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Dynamic Impact of Power Electronics Converters at the Grid Edge

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Abstract—Future distribution systems will be penetrated with massive power electronics (PE) devices. This paper classifies the dynamics of future PE-rich distribution systems into four categories: dynamics introduced by network, dynamics introduced by PE interfaces, dynamics introduced by control of PE interfaces and dynamics introduced by load, generation and battery energy storage system. The purpose of such a categorization is to facilitate the analysis and control design of future distribution grids as well as to investigate the cause of instabilities. As a grid-edge technology, a PE interface named Power Electronics Intelligence at the Network Edge (PINE) is used in numerical studies to demonstrate these four categories of dynamics and show how each of them influences the system dynamics and stability.

Keywords—Grid edge, dynamics, instability, power electronics, renewable energy, solar PV.

I. INTRODUCTION

In the first two decades of 21st century, power grids all over the world have been experiencing a significant change in both generation and load. The traditional centralized power generation is being gradually replaced by distributed generations, i.e. renewable energy resources [1]. In 2016, renewables accounted for 23.8% of world's electricity generation, ranked second after coal (39.2%) [2]. In 2018, two-thirds of the world's new generation capacity came from renewables, where solar and wind as two major resources leading such a change gained an additional capacity of 140GW [3]. It is expected that through at least 2020, more than half of total U.S. photovoltaic (PV) capacity will be from distributed PV connected to distribution systems [4].

When it comes to the load, transportation electrification and increasing penetration of power electronics (PE) interfaces will also significantly change the load behaviors. It is expected that 57% of all passenger vehicles will be electric by 2040 [5]. In addition, as a production-level PE interface for connecting motor loads to the grid, variable-frequency drive (VFD) has a global market size of $18.32 billion in 2016 which has been and will be growing [6].

Most of the above changes involve an addition of PE interfaces, e.g. converters used in wind and solar PV generators, electric vehicle charging stations and motor load interface VFDs. Thus, PE-rich distribution grids will be inevitable in future for integrating massive renewable energy resources to achieve a low carbon energy system. However, the presence of PE interfaces will not only change the dynamical behaviors of the existing devices in desired ways according to their designed control strategies, but also affect the dynamics of the existing dynamic elements in a complicated way as well as bring in their own dynamics, which should be well-studied in the design stage. Along with the potential undesired characteristics with the newly added devices, e.g. variabilities of PV power output and harmonics of VFD, the impact on the distribution system is considerable and raises concerns, such as voltage regulation, reverse power flow and protection coordination, for utility companies, potentially limiting the allowable penetration of such devices [7].

A comprehensive investigation always calls for detailed studies of all elements whose dynamics cover a wide range of time scales, under the background of the fact that interactions among these elements may be significantly altered by the growing PE interfaces. A better understanding of dynamics involved in PE-rich distribution grids is being increasingly needed for proper designs of system planning, operation and control [8], further providing a guarantee of reliable integration of renewables and boosting the realization of low carbon energy systems.

This paper aims at providing a taxonomy of the dynamics involved in future PE-rich distribution grids. The rest of the paper is structured as follows: Section II presents a typical future PE-rich distribution system. Section III introduces the four categories of dynamics involved in future distribution grids. Section IV presents an example to show these four categories of dynamics and explain how they impact the system stability. Conclusions are drawn in Section V.

II. A TYPICAL FUTURE PE-RICH DISTRIBUTION SYSTEM

Distribution system is the last stage to deliver electricity to end users. The traditional infrastructure usually consists of switches, transformers, overhead lines and/or underground cables, shunt capacitors and loads. Future distribution systems will be additionally penetrated with massive distributed energy resources, plug-in electric vehicles (EVs) and battery energy storage systems (BESS). These new elements are usually connected to the distribution systems via power electronics interfaces, e.g. PV inverter, PE converters in variable-speed wind turbines and EV charging stations. Controls are properly designed for these PE interfaces to achieve desired functionalities, such as maximum power point tracking for PV and fast charging for

EV charging station. Due to the fast-acting nature of PE devices, dynamical behaviors of future distribution systems could be fundamentally different from traditional ones. This section briefly introduces different types of elements in traditional distribution systems, as well as the discussion on where these new PE devices will be installed in future, as shown in Fig. 1.

