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Electrification, Decentralization and IT/OT Digitization of Grid-Connected Rooftop PVs in Residential Feeder

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Abstract: ***During last decade, technological advances and global objectives which is related to sustainability, security of supply and competitiveness and also the policy and regulatory frameworks have been significantly driving the physical outlook of the power grid. As for the determination of electrification demand, the decentralization of distributed generators (DG) within the transmission/distribution network, and the digitization of information-technology/operation-technology (IT/OT) of smart grid communication devices, marks the transformation the electric infrastructure to put into account. Since it is commonly known that the ancient power plants were categorized as centralized generation, such as fossil fuel, nuclear and large hydropower plants, however, because of the demand at the customer side has raised continuously, the ancient model of power plant could no longer fulfill the requirements. In addition, from a technological perspective point of view, it is discovered that maintaining power quality, managing voltage and frequency levels, increasing consumption, standardization and interoperability issues are major challenges that are related to the decentralized DGs. Therefore, due to coordinate and communicate DGs in this case the photovoltaics (PVs) within the network, the communication infrastructure must also put into account. Since the single-phase rooftop PVs are installed into the three-phase residential feeder of low voltage (LV) distribution network, the voltage profiles of the network become unbalanced. Although the load at the customer side has already imbalanced the network, but as the single-phase rooftop PVs with the ratings of 1-5kW are installed along the feeder, the power quality issues, such as the voltage magnitude and angle, the frequency, the active and reactive powers become significantly noticeable. This is because of the grid infrastructure from plants to beyond the customer side is disrupted as several utility devices added into the network. As the infrastructure problem raised, the power quality issues appeared. Several studies have been conducted to overcome the power quality issues along the feeder whereas the PVs are installed. Nevertheless, as the trend of smart-devices technology developed, another utility problem such as the coordination and communication amongst grid-connected PVs has upraised. This paper aims to implement the concept of developing the contribution of electrification, decentralization, and (IT/OT) digitization into the electric and communication infrastructures as they are virtuously cycling, enabling, amplifying and reinforcing the infrastructure development. This concept in certain ways also apply the voltage regulation technique (VRT), in order to improve the voltage unbalanced and other power quality issues. The proposed methods to implement the concept are built through the considered network, and applied the communication-based VRT that has been studied through several researches that have been conducted by the authors. As the method applied, the results show the concept might accomplish if the selected and designed of both communication devices and technology properly. In addition, the considered classifying of communication layers also plays the important roles. As the concept of electrification infrastructure, decentralization of PV system along the***

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residential feeder and IT/OT digitization of the communication among sensor, actuators and meters are applied. Thus, to implement the concept the development of the electric infrastructure as well as the inclusion of decentralization DGs' set and communication of devices from plant to beyond the load at the customer side must coordinate in such way that the improvement of communication-based VRT to overcome the imbalanced voltage profile can be successfully conducted.

Keywords: **Rooftop PVs, electrification, decentralization, IT/OT digitization, communication-based VRT, and voltage profile improvement.**

I. BACKGROUND/ OBJECTIVES AND GOALS

Photovoltaics (PVs) have been widely conveyed can cause power quality problems for electricity distribution networks. It is particularly in low voltage (LV) networks, whereas the LV networks were effectively and proficiently manageable and operable before the rise of PVs (Miller et al., 2018). Three trends that disrupt the electricity infrastructure, which is currently as technology and innovation transform the ancient models from plants to beyond customer meters known as, electrification, decentralization and information technology/operation technology (IT/OT) digitization. These three acts in virtuously cycling, enabling, amplifying and reinforcing developments beyond their individual contributions. One of the electrification model as renewable energy contribution is grid-connected PV system. The schematic of this system is illustrated in Fig. 1.

