Power Electronics Intelligence at the Network Edge (PINE)

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***Abstract*—This paper puts forth a vision for scalable distribution grid integration of energy resources such as rooftop photovoltaics (PVs) and electric vehicles (EVs). The output of these resources vary temporally in an unpredicted manner. Therefore, they bring substantial challenges to utilities vis-a-vis massive deployment of such resources. By leveraging the fact that most of the distributed energy resources are interfaced with power electronics converters, we propose a fully decentralized architecture for achieving the main objectives of utility companies, namely, (1) end user voltage regulation; and (2) delivery system loss minimization. The proposed framework provides a bottom-up approach to integrating many such distributed resources without substantial capital investment. This framework, termed as Power Electronics Intelligence at the Network Edge (PINE), provides a possible pathway toward supporting a very high level of PV and EV penetration in future distribution systems. The operational benefits to end users as well as the utilities are elaborated with the IEEE 123-node Test Feeder.**

I. Introduction

Traditionally, the operation of distribution utilities has three major objectives. The first objective is to improve reliability. Whenever there is a fault, the switches are operated in such a way that the fault is isolated and the affected area is restored quickly. The second objective is to minimize the delivery losses. The delivery losses are not paid by customers but by the utility. For the given amount of real power delivery, it is desirable to minimize the delivery losses to maximize the profit and social welfare. The third goal is to deliver high quality of electricity, especially voltage magnitude [1] and power factor. The voltage magnitude at all nodes of the distribution system should be within a certain range, no matter the time or the loading of the system.

These objectives are typically achieved via distribution management systems (DMS). One of the functions of DMS is fault location, isolation and service restoration (FLISR). FLISR controls the opening and closing of circuit breakers to increase reliability. The other function of DMS is volt var control (VVC). VVC controls voltage control devices, such as load tap changers, voltage regulators and capacitor banks to minimize delivery losses while maintaining a good voltage profile along feeders.

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Traditionally VVC is regarded as operating satisfactorily. However, with high penetration of PVs varying their output intertemporally in an unpredicted manner, maintaining a good voltage profile becomes challenging due to the low spatial and temporal resolution of voltage control devices. Actually, the challenges to maintain a good voltage profiles limit how much PV can be connected to distribution systems [2]. Distribution systems do not have many voltage control devices. For example, in the IEEE 123-node Test Feeder, there are one load tap changer, three voltage regulators and four capacitor banks. Using just these eight voltage control devices to maintain the voltage magnitude of these 123 nodes is difficult. In addition, because voltage control devices are mechanical devices, the operating time is long and there is a limit on how many times a day the devices can operate. These voltage control devices would not be sufficient to respond to the fast fluctuation of PV generation and end-users' consumption [3] . Fig. 1 shows the voltage profile of the IEEE 123-node Test Feeder with 100% PV penetration and with normal solar radiance fluctuation pattern. Clearly the voltage profile is not satisfactory.

On the other hand, most of the distributed energy resources are interfaced with power electronics converters. We will show that such power electronics converters offer a disruptive opportunity for a complete bottom-up approach to simultaneously maintain end-users' quality of electricity and achieve utility business objectives. In this work, we propose a new framework, called PINE technology. We put forth a power electronics-enabled technology and control framework that is

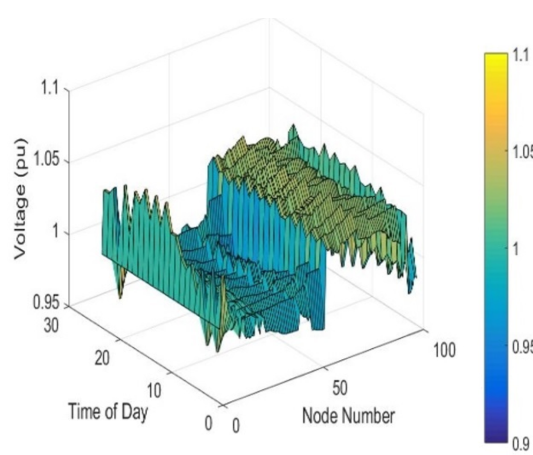

Fig. 1. Voltage profile with traditional voltage control scheme.