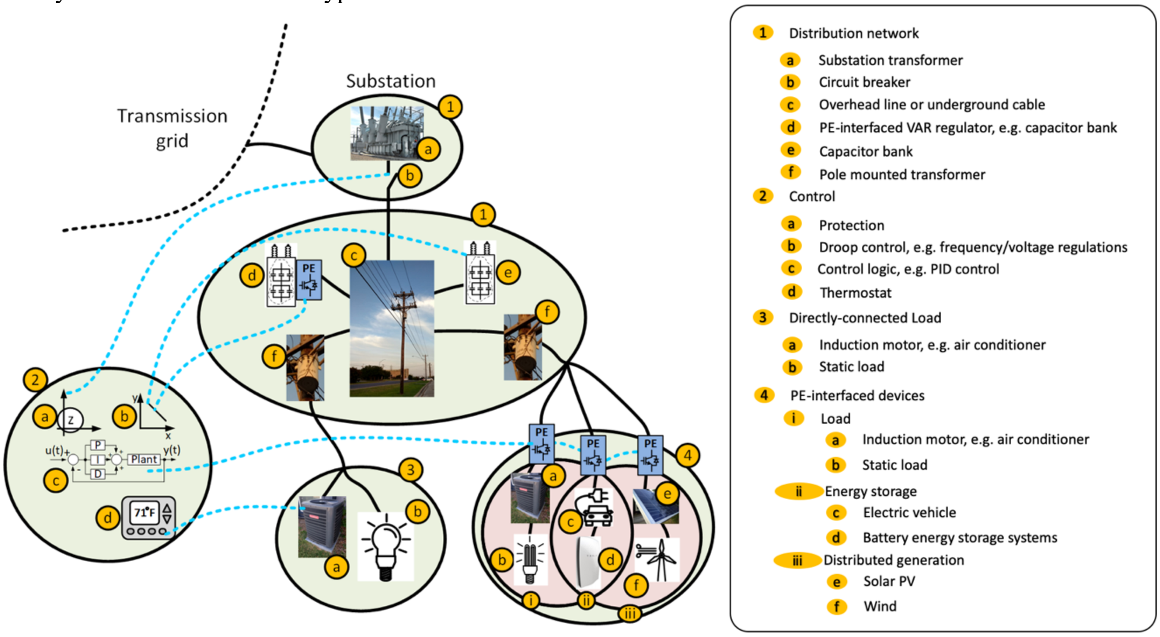


Fig. 1. Typical future distribution system.

A. *Distribution Substation and Network*

A distribution substation acts as a power router which first reduces the voltage from the transmission level (≥35kV) to the distribution level (4-35kV), and then injects the power to the connected distribution network. Tap-changing transformers and protection relays are always necessary parts of a distribution substation to guarantee the quality of the service and the safety of all participating equipment. Typically, system dynamics can be initiated by discrete activities inside a distribution substation, including switching actions of transformer taps and circuit breakers. Resulting consequences to the rest of the system are abrupt changes in transformer impedance, system topology and/or system steady state, as well as disturbances that cause transient dynamics in continuous dynamical states of the system.

A traditional distribution network is composed of overhead lines, underground cables, service transformers and shunt capacitors. The electricity is delivered through the network from its source, i.e. the distribution substation, to its load, i.e. residential users. A traditional distribution network usually only contains passive components, i.e. resistors, inductors and capacitors, from the perspective of circuit. Dynamics resulted from traditional network activities include fused disconnections of lines and discrete switches of shunt capacitors. Future distribution systems will contain more PE-interfaced passive components, e.g. PE-interfaced capacitor banks [9], where dynamics can be fast and continuous and highly dependent on the control of PE interfaces.

B. *Load and Generation*

A load (or demand) in the traditional distribution system represents the element consuming active power, which could be a single physical device, an individual customer or a group of customers. Mathematically speaking, loads can be modeled as a function between the power consumption and the voltage and/or frequency of the connected node. Loads are dynamic in nature. Even under normal grid operation, loads are constantly changing over time, driven by external activities like manual switching or automatic control actions of small domestic appliance and large industrial equipment. Thus, loads directly participate in and contribute to system dynamics. Traditionally, from the circuit point of view, a load could be, or could have a component of, a resistor (incandescent lamps, electric cookers and heaters) or (ii) an induction motor, either directly-connected (water pumps, washing machine and dryers) or PE-interfaced (air conditioners).