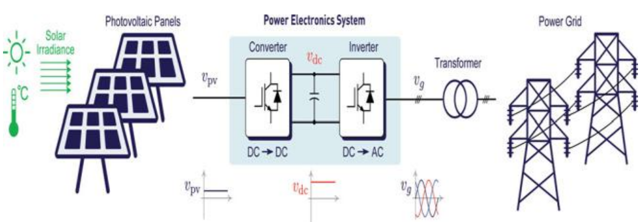

Fig. 1: PV energy conversion system (Blaabjerg and Ionel, 2015)

This figure illustrates the inclusion of a power electronics DC/DC converter, which ensures a maximum sun energy harvesting through a maximum power point tracking (MPPT) control, and a DC/AC converter for interconnection to the grid. PV systems gained large popularity not only for multi-MW utility scale power plants/farms, but also as rooftop installations on commercial and residential buildings with ratings as small as hundreds of Watts (Blaabjerg and Ionel, 2015). Many developed countries have implemented the rooftop solar PV system as for residential and industrial used. However, as distributed generators (DGs) have been introduced into the network, the challenges that appear required to use the most practical approach and an understanding by the new generating entities of the importance of a grid that can eventually be more flexible to allow more customers at the load side. Thus, developed countries such as Denmark, Ireland, Japan, Canada, Korea, Australia and United States have been implemented the approach to help the introduction and further growth of distributed generation which is able to overcome the various grid issues such as VAr voltage management, self-healing grids, dynamic line rating, greater interconnectivity between system operators, active network management, demand response mechanisms, micro-grid, advanced metering solutions, energy efficiency and improved data analytics of the above area (GSGF, 2014).

In addition, according to Chidurala (2016) in his PhD thesis, the various power quality issues imposed by PV system could be the voltage issues in the low voltage unbalanced distribution network with high PV penetration and the voltage quality problems in real grid connected PV sites, also the development and validation of new control methodology for solar PV inverters to enhance grid power quality have been studied. Therefore, in order to overcome the raising issues, the concept of grid modernization has been proposed by McDonald, J.D. (2016) for GE grid solutions. The proposed concept of the electrical and information infrastructures integration, and the incorporation of automation and information technologies through existing electrical network as illustrated in Fig.2.

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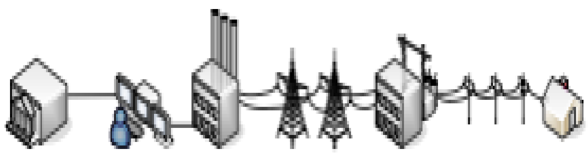
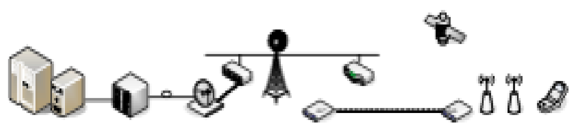
As can be seen in Fig. 2, the electrical distribution is from plant to customer (Fig. 2(a)), as the information as well (Fig. 2(b)). As previously mentioned, the electrification is being disrupted by the decentralized instalment of distributed generators (DGs) in this case, the rooftop PV system. Then the system digitalized by adding the smart meters along from plant to customer sides.



(a)



(b)

Fig. 2: Grid infrastructures, (a) Electrical infrastructure, (b) Information infrastructure (McDonald, 2016).

In this paper, the review of smart grid concept which has single-phase rooftop PV system as DG along the three-phase residential feeder and a proposed VRT implemented to overcome the voltage imbalance as one of power quality issues by considering the electrification, decentralization and IT/OT digitization of the PV system in residential feeder through simulation environment is deployed.

This paper is organized as follow, section one is discussed about the background situation of the electric infrastructure and several studies that mitigate the DGs over the network, and the inclusion of PV system that need to consider the communication backhaul. Section two is discussed about the methods that have been proposed as the concept is implemented into the considered unbalanced three-phase residential feeder with PVs. Last but not least, section three is discussed about the results as the methods applied in detail. Section

II. METHODS

As the infrastructure of grid developed in Fig. 3, as well as the differences between the ancient and modern grid or known as smart grid system can be seen in Table 1, then this considered three-phase unbalanced LV distribution network with single-phase rooftop PVs is used for the rest of this paper.

