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Impact of IEEE 1547 reactive power support functions on voltage regulation of a synthetic residential distribution network

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SUMMARY

Conventionally, utilities required distributed energy resources (DERs) to operate at unity power factor (PF). Although this approach helped utilities predict DER behaviours, it limited the DERs' potential to provide other grid-support functions. Recent standards, such as IEEE Std 1547 and CSA Std C22.3 No. 9, require DERs to be able to provide grid-support functions, such as reactive power support in different modes, such as the volt-reactive power (volt-var) function. These functions allow DERs to support the grid in terms of stability and voltage regulation. In this context, it is important to assess the impact of each of these functions on the different levels of transmission and distribution networks.

The focus of this work is to investigate the effect of the volt-var function on voltage regulation of a low-voltage (LV) distribution network under high solar irradiance variability. Accordingly, this study assumes a synthetic residential neighbourhood at a location in Varennes, Quebec, Canada, in which measured solar irradiance data were recorded for an extended period. The network is assumed to be fed from a medium voltage (MV) distribution feeder, which is also feeding other residential, commercial, and industrial customers. The residential neighbourhood comprises 15 houses, each integrating a 5.5-kW rooftop solar PV array and a 5-kW smart PV inverter with reactive power support capabilities.

The synthetic distribution network is modelled in time domain in the Matlab/Simulink environment, which allows detailed analysis of the inverter and network behaviours under rapid solar variations. A 10-minute period with high solar irradiance variability is chosen to conduct the simulations. Spatiotemporal solar irradiance data is interpolated for each house to estimate the average solar irradiance over its solar PV array. The simulations are first run with the inverters operating at unity power factor (i.e., conventional mode) as a base case. Then, the simulations are repeated with the volt-var function under two different settings adopted from IEEE Std 1547.1, namely "Most Aggressive" and "Default" settings. The load voltage profiles are observed and compared with the base case.

Overall, the volt-var function enhances the voltage regulation when compared with operation at unity power factor. Furthermore, comparing Default and Most Aggressive volt-var settings, the latter provides better voltage regulation, yet in the expense of active power curtailment. Meanwhile, Default settings implement a dead band around the reference voltage, and hence the inverter responds only to large voltage deviations beyond the dead band. Despite the former's worse voltage regulation, it might be desirable for utilities favouring DER grid support only during extreme conditions.

The paper provides a platform for analysis of inverter reactive power support functions, as defined in IEEE Std 1547, and adopts measured solar irradiance data for the analysis. In this work, the volt-var function is assessed and recommendations for inverter settings are concluded from the analysis.

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KEYWORDS

Active distribution networks, distributed energy resource (DER), IEEE Std 1547, PV, volt-var.

I. INTRODUCTION

Interest in sustainable renewable energy resources (RERs) has been constantly on the rise for the past few decades due to environmental as well as economic factors. Dependence on conventional fossil fuels for energy production has had a significant impact on the environment, as it is directly related to pollution and global warming due to emission of greenhouse gases (GHGs). Meanwhile, the production cost of solar photovoltaic (PV) panels and PV inverters, as well as other RERs, have dropped significantly in the past two decades due to steady evolution of these technologies. Accordingly, deployment of solar PV generation has been rapidly increasing in many countries around the world, with a global record of 156 TWh (23%) growth in 2020 alone [1].

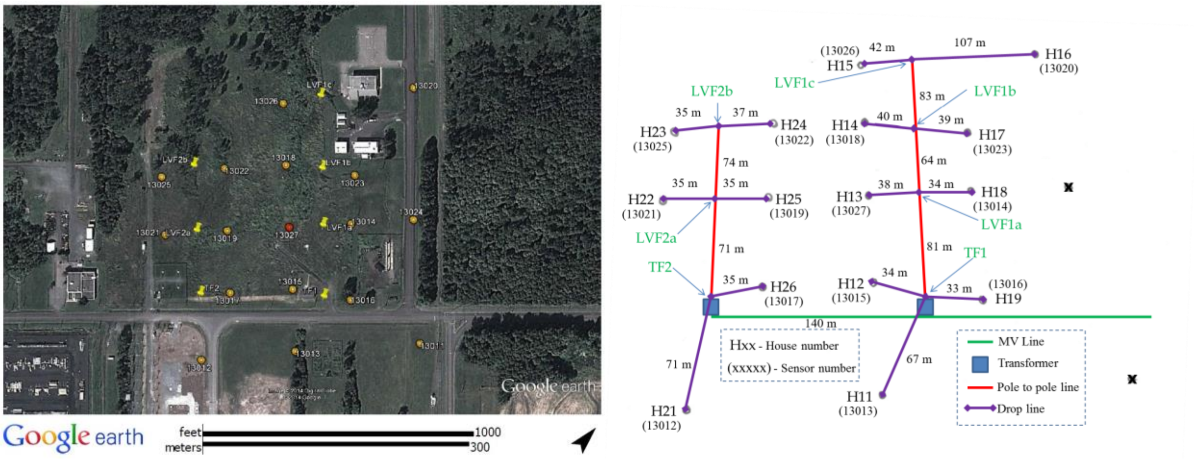
Direct integration of small-scale distributed generators (DGs) close to loads into distribution networks has shown many technical benefits, such as deferring infrastructure upgrades and increasing system efficiency by decreasing system losses. Therefore, many utilities encourage customers to install small-scale solar PV inverters by offering programs such as the feed-in-tariff (FIT) program in Ontario and the "Net Metering" option in Quebec, Canada. However, installing DGs at distribution networks introduces numerous technical challenges, since these networks were conventionally designed to solely serve loads and not to accommodate local generation. Furthermore, utilities conduct several technical studies (e.g., hosting capacity studies) to determine the maximum DG capacity that a specific distribution network can accommodate without violating any operational constraints [2].