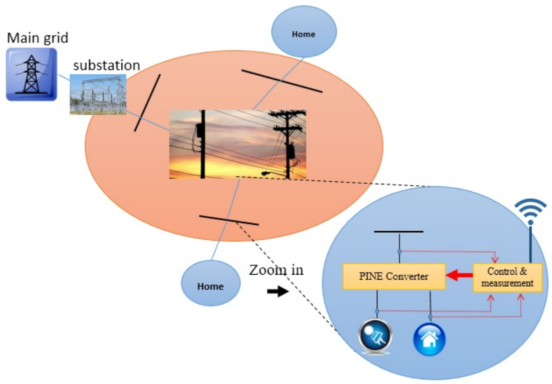

Fig. 2. Power electronic intelligence at the very edge of the network.

entirely distributed down to the end-user level i.e., the network edge of the system. As shown in Fig. 2, the distribution system need not to be very sophisticated and in fact can be considerably loosened and simplified compared to what it is now, by embedding all the intelligence at the very edge of the distribution system. The power delivered to each end-user's load is processed via an intelligent power electronic converter, called PINE converter. This architecture makes plug and play end-user solar integration very simple, as well as utilities' voltage/var optimization. It therefore caters to the evolving needs of both the end-user as well as the distribution system.

There are several approaches to optimizing distribution systems while integrating PV from end-users. Unified power quality conditioner [4] is designed to compensate for voltage flicker, reactive power and harmonic compensation with series and shunt power switching converters at the distribution system level. This technology is targeted for feeder level control and is not at the end-user's level.

Reference [5] proposed dynamic distribution line shunt capacitance control. It employs a shunt connected power electronic converter to regulate voltages by injecting reactive power on-demand at the grid edge. Real-time control features can be implemented by the distribution company to regulate feeder level voltage profile.

Electric springs introduced by Hui *et al* [6] proposed to regulate end-users' voltage via a combination of reactive power injection and damping of voltage disturbances. Implementation of this technology requires the separation of non-critical loads (water heater/refrigerator) from critical loads (TV/lighting) that require well-regulated voltage in a household. Such a requirement cannot be always implemented and the design of the system depends on the rating of the non-critical/critical-load ratio.

Carvalho *et al* [7] proposed a distributed algorithm to determine the reactive power injection such that the voltage problems caused by active power injection can be eliminated. This method is based on sensitivity of active power and reactive power injection on the voltage magnitude. Based on the amount of active power and the sensitivity information, the reactive power injection can be determined. While no optimization is needed, the voltage can be maintained at the nominal range. A similar method is used in [8].

Turitsyn *et al* [9] proposed a droop control based on the reactive power and voltage sensitivity information. Only a local voltage measurement is needed. Several ways to adjust the reactive power injection from PV inverters are proposed. One is based on local voltage measurements while another is based on local voltage measurements and branch flows. Also, in the optimization problem, the relative weights of loss minimization vs. voltage deviation are determined by a heuristic rule. This heuristic rule considers the system status. If the system has high voltage deviation, the weight of voltage deviation in the optimization problem is increased. A similar concept is used in [3].

Robbins *et al* [10] proposed a two-stage distributed method to determine the reactive power injection. The sensitivity of voltage magnitude to reactive power injection is first determined. For a given amount of the desired voltage magnitude change, the required amount of reactive power injection is calculated. At the first stage, this required reactive power injection is delivered by the inverters at the same bus. If these inverters do not have enough reactive power capability, then, in the second stage, the inverters at neighboring buses are requested to provide the reactive power.

DallAnese *et al* [11] formulated an optimal power flow problem where the active and reactive power of inverters are the decision variables. The objectives of the optimization are to reduce delivery losses, the active power curtailment and the voltage deviation from the reference value. This optimization problem is converted into semidefinite program so that it can be solved efficiently.

Zhang *et al* [12] determined the optimal reactive power dispatch for the inverters to minimize the delivery loss and voltage deviation. A sufficient condition is found such that this optimization can be solved by semidefinite program. Also, a distributed algorithm is proposed to solve this optimization problem even with communication failure.

A time-scale separation concept is used in [13] and [14], with voltage regulators belonging to the slower timer-scale and inverters belonging to the faster time-scale. In [13], the optimal tap position of the voltage regulator is determined by using a rank relaxed semidefinite program. The objective of the optimization is to minimize the delivery loss and voltage deviation. To solve this optimization in a distributed way, alternating direction method of multipliers (ADMM) is used. In [14], the objective is to minimize the voltage deviation by using the reactive power of inverters. The optimization is converted into a quadratic program and ADMM is used to solve it in a distributed way.

The key differences between our proposed technology and the other technologies mentioned above are: (a) Our proposed technology is deployed down at the very edge of the network, i.e., behind the meter; (b) The proposed technology not only keeps the end-users' voltage magnitude constant and at the desired level, but also maintains unity power factor at the grid interface level, which minimize the delivery losses; (c) The proposed technology is capable of injecting reactive power at the distribution edge on demand; and (d) The proposed technology is based on distributed decision-making without any need for coordination.

The rest of the paper is organized as follows. Section II describes the circuit topology and features of PINE converters. Section III discusses the benefits of PINE technology from the perspective of customer, utility and society. Section IV analyzes the reduction of power delivery losses made possible by PINE technology. Section V demonstrates the performance of PINE technology using numerical simulations. Section VI concludes the paper and lists several future lines of inquiry.