In the traditional distribution system, power is supplied from the substation, originally produced by synchronous generators connected over transmission network. In future distribution systems, distributed energy resources such as PV, wind, BESS and distributed gas/diesel generators will be ubiquitous, where PE interfaces can be very advantageous to integrate these generations.

C. *PE Interfaces in Future Distribution Systems*

As discussed in the previous two subsections, other than air conditioners, future distribution systems will be massively penetrated with additional PE-interfaced devices. These PE interfaces are placed in different parts of a distribution system to achieve desired functionalities by using different control strategies.

PE interfaces in distributed energy resources are among the fastest growing applications of PE devices. AC/DC and DC/AC converters are ubiquitous in type-3 and type-4 wind turbine generators, and in PV integration systems to collect the generated renewable energy. The control of these PE interfaces usually take the maximum power point tracker (MPPT) scheme to maximize the benefit of available renewable energy. However, more complex control strategies may be desired in future to provide grid services, e.g.

frequency support and voltage regulation, and PE devices with these controls are called smart inverters.

PE-interfaced loads will also be growing, since PE interfaces are capable for providing desired output frequency and voltage. For instance, VFD [10] can be used to control the speed and torque of AC motors and, in the meanwhile, improve the efficiency of electricity usage.

PE-interfaced BESS will also be popular in future distribution systems. Utility-scale BESS not only can smooth the output of distributed energy resources and help their integration to the grid [11], but also can provide frequency regulation service and gain profit [12].

The above three types of elements can be combined together and interfaced by a single PE interface in practice for synergized functionality as well as (i) lower cost, (ii) smaller volume and (iii) easier installation. Roof-top PV is installed with residential load to reduce the demand [13]. BESSs are combined with PV to help mitigate the variations of PV output [14]. Vehicle-to-grid, vehicle-to-vehicle, and vehicle-to-home have been proposed and substantially investigated in the field to seek benefit for grid operators, asset owners and users [15]. Power Electronics Intelligence at the Network Edge (PINE), i.e. a single PE interface connecting load, PV and ESS to the grid, was proposed in [16]-[18] to benefit both grid operators and end users.

D. *Control of PE Interfaces*

PE interface controls are usually realized by proportioner, integrator, differentiator, limiter, adder or their combinations to achieve certain functions like power-angle droop, power-frequency droop, Volt-Var droop, constant voltage and constant power.

III. Four Categories of Dynamics Causing Instabilities

With the ever-increasing penetration of PE interfaces and PE-interfaced devices, dynamics of future distribution systems will be significantly different from what they are. The dynamics causing different unstable phenomena involved in future distribution systems are classified into four categories in this paper: dynamics introduced by network, dynamics introduced by PE interfaces, dynamics introduced by control of PE interfaces and dynamics introduced by load, generation and ESS.

In general, stability is a property of the dynamical system as a whole, representing its ability to maintain its dynamical behavior close enough to its steady state, either limit cycle or equilibrium point. In terms of power systems, the stability is about the ability of a power system to have a steady state and to stay close enough to it subject to disturbances. An instability can be (i) a loss of steady state, i.e. long-term voltage unstable, (ii) small-signal instability at a certain frequency such as 50/60 Hz or a certain harmonic frequency, (iii) or the large-disturbance instability, e.g. transient angular instability in synchronous-machine-dominated transmission system. The following will introduce the four categories of dynamics that may cause instabilities in future PE-rich distribution systems.

A. *Dynamics Introduced by Network*

As introduced in Section II, the network is fundamentally composed of resistors, inductors and capacitors, whose dynamic states are the three-phase current, voltage and active and reactive power, which are close to ideal equal-amplitude sinusoidal waveforms under steady state having all their amplitudes within designed limits. A typical three-phase voltage profile is shown in Fig. 2.