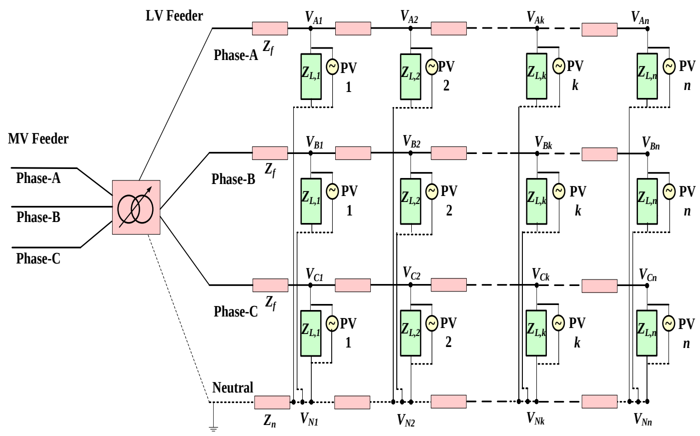


Fig. 3: Considered LV network with random single-phase PV rated 1-5kW (Rachmawati et al, 2018).

Table 1: Differences of the ancient and modern grid (McDonald, 2016).

Ancient Grid	Smart Grid
Uni-directional power flow	Two-ways directional power flow
Utility pays whatever it takes to meet peak demand	Utility suppresses demand at peak
Difficult to manage high wind and solar penetration	No problem with higher wind and solar penetration
Cannot manage distributed generation safely	Can manage distributed generation safely
~10% power loss in T&D	Power Loss reduced by 2+%

As can be seen from Fig. 3, the consider 11 kV three-phase medium voltage feeder supplying a 380 V three-phase four-wire low voltage residential feeder, as the residential feeder is assumed to be unbalanced due to the distribution of loads and unequal distribution of single-phase rooftop PVs with the rating of 1-5kW. The configuration of this considered network is listed in Table 2.

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To reach the constructive smart grid as mentioned in Table 1, firstly let us consider the electrification issue. As we realize, two main problems are basically happening to the network while the PVs available. During the days, PVs inject active power while most household loads are at their nominal levels which could result in active power flow in the opposite direction toward the grid causing voltage increase at some nodes along the residential feeder. While in the evenings, and during peak load hours, power output of PVs vanish that could result in voltage drops (Safitri, et al. 2015).

Table 2: Technical parameters of the simulated test network (Rachmawati et al, 2018).

Network	Specifications
Transformer	11/0.415 kV, 50 Hz, 150 kVA, 50 Hz, Dyn, *z* = 0.05 pu
MV Feeder	11 kV L-Lrms, 3-phase 3-wire, 5 km, 1.08 + *j*0.0302 Ω/km
LV Feeder	415 V L-Lrms, 3-phase 4-wire, 400 m, 0.452 + *j*0.270 Ω/km

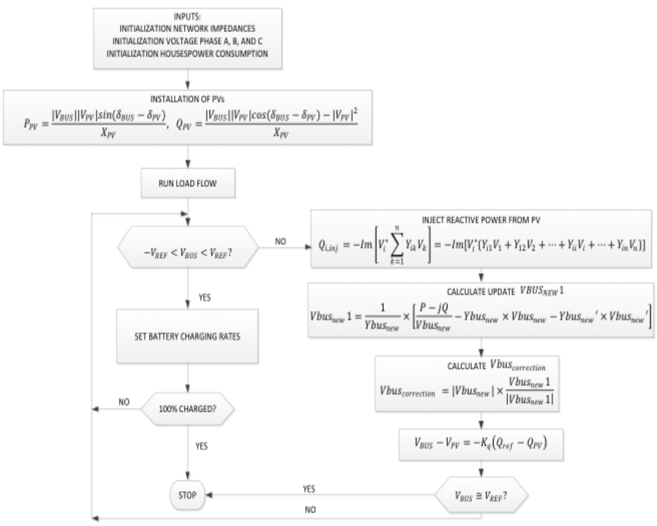

Fig. 4: The algotirhm applied for scenario in Safitri, et al. (2015)