II. The PINE converter

The PINE converter prototype is sketched in Fig. 3 [15]–[17]. A detailed circuit topology consisting of an active rectifier stage, dc-link and inverter/output-filter stage to power the 120/240V split phase loads in a typical home is shown in Fig. 4.

The front end of the PINE converter is connected to the distribution system. This circuit is designed to be able to operate over a wide range of input voltages, such as 0.7 pu to 1.3 pu. This is one of the key factors that makes PINE technology unique. In addition, this circuit allows bidirectional power flow and independent real and reactive power control. For example, the reactive power can be controlled such that the PINE converter has unity input power factor. Moreover, this circuit can be controlled such that the input current drawn from the distribution system is purely sinusoidal. No harmonics exist in the current. With unity power factor and minimized harmonics current, the power delivery losses, overheating and K-rating of transformers in the feeder and the distribution system are greatly reduced.

The output PWM converter generates split phase ac output (120/240V, 60Hz) suitable for home loads. The output L-C filter is designed such that sinusoidal output voltages are maintained under a variety of linear/non-linear/unbalanced load conditions. Moreover, the digital closed-loop control of the entire system guarantees regulated output voltage at the output terminals under a wide variety of input utility distribution voltage conditions.

The middle stage of the PINE converter, the dc-link, can function as the energy hub. Installed roof-top solar and/or battery energy storage devices are interfaced at the dc-link via a unique power sharing converter followed by a dc-dc boost converter (Fig. 4). Independent electronic control of the roof-top solar system to extract maximum power via maximum power point tracking (MPPT) [17]–[19]. Simultaneous adjustment of charge rates of the battery energy storage is possible

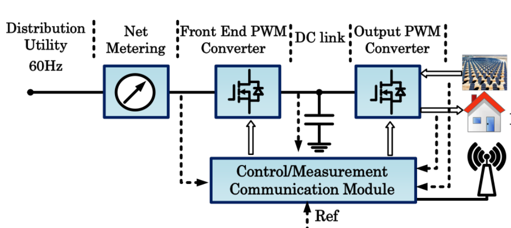

Fig. 3. Proposed Power Electronic Intelligence at Network Edge (PINE); a technology for enabling massive, even 100%, solar penetration.

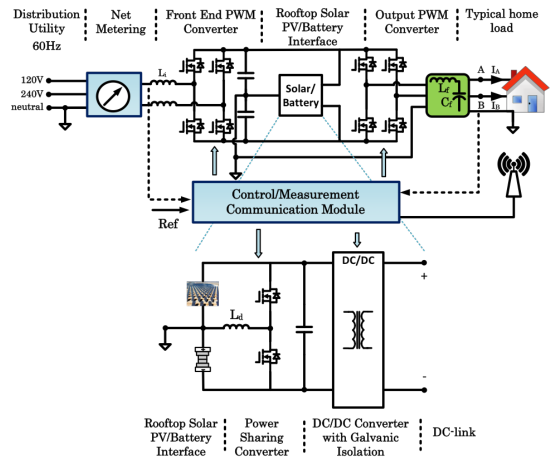

Fig. 4. Complete circuit topology of the Power Electronic Intelligence at Network Edge (PINE) converter.

via closed-loop control of the high frequency PWM converter. In addition, the proposed approach allows for providing a ground reference to the solar PV and battery energy storage system for safety.

The proposed PINE converter has several other important features. First, when solar generation exceeds the local load demand, the PINE converter can inject power into the distribution utility at unity power factor. Second, the PINE converter can enable power exchange among peer end-users by independent control of real and reactive power injection. Third, the measurement module of the PINE converter can be designed such that the net energy transacted between neighbors, or between homes and the utility can be measured. This essentially replaces the functionality and therefore the need for a separate smart meter.

In order to achieve high reliability, the PINE converter is designed so that it can operate under fault conditions [20], [21]. Fig. 5 shows the block diagram of the reconfigurable PINE converter with fast acting static switches (SS) to provide uninterruptable power to the home under fault conditions. There are totally four configurations. Under normal conditions, SS_1 is open, while SS_2 and SS_3 are closed. The home is powered via the PINE converter. When PINE converter input module fails, by opening SS_2, and closing SS_1 and SS_3, the utility and the installed solar PV/battery system can supply the home. When PINE converter output module fails, by opening SS_3, and closing SS_1 and SS_2, the power from the solar PV/battery system can be channeled to the utility, while the home is supplied by the utility. When both input module and output module fail, by closing SS_1, and opening SS_2 and SS_3, the PINE is completely passed and the power is delivered to the home directly from the utility.

