective merchant generators may connect to utility distribution lines. See Section 2. CPUC Rulemaking Proceeding 11-09-011 for updating the rule is presently underway.

Transfer Trip: The opening of a circuit breaker or recloser from a remote location by means of a signal over a communication channel such as microwave, power line carrier, radio, or, most likely for devices at the distribution level, a leased telephone line.

VAR: This acronym stands for Volt Ampere Reactive, a somewhat abstruse electrical concept involved in the control of voltage. Induction motors, such as used in refrigerator compressors and furnace blowers, transformers, fluorescent light ballasts and other electrical devices absorb VARs; if insufficient VARs are available, the voltage goes down. Synchronous generators, capacitors, smart inverters and electronic power devices produce VARs.

Voltage regulator: A device which senses the voltage on its load side and automatically increases or decreases that voltage to maintain it at a set value.