Fig. 4 illustrates the load flow scenario. As to overcome these problems, the scenario that has been developed by Safitri, et al. (2015), has successfully reduced the voltage unbalanced as the effect of non-uniform PV system (1-5kW) that located randomly in the single- and three-phases network. Secondly, as we consider the decentralized issue of the PV system, adopted from the study that has been done by Safitri, et al. (2015), by applying voltage regulation technique (VRT) in certain unbalanced three-phase LV network, it has successfully coordinated the single-phase rooftop PVs as DGs that installed randomly rating and location along the residential feeder. Finally, as further study by Safitri, et al., in 2016, the communication-based VRT which composed by three steps of On-load tap changing (OLTC) transformer adjustment, distributed reactive power exchange, and active power curtailment has been developed. Fig. 5 illustrates the VRT algorithm.

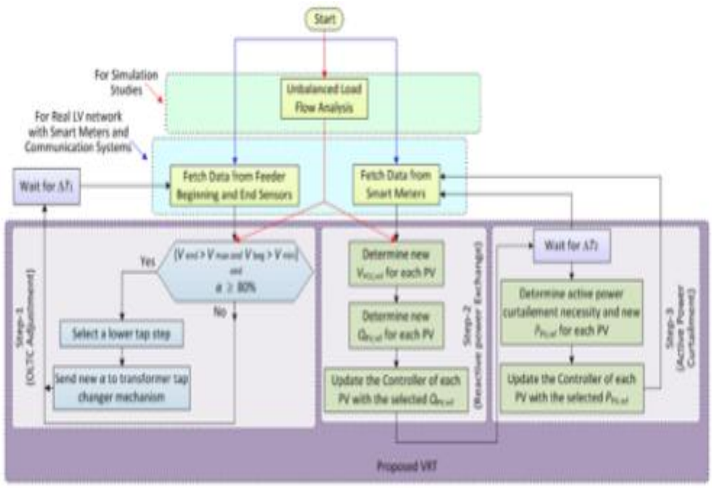

Fig. 5: Algorithm of VRT communication-based in Safitri, et al. (2016)

The communication-based VRT should be capable of scattering the location of PVs and customer loads, and handling numerous and massive number of sensors/meters, and coverage a geographical area. Thus, the IT/OT digitization must put into account to further improve the performance of the communication-based VRT which has been studied.

III. RESULTS

The IT/OT digitization is the most important part of the power quality issue in LV three-phase distribution network

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due to coordinating the PV-grid connection along the feeder. Both wired and wireless communication technologies can be employed in this considered system. According to Setiawan, et al (2015), the popular wired technologies, used in power systems, are serial communication RS-232/422/485, bus technology (e.g., ModBus, ProfiBus, and CANBus), power line communication and broadband power line communication, and Ethernet (e.g., LAN and optical cable). On the other hand, the popular wireless technologies, used in power systems, are cellular, Wi-Fi, WiMax, ZigBee, Z-Wave, Bluetooth, Insteon, radio frequency, and Microwave. They also state the comparison of both communication technologies that describe the benefits and drawbacks within the network.

Therefore, to imply the communication-based VRT of coordinated single-phase rooftop PVs in the residential LV feeder, there are two proposed methods, i) selecting and designing the proper communication technology, and ii) the classifying the communication layer due to provide data transfer capability of PVs' controller and grid controller.

A. *Selecting and designing the communication technology*

Due to transfer the data to the grid controller, several parameters should be considered in selecting and designing the communication technology, such as i) the area size whereas the PVs are distributed; ii) the costs of the installation, operational and maintenance; iii) the inclusion of sensors, actuators, meters and supporting devices; iv) the requirements of minimum data transmission rate, data precision, and maximum data packet error; v) the future expansions flexibility; and vi) the access data different techniques. In this paper, the following design in LV network communication are presented as illustration in Fig. 6.

It is to be noted that the electrification and decentralized control of the grid-connected PV system within the LV feeder is obviously possible, since the VRT communication-based performances are within the communication layers. The PV controller, the grid controller and the power quality parameters controller, respectively, are classified into three different communication layers.