III. Benefits of PINE

The benefits of PINE can be described from several perspectives: the end-user, the utility perspective, and from the viewpoint of social welfare.

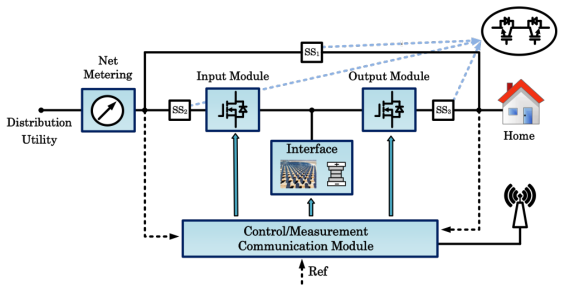

Fig. 5. Reconfigurable PINE with fast acting static switches (SS) to provide uninterruptable power to homes under fault conditions. The topology also allows for channeling solar PV/battery power to the utility and/or to power the home.

A. *Benefits for end-users*

PINE can help end-users reduce their utility bill. With PINE, end-users can take full advantage of installed PV capacity. No PV curtailment is necessary anymore. The consequent better utilization of PV generation reduces the amount of electricity purchased from the utility, as well as and the peak demand. This in turn reduces the energy charge and the power charge on the electricity bill. Furthermore, because of the unity power factor resulting from the PINE converter, the end-users do not need to pay power factor penalties.

The PINE converter can also serve as an energy hub for the end-users. Different components, such as electric vehicles, PV panels, energy storage, etc., can be interfaced via the PINE converter. Direct power exchange between these components is possible. By using an intelligent power management system, end-users can perform electricity arbitrage, further increasing economic benefits for customers.

The PINE converter makes each individual end-user function as a microgrid. Because of the energy storage, on-site PV generation, and intelligent control of PINE converter, end-users can continue to have electricity even when the distribution system is down. They can even disconnect themselves from the utility when necessary. The end-users thereby can enjoy higher reliability of electricity.

B. *Benefits for the utility*

PINE can reduce the operating cost of the utility company. Delivery losses can be greatly reduced due to the reactive power injection capability of the PINE converter, the elimination of harmonics and voltage relaxation. The detailed calculation is shown in Sec V. Moreover, PINE can increase the effectiveness of voltage conservation reduction (VCR) to reduce the loading of the distribution system. Without PINE, due to the low spatial and temporal resolution of voltage control devices, the voltage profiles cannot be reduced in an optimal way. The voltage at the upstream needs be high enough so that the voltage at the downstream can be at the minimum required voltage magnitude. Therefore, some parts of the feeder have higher voltage while others have a lower voltage. Uniformly low voltage along the feeder is not possible. However, with the much higher spatial and temporal resolution made possible by PINE, the voltage profile can be controlled in such a way that the voltage at all buses can be reduced to the minimum required voltage, maximizing the impact of VCR.

PINE will allow the deferment of the need for investments for upgrades, such as line upgrades and voltage control device upgrades. This is because PINE relaxes the voltage requirement. Without PINE, as the load grows, the system needs to be upgraded to serve the increased load. However, with PINE, the distribution system does not need to upgrade the line to reduce voltage drop when faced with increased loads. The load reach of the distribution system with the same infrastructure is increased. Moreover, voltage relaxation also allows the utility to defer the investment needed for of voltage control devices. No complicated voltage control scheme is needed anymore. The utility can take advantage of the PINE technology to control voltage, whenever it wants to control voltage.

PINE will also defer the investment requirements for transformers. PINE eliminate harmonics from the system, which decreases the K-rating of transformers. For the same transformer, the amount of the load they can serve is increased without any additional investment .

PINE also enables advanced applications of distribution system. Because PINE has built-in sensors and communication capability, the state of the distribution system can be observed down to the customer level. With the higher sampling rate of PINE measurements, the load information of the customer and the loading information of the feeder can be measured more accurately. The load forecast of the load can be further improved with the high amount of load data gathered. Notice that the communication requirement is not very high. A two-second refresh rate is enough for distribution system operation. This communication can be done via Ethernet, further reducing the cost of system communication. By using signal processing and big data techniques, the loading in each phase, the distribution system topology, and the status of each lateral, can be determined or estimated. With this information, advanced application of the distribution system can be achieved.

As an example, fault isolation and service restoration (FISR) can be further improved due to the detailed information on the feeder. The location of a fault can be identified more accurately and quicker. Another example is that by controlling the real and reactive power injections, the three-phase unbalanced distribution system can be operated in a much more phase-balanced way, further decreasing power delivery loss. Without PINE, to make unbalanced distribution system more balanced, it is necessary to mechanically switch the load from one phase to another phase. The speed of such mechanical switching is slow and there is a limit on how many times such mechanical switches can be operated. With PINE, switching is much faster, and there is no limit on the control of real and reactive power to make the system more balanced.