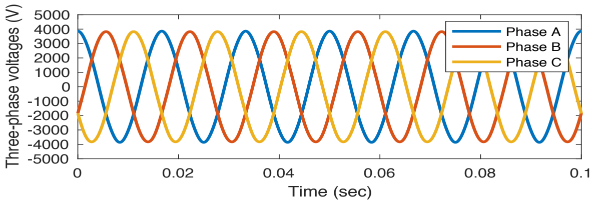


Fig. 2. Typical three-phase voltages under normal condition.

Disturbances originating from the distribution network cause dynamics of the entire distribution system, which include the disconnection of a line by a circuit breaker, the switch of tap-changing transformer and shunt capacitor banks, and the operation of voltage regulator. The net effect of any of these disturbances is a sudden change in the topology or parameter of the network plus a perturbation, either slight or significant, in all system states.

Following the change of network topology or parameter, if a steady state does not exist, the distribution system becomes unstable. For example, when a loss of a line resulting in a maximum power transfer smaller than the load demand, a static voltage instability happens.

If any small dynamics around the post-disturbance steady state grow over time, the system is unstable in the sense of small-signal stability. For instance, the post-disturbance distribution network has a resonance frequency coincident with the harmonics produced by a connected nonlinear load or a PE interface, then harmonic instability may occur, as shown in Fig. 3.

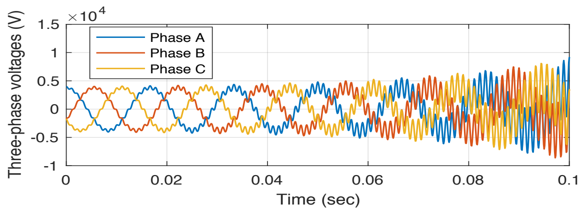


Fig. 3. Harmonic instability.

In addition, a small-signal stable distribution system can still be transient unstable if the disturbance is too large.

B. *Dynamics Introduced by PE Interfaces*

Since PE interfaces can provide desired output voltage and frequency via their fast-acting controls, they are widely used in the integration of distributed wind, solar PV, BESS, EV charging stations, induction motor loads as well as voltage regulation devices. A PE interface usually has multiple circuit states which are constantly switched from one to the other by properly turning on/off switches. These switching actions may produce harmonics in the current flowing through it. The order and magnitude of these harmonics depend on the topology and control of PE devices, and the operating condition of the connected grid. For instance, (i) the AC current harmonics produced by a p-pulse converter are ($pN\pm1$), where N=1, 2, …; (ii) a delta-grounded wye transformer can block third-order harmonics; (iii) if the connected electronic loads have the property of half-wave symmetry, the current responses do not contain even-order harmonics.

If the harmonics produced by PE interfaces have a harmonic frequency equal to a certain natural frequency of the network, the resonance condition would be satisfied and harmonic instability may occur. To mitigate such a risk, especially when the level of harmonics reaches an unacceptable level, active or passive filters are properly designed and installed to eliminate the resonance condition by altering the natural frequency of the network and the harmonic frequencies from PE interfaces.

C. Dynamics Introduced by Control of PE Interfaces

PE interface controls, along with control blocks used in measurement process such as phase-locked loop (PLL), introduce additional dynamical states leading to potential control instability problems, which belongs to the small-signal instability. Commonly seen control instabilities can be caused by a too large gain or a too small time constant in certain feedback loops. For example, (i) PLL of inverters may result in instability in low-frequency range; (ii) the time delay present in converters or the frequency-coupling between switching modulation and the sampling process may lead to instabilities in high-frequency range [19].

The control is usually designed to properly function within a certain range of operating conditions. However, the control instability can still happen if the system operating condition changes to a certain unacceptable level leading to an small-signal instability [20].

D. Dynamics Introduced by Load, Generation and BESS

Loads usually have multiple components, including static, dynamic and nonlinear. Static loads are always passive, which react to the terminal voltage and do not have any stability problem as long as the entire system has a steady state. For dynamic loads, e.g. an induction motor, the underlying differential equations have dynamical states like slip and flux linkages. Therefore, the current (or power) response not only depends on the present terminal voltage and frequency, but also relies on dynamic states of the load. For nonlinear loads, even if the connected bus has an ideal sinusoidal voltage profile at 60/50 Hz, their current responses contain not only the fundamental component, but also significant harmonics. For example, the ignition-induced second peaks in fluorescent lamps contribute to the dominated third-order harmonics [21]. Other nonlinear loads include arc furnaces and switched-mode power supplies such as electronics and computer devices.