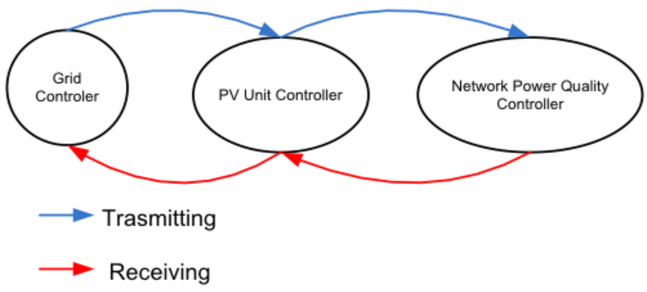

Fig. 6: Design of the communication technique in LV network with PV

B. *Classifying the communication layers*

Considering the location of the communication devices and also the characteristics of the data that has to be transferred, the communication technologies in the grid-connecting PV system are classified in three layers, as shown schematically in Fig. 7.

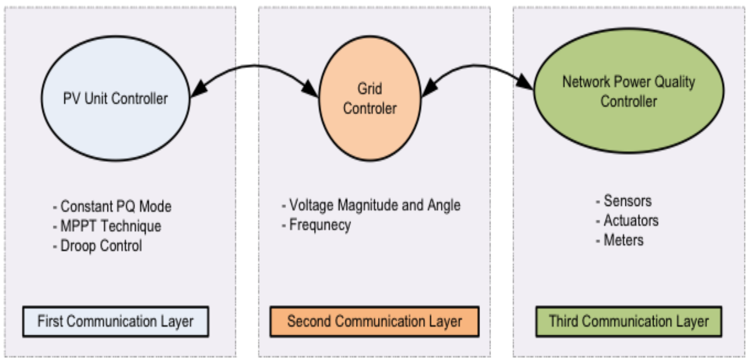

Fig. 7: Hierarichal of communiation layer of the considered LV distribution feeder of Fig. 3

Table 3: Power electrical networks concept trough decades

Networks	Infrastructures		
	Electrical	Electrical & Geospatial	Communication
Ancient Network	√	-	-
Grid-connected PV	√	√	-

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Network with Electrification, Decentralization, and IT/OT Digitization Concept	√	√	√

The first communication layer is the control system within every PV's unit that primarily control the operation of PV based on its local measurement. The data is fetched from the local sensors/meters using time steps of the very small sampling and eventually produces the required outputs for the PV's actuators. The PV unit operates within the constant PQ mode and generates power based on MPPT technique. In self-sufficient mode, the PV essentially operates in droop control. The second communication layer is the grid controller that responsible to control the voltage magnitude and angle and also frequency at the grid side. As the main controller, it fetched data from the installed voltage sensors. The third communication layer is the power quality of network controller.

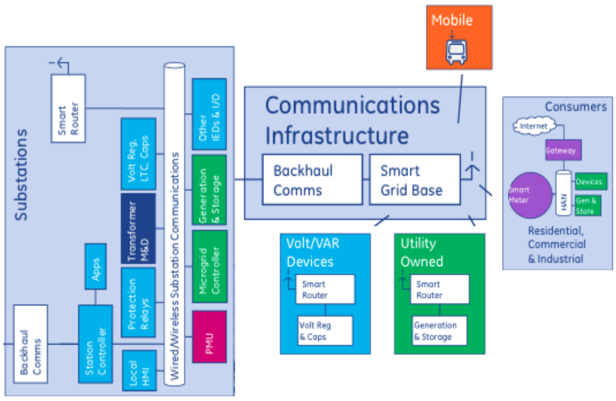

Fig 8: Eletrification, decentralization and IT/OT digitization concept

This controller responsible for the general operational of the network power. It also defined as the operational mode of the grid, either in grid or self-sufficient mode. Although the electrification, decentralization, and IT/OT digitization interrupted the LV network while the PVs are available, the implemented concept of those interruptions into the infrastructure network conveyed the tremendous power quality from grid to customer sides. The concept is clarified in Table 3, as it is compared to other network models, and illustrated in Fig. 8.

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