C. *Benefits for society*

The PINE technology can increase social welfare. With independent control of real and reactive power in each PINE converter, and with much simplified and improved utility operation and control, it is possible to achieve peer-to-peer energy transactions among neighbors (in the same secondary feeder) or even among neighbors in different primary feeder locations. With such peer-to-peer energy transactions, end-users can sell their surplus energy either to the utility or directly to other end-users, making the best use of their distributedly generated electricity.

IV. Cost analysis

The major concern with PINE technology is that the cost of the PINE converter is high, because the rating of PINE converter needs to be the same as the peak load of end-users. However, there are two reasons why PINE technology is not that costly. First, suppose end-users already have PV inverters that can serve their peak loads. In other words, the PV penetration is 100% for these end-users. The installed PV inverters are rated at the end-users' peak load. These PV inverters can be utilized to function as the output PWM converter shown in Fig. 3. This can be easily done by changing the controllers of these PV inverters. To avail of the benefits of PINE, end-users only need to purchase the other half of the PINE converter: the front end PWM converter shown in Fig. 3. Fig. 6 and Fig. 7 show the necessary changes and purchases needed to complete the PINE converter installation.

In addition, the cost of PINE converter is continuously getting lower. In the proposed PINE technology, every end-user has a PINE converter. The number of PINE converters is large. Because of economy of scale, even though the rating of a PINE converter is the full load of end-user, the cost is decreasing. Moreover, the cost of a PINE converter inverter is not the major part of the overall PV installation. According to [22], the cost per watt of PV inverters is $0.29 per watt. This cost of an inverter is only 10% of the total cost of a PV system and about half the cost of installed PV panels, as shown in Fig 8. Therefore, to install the other part of the PINE converter, the extra cost is only 10% of the cost of the original PV system.

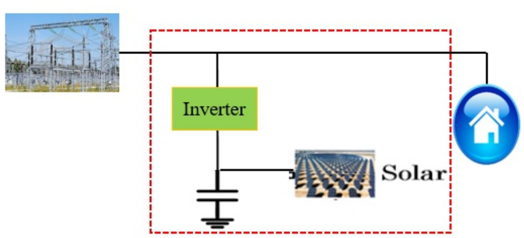

Fig. 6. Existing components as present today for end-users with PV generation.

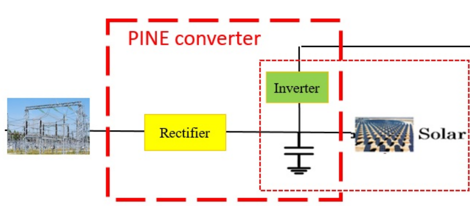

Fig. 7. Required changes to deploy PINE converters.

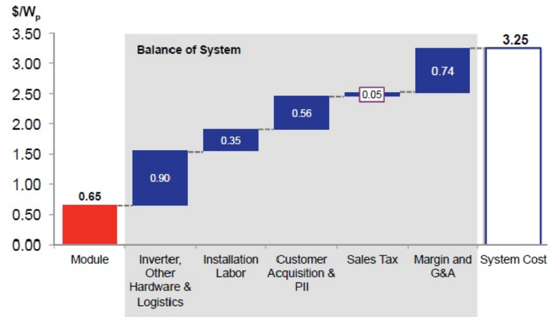

Fig. 8. Estimated capital cost of PINE deployment for a residential PV system [22].

V. Minimization of power delivery losses

A. Minimization of loss by reactive power dispatch

To minimize power delivery loss, the reactive power injection capability of PINE converters can be used. Because PINE converters are located at the very edge of the network, the number of control variables is very large. It is costly to have communication links between the control center and each PINE converter. We will use a model-free scheme with a low communication requirement.

The first and simplest way is to locally control the PINE converters such that all PINE converters have unity power factor. For a given amount of real power demand, with zero reactive power demand, the current flow of the branches to which the PINE converters are connected is minimum. This can be shown by using a simple two bus example. Given the source voltage $\vec{V}_1$ and real power load demand P, the current flowing on the branch can be found by solving the following equations:

$$\vec{V}_2 = \vec{V}_2 I - (R + jX)\vec{I} \tag{1}$$

$$\vec{V}_2 \vec{I}^* = P + jQ. \tag{2}$$

The magnitude of $\vec{I}$ can be found as

$$I^2 = \frac{-B \pm \sqrt{B^2 - 4(R^2 + X^2)(P^2 + Q^2)}}{2(R^2 + X^2)}. \tag{3}$$

where $B := 2PR + 2QX - V_1^2$. It can be shown that when $Q = 0$, $\mathrm{d}(I^2)/\mathrm{d}Q = 0$. Therefore, the power delivery loss for these branches is minimized when there is no reactive power load.