Fig. 4 shows a typical starting current of an induction motor when connected to an ideal voltage source. It can be expected that if connected to a certain point in the network, the large starting current, e.g. up to several times of the normal full-load current, can cause undesired voltage dips. When subject to a disturbance destroying the active power balance, periodic power exchanges among electrically connected rotating masses, i.e. generators and motors, would occur due to their mechanical inertias, causing dynamics in magnitude and phase of all involved electrical quantities and could possibly lead to transient angular and voltage instabilities. Fig. 5 shows three typical current responses with significant third-order harmonics respectively from a residential air conditioner, a refrigerator and a personal computer. These produced harmonics may cause harmonic instability if amplified when interacting with the distribution networks.

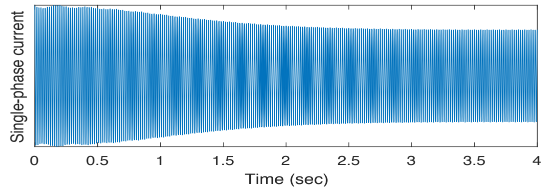


Fig. 4. Typical induction motor starting current.

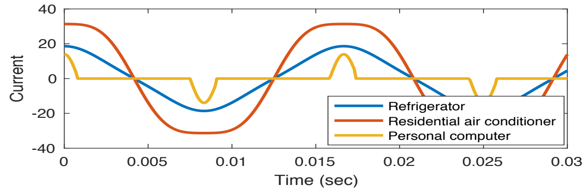


Fig. 5. Typical load current responses with third-order harmonics.

Distributed generation include gas/diesel synchronous generators (SGs), solar PV panels and wind turbine generators. Potential oscillations, even instabilities, may happen when mutual excitations, e.g. via power exchanges, among these elements exist. For instance, if there are two SGs connected over the distribution network, transient angular instability (TAI) between them may occur when subject to a large disturbance. This is similar to that in traditional transmission systems. Table I shows all potential mutual excitations that may cause issues, where only a few of them have been practically observed, including TAI, sub-synchronous oscillation (SSO) and harmonics/harmonic instability (H/HI), while interactions marked with "X" have not been reported to cause any issues by now, which may or may not be causes of instability in future distribution systems.

TABLE I. MUTUAL EXCITATIONS CAUSING POTENTIAL INSTABILITY

	SG	**PV**	**Wind**	**ESS**	**Inductor/ capacitor in network**	**Non-linear load**
SG	TAI	X	X	X	SSO	X
PV	-	X	X	X	H/HI	X
Wind	-	-	SSO & H/HI	X	SSO & H/HI	X
ESS	-	-	-	X	X	X
Inductor/ capacitor in network	-	-	-	-	X	H/HI
Non-linear load	-	-	-	-	-	X

E. Remarks

The aforementioned four categories only cover dynamics involved within a distribution system, while the impact from external transmission system has not been covered. The transmission system is usually modeled as a voltage source behind an impedance [23], which is fine as long as the transmission system is strong enough, i.e. having a stiff voltage [24]. Otherwise, modeling has to be extended to cover those external interacting dynamic elements. In this paper, we use a voltage source in series with an impedance to represent the transmission system, while external disturbances are represented by changes in the voltage magnitude and the impedance.

IV. Examples

This section shows the four types of dynamics in PE-rich distribution systems based on PINE [16][18]. PINE is a back-to-back converter topology that can act as an multi-terminal interface connecting the load of a typical house, rooftop solar PV/battery system and the distribution network, as shown in Fig. 6. Note that PINE is installed behind the customer's electric meter i.e. at the very edge of the grid. Three parts of a PINE:

- **A front-end rectifier** connects to the grid, which is controlled to minimize the current harmonics from/to the grid.
- **A DC link** between the two converters connects to the rooftop solar PV/battery system, which can be controlled to power the load and provide real/reactive power to the grid.
- **An output inverter** connects to the load in a residential house that is controlled to maintain a constant 120/240 split-phase voltage.