Note that this scheme does not result in minimized total delivery losses, because other branches, especially the branches on the primary feeder, do not have minimized current flow. The upper branch current is a vector sum of the lower branch currents. For example, suppose branch 1 is an upper branch while branch 2 and 3 are lower branches. The relationship between the current phasors of these branches is $\vec{I}_1 = \vec{I}_2 + \vec{I}_3$. Even though the current magnitudes of each lower branch current, $|I_2|$ and $|I_3|$, are minimized, the resulting current magnitude $|I_1|$ is not necessarily minimum because of the impact of the angles θ_2 and θ_3.

Second way is to determine the required reactive power injection off-line. It can be determined via a centralized optimization problem with given system parameters and loading information. For different times of the day, using different inputs to the optimization problem, the resulting reactive power injection can be calculated. The results can be stored in the memory of controllers. Based on the time of the day, the reactive power injection can be determined by table look-up. Even though this may not lead to the optimal reactive power dispatch, it can yield a satisfactory result. Moreover, with this scheme, no complicated communication or real-time computation are needed. We can also take advantage of a "scenario based" stochastic optimization technique [23] to achieve minimum expected delivery loss.

There are two optimization problems to be solved. In the case where all customers have a PINE converter, the voltage can vary in a wide range. In fact the voltage constraints traditionally imposed on the distribution system can be eliminated. The corresponding optimization problem is

$$\begin{aligned}
&\underset{Q_k}{\text{Min}} \sum_{i,k} r_{i,k}\frac{|S_{ik}|^2}{|V_i|^2}\\
&\text{subject to}\\
&\quad V_0 = V^s\\
&\quad |V_k|^2 = |V_i|^2 - 2(r_{ik}P_{ik} + x_{ik}Q_{ik}) + |z_{ik}|^2\frac{|S_{ik}|^2}{|V_i|^2},\\
&\quad P_{ik} = \sum_{j\in H_k} P_{kj} + P_k^d + r_{ik}\frac{|S_{ik}|^2}{|V_i|^2}, k\in N\\
&\quad Q_{ik} = \sum_{j\in H_k} Q_{kj} + x_{ik}\frac{|S_{ik}|^2}{|V_i|^2} + Q_k, k\in N.
\end{aligned} \tag{4}$$

where r_{ij} and x_{ij} are the line resistance and reactance, $z_{ij} = r_{ij} + jx_{ij}$, S_{ij}, P_{ij} and Q_{ij} are the complex, real and reactive power flows of branch ij, V_k, P_k^d and Q_k are voltage phasor, real power load and reactive power injection at bus k, N is the set of buses, and H_k is the set of buses connected to bus k.

However, to transition to 100% PINE deployment from 0% PINE deployment, we need to consider the case where some customers do not have PINE, i.e., the partial PINE deployment scenario. For those customers who have not deployed a PINE converter, the voltage magnitude should be maintained within the required range. The voltage regulation can be achieved by dispatching reactive power injection from the existing PINE converters and using traditional voltage control devices, such as LTC, voltage regulators and capacitor banks. The reactive power dispatch problem can be formulated as the following optimization problem:

$$\begin{aligned}
&\underset{\substack{Q_k\\ k\in N_{\text{PINE}}}}{\text{Min}} \sum_{i,k} r_{i,k}\frac{|S_{ik}|^2}{|V_i|^2}\\
&\text{subject to}\\
&\quad V_0 = V^s\\
&\quad |V_k|^2 = |V_i|^2 - 2(r_{ik}P_{ik} + x_{ik}Q_{ik}) + |z_{ik}|^2\frac{|S_{ik}|^2}{|V_i|^2},\\
&\quad P_{ik} = \sum_{j\in H_k} P_{kj} + P_k^d + r_{ik}\frac{|S_{ik}|^2}{|V_i|^2}, k\in N\\
&\quad Q_{ik} = \sum_{j\in H_k} Q_{kj} + Q_k^d + x_{ik}\frac{|S_{ik}|^2}{|V_i|^2}, k\in N_{Non-PINE}\\
&\quad Q_{ik} = \sum_{j\in H_k} Q_{kj} + x_{ik}\frac{|S_{ik}|^2}{|V_i|^2} + Q_k, k\in N_{PINE}\\
&\quad 0.95 \le V_k \le 1.05, k\in N_{Non-PINE}
\end{aligned} \tag{5}$$

where N_{PINE} and $N_{\text{Non-PINE}}$ are the set of buses with PINE and without PINE converters, respectively.

A third potential way in the future may be to directly employ a distributed optimization to solve the optimization problem. This is contingent on the ability to obtain the appropriate sensitivity information in a distributed manner.