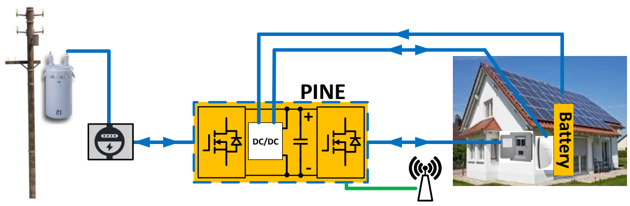
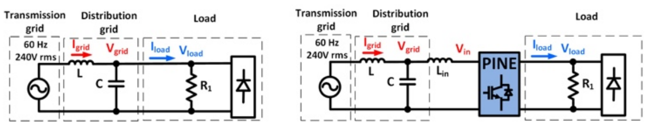


Fig. 6. Power Electronics Intelligence at the Network Edge (PINE) technology.

The first example uses a simple system, as shown in Fig. 7, to show the dynamics from the network, dynamics from the load and the dynamics from the PE interface. Two cases, one without PINE and the other one with PINE, are simulated and compared to show that PINE, as a PE interface, can significantly change the dynamics of the entire system. Specifically, PINE can (i) maintain a constant load voltage even in the presence of nonlinear load, (ii) block harmonics from nonlinear load to limit potential interactions with network dynamics.



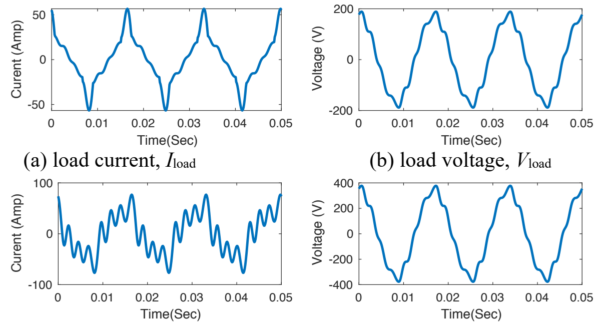
(a) Without PINE (b) With PINE

Fig. 7. Tested system in the first example.

For simplicity, the grid is modeled as an ideal voltage source, the network is modeled by a series inductor (representing lines and cables) and a shunt capacitor (representing reactive compensations), the load contains a linear component represented by a resistor and a nonlinear component represented by a diode rectifier. The nonlinear load injects odd-order harmonics into the grid as shown in Fig. 8a, which may interact with the network if one of whose natural frequencies coincide with any of these harmonic frequencies. The dynamics of the system without PINE are show in Fig. 8, while the dynamics of the system with PINE are shown in Fig. 9.

It can be seen in Fig. 8b that without PINE, dynamics of load voltage may contain severe distortions, having a Total Harmonic Distortion (THD) greater than 9%, while with PINE the THD is reduced to less than 2% as shown in Fig. 9b. When it comes to the dynamics of grid current and grid voltage, significant harmonics may exist in the case without PINE, as shown in Fig. 8c and 8d, while even such severe harmonics can be turned into a nearly harmonics-free case by PINE, as shown in Fig. 9c and 9d. In addition, Fig. 8c shows that if without PINE, the current injected to the grid interacts with one natural frequency of the network at 460Hz, which could potentially lead to harmonic instability in a weak grid. With PINE implementation, the current harmonics injected to the grid are minimized (THD < 3%), as shown in Fig. 9c.

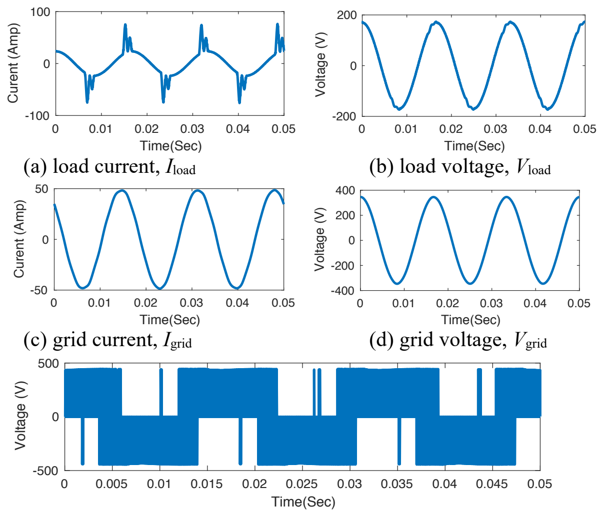
With PE interfaces such as PINE, high frequency harmonics induced by switching actions are injected to the grid. These high frequency harmonics are usually not very significant since they are filtered by the input impedance of PE interfaces. Fig. 9e and 9d show the voltages before and after the input impedance of PINE. To guarantee the quality of the electricity services, new requirements for smart inverters include to limit their harmonic current distortion [7].



(a) load current, I_{load} (b) load voltage, V_{load}

(c) grid current, I_{grid} (d) grid voltage, V_{grid}

Fig. 8. Dynamics of the system without PINE.



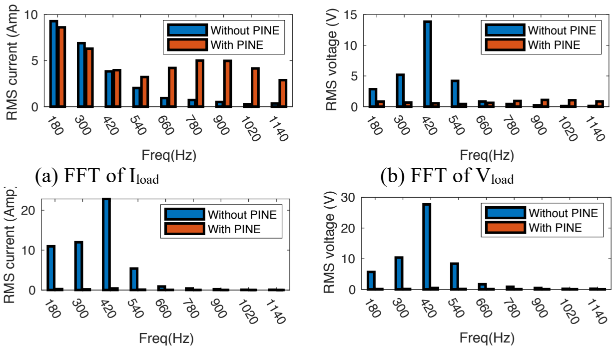
(a) load current, I_{load} (b) load voltage, V_{load}

(c) grid current, I_{grid} (d) grid voltage, V_{grid}

(e) voltage before the impedance, i.e. V_{in}

Fig. 9. Dynamics of the system with PINE.

PINE brings both benefits and challenges. Benefits illustrated above include that PINE can (i) provide better voltage quality to the residential users, immune to the nonlinear loads connected to the same node, as shown in Fig. 10b; (ii) block majority of the harmonics to the load side, as shown in Fig. 10c and 10d. Challenges include that PINE can introduce potential control instability issue if its control parameters are not properly designed, to be discussed below.



(a) FFT of I_{load} (b) FFT of V_{load}
(c) FFT of I_{grid} (d) FFT of V_{grid}

Fig. 10. FFT analysis of grid and load current and voltage.

The second example below demonstrates the dynamics introduced by the control of PE interfaces using PINE in a 5-bus distribution system, as shown in Fig. 11, which contains two lines, two transformers and two PINE-interfaced loads. For simplicity, lines and transformers are represented by R-L branches and the loads are represented by resistors.

If control parameters are not properly designed, e.g., too large gains in rectifier control will lead to small-signal instabilities, as illustrated in Fig. 12a and 12b, which may cover a large frequency band, ranging from a few hundred to a few thousand Hz.

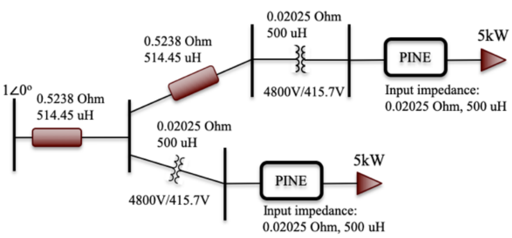


Fig. 11. A 5-bus distribution system with two PINE-interfaced loads.

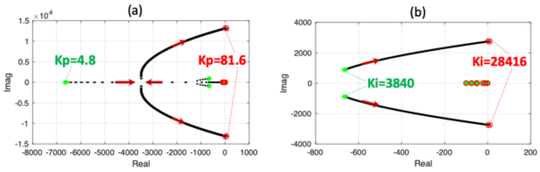


Fig. 12. Illustration of small-signal instabilities by root loca: (a) a too large K_P gain in rectifier control, (b) a too small K_I gain in rectifier control.

V. Conclusion

This paper classifies the dynamics of future power-electronics-rich distribution grids causing potential issues, e.g. instabilities and harmonics, into four categories, and show that the growing PE interfaces for integrating renewables could significantly change the dynamics of the system using example systems with a novel grid edge PE interface technology named Power Electronics Intelligence at the Network Edge (PINE).

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