B. Minimization of loss by harmonic elimination

PINE can reduce the power delivery loss significantly by eliminating undesirable harmonic current. The input current total harmonic distortion (THD) of a typical North American home is 50% to 80% [24]. In view of this, the I^2R line loss in a distribution system is in the range of 6-10% [25]. If the current magnitude in fundamental frequency is I, and the 3rd and 5th harmonic current magnitude I_3 and I_5, then the I^2R line losses is $(I^2 + I_3^2 + I_5^2)R$, while the line losses without harmonics would be I^2R. In a typical system, $I_3 = 0.7I$ and $I_5 = 0.5I$. Since the PINE converter draws harmonic free current (i.e., 0% THD), the loss is reduced from $1.74I^2R$ to I^2R, an approximately 40% reduction in power deliver loss.

In addition to reducing power delivery loss, the PINE technology also eliminates overheating of the capacitor banks and distribution transformers caused by harmonic currents. The net reduction in RMS current drawn by a typical home due to the PINE converter will also result in increased distribution system capacity to supply additional homes on the same feeder.

C. Minimization of loss by voltage relaxation

With PINE, bus voltages in the system can be allowed to fluctuate a larger range. This relaxed voltage control enables easier distribution system operation and allows higher penetration of PV. In addition, by increasing voltage magnitude, the line losses can be reduced further. Suppose that in the base case, the voltage is 1 pu and the current is 1 pu. If the voltage is increased to 1.3 pu for the same load, then the current is changed from 1 pu to 1/1.3 = 0.76 pu. Therefore, the loss of the system is reduced from $1^2R = R$ to $0.76^2R = 0.58R$.

Fig. 9 shows the back-of-envelope calculation of loss reduction. Suppose that the loss in the base case is 100%. By using traditional VVC, the loss can be reduced by 6%. However, with PINE, the loss can be reduced further. Assume that PINE converter efficiency is 95%, the current harmonic content are $I_3 = 0.7I$ and $I_5 = 0.5I$, and the voltage magnitude is relaxed such that every node has 1.3 pu voltage magnitude. The loss can be reduced from 100% to 51%.

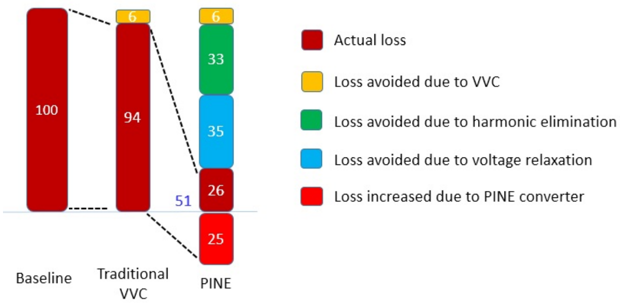

Fig. 9. Comparison of line losses under minimization in different schemes.

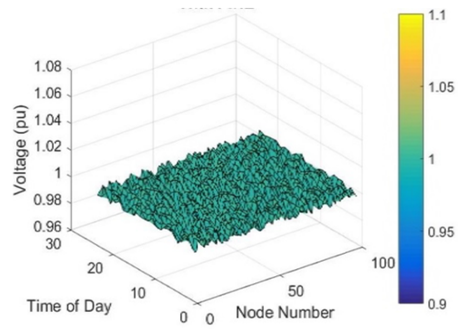

Fig. 11. High quality voltage at customers' side under PINE.

TABLE I
POWER DELIVERY LOSSES UNDER DIFFERENT LOADING FACTOR WITHOUT AND WITH PINE

Loading factor	Without PINE	With PINE
1	95.3 kW (2.7%)	92.4 kW (2.61%)
1.5	225.6 kW (4.35%)	193.3 kW (3.69%)
2	414.3 kW (6.13%)	344.1 kW (4.93%)

VI. Numerical Examples

We use the IEEE 123-node Test Feeder shown in Fig.10 as the example system. We analyze the extreme case where the PV penetration level is 100%. The PV generation is assumed to be varying through the day. Even though the voltage control devices are used to maintain the voltage profile, due to the low temporal and spatial resolution of the voltage control devices, the voltage profile of the system is not satisfactory. Fig. 1 shows the voltage profile in the base case. The voltage at certain nodes is outside the required range. However, with PINE technology, even though the voltage at the input side of the PINE converter fluctuates, the output of the PINE converter provides customers a perfect voltage magnitude, as shown in Fig. 11.

In addition to having a better voltage profile, the loss in the distribution system is minimized. By using simple local control, each PINE converter has unity power factor. The resulting power delivery loss is reduced. Table I shows the loss reduction due to PINE for different loading levels of the system.

An example of a 5 kVA residential load was designed and simulated in PSIM, which was connected to the distribution utility grid using the proposed topology as the interface, as shown in Fig. 4. The main objective was to demonstrate how the PINE topology acts to maintain a constant output voltage in the residential load regardless of the voltage variations in the grid, as shown in Fig. 12. Fig. 13 depicts how the output voltage is maintained regardless of non-linear and/or unbalanced conditions of the load. Fig. 14 shows how the PINE topology draws sinusoidal input current from the utility grid. As a result, it reduces the line losses and the overheating of the capacitor banks and the distribution transformers.

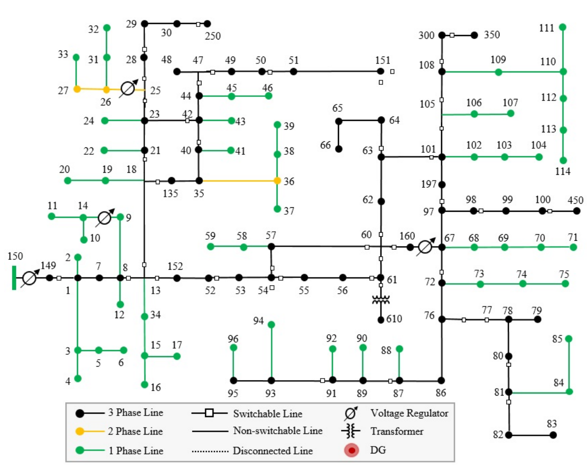

Fig. 10. The IEEE 123-node Test Feeder.

VII. Conclusions and Future Work

PINE technology endows the nodes at the very edge of distribution system with intelligence, and allows them to engage in transactions such as inter-node direct power transfer, eliminates the need for smart meters, while increasing the efficiency of the distribution system by reducing the harmonic current, allowing higher voltage operation, relaxing the need for tight control of voltage, and reduced wear and tear on voltage control devices. Customers can even increase their PV installation to up to 100%, obtain high quality of electricity, and reduce their utility bill, while utilities can defer their investments, reduce power delivery losses and employ advanced grid application. PINE is potentially a fundamental component of future distribution systems. With PINE, a new paradigm of distribution system is possible.

To enhance PINE technology, some potential future directions of work are the following. It is of interest to examine the full extent to which a decentralized and model free reactive power dispatch is feasible. Currently, a centralized and model-based VVC is implemented. It would be useful to investigate methods that do not entail a model of the distribution system, and which are scalable to larger numbers of nodes. In addition, under partial PINE deployment, for customers without a PINE converter, the voltage magnitude at these customers needs to be regulated to within a specified range. It would be desirable to address how to achieve voltage regulation by controlling existing PINE converters in conjunction with other traditional voltage control devices.

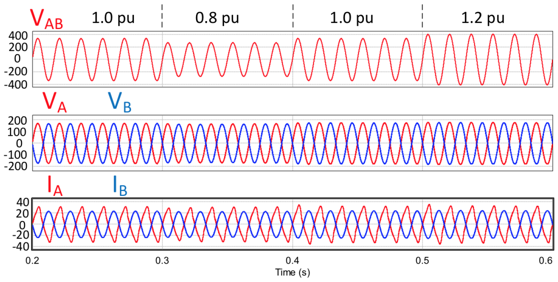

Fig. 12. Simulation results for PINE when the input voltage changes a wide range (0.8 - 1.2 pu). The topology maintains a constant output voltage for every condition.

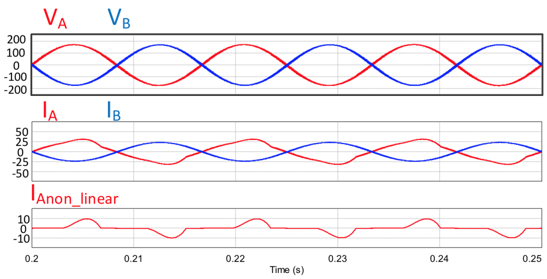

Fig. 13. Simulation results for PINE for unbalanced load. A non-linear load is added to Phase A to show how the output voltage is unaffected.

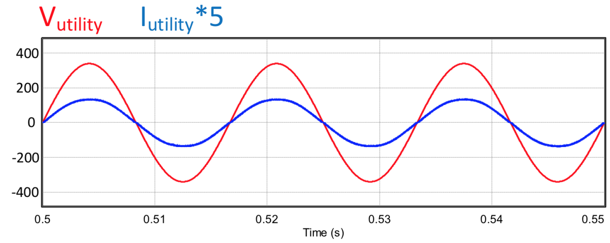

Fig. 14. Simulation results for PINE depicting when the load is being supplied by the grid. It can be seen that the current THD is less than 3%.

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