When utilities first allowed connecting DGs to distribution networks, they adopted a conservative approach, in which DGs were permitted to inject active power only (i.e. operate at unity power factor (PF=1)). Although this restriction simplified system analysis and guaranteed relatively predictable operation of DGs, it limited the DG potential capabilities where they could actively contribute to maintaining the system variables within their safe limits. Hence, in recent years, standards have been introduced and/or revised to define more advanced inverter functions (AIFs) – also referred to as grid-support functions (GSFs) – for grid-connected inverters; IEEE 1547 [3] and CSA C22.3 No. 9 [4] are examples of such standards in USA and Canada, respectively. With the introduction of new AIFs, it becomes necessary to analyze and assess the system operation with inverters employing these functions. Many studies with various scopes (e.g., hosting capacity, PV power curtailment, etc.) have been recently reported for inverters employing AIFs, which have generally shown improved system performance when compared with the conventional unity PF inverter operation [5]-[7].

This study investigates the operation of PV inverters under high variability of solar irradiance. The study considers a synthetic distribution network representing a residential neighbourhood comprising 15 houses, each with a 5.5-kW PV array and a 5-kW/5-kVA grid-tied inverter. The study incorporates measured solar irradiance data collected using sensors at a site in the city of Varennes, Quebec, Canada, as part of a research project. The synthetic network is constructed at the same geographical area where the solar irradiance data was collected, with houses assumed at sensor locations. This assumption allows accurate study of the impact of solar irradiance variations on distribution networks, considering measured spatiotemporal solar irradiance data. The presented work investigates and compares the effects of the volt-var function on the system operation, with emphasis on its role in regulating the system voltages.

II. SYSTEM MODEL

The synthetic residential distribution network under study is constructed around a site located in the city of Varennes, Quebec, Canada, where high-resolution solar irradiance data is available for a few years. Fig. 1(a) shows the Google Earth view of the test site at the Institut de recherche en électricité du Québec (IREQ). The site incorporates multiple sensors, numbered from 13011 to 13027, for collecting high-resolution solar irradiance data, as detailed in [8]. Irradiance data is measured every 10 ms and stored every minute and whenever a change of 5 W/m^2 or more is observed. To build a residential neighbourhood at the test site, 15 houses were considered at the location of 15 individual sensors. The houses are fed from two 240 V feeders, LVF1 and LVF2, which in turn are supplied from a MV network through two distribution transformers, as shown in Fig 1(b). The MV network layout and parameters along with the LV network parameters can be found in [9]. Each house is equipped with a 5.5-kW rooftop PV array and a 5.0-kW grid-connected smart PV inverter, complying with the CSA C22.3 No. 9 standard.



(a) Physical layout on Google Earth (b) Electrical layout

Fig. 1 Layout of the residential neighbourhood

The network is modelled in the Matlab/Simulink environment, where the inverters and houses are modelled as constant-power sources and loads, respectively. The simulations are run for the solar irradiance data of March 4, 2015, starting at 11:12:39.00 AM for 10 min. The solar irradiance data were interpolated to estimate the average irradiance over a 5.5 kW solar PV array on each house [10]. Based on the analysis of average loading of similar houses around the same time of the day, house loads are assumed constant at 1.7 kW, unity PF for the duration of these simulations. Furthermore, the transformer tap of the MV substation is set at 1.05 pu to account for feeder voltage drops, which results in voltages of ~1.0 pu at the farthest houses if no PV inverters are employed.

III. CASE STUDIES

Three case studies are conducted to evaluate the inverters' performance without and with the volt-var function under high solar variability. First, the inverters operate at unity power factor as a base case, and then the volt-var function is enabled under two different sets of settings, Default and Most Aggressive, as defined in IEEE 1547.1. The results of the different case studies are assessed to evaluate their performance in terms of their voltage regulation capabilities.

The CSA C235 [11] standard defines appropriate distribution system steady-state voltage levels. For a 240 V single-phase connection, the Normal Range (NR) for voltage levels at the point of connection between the utility and the client is between 220 V (0.917 pu) and 250 V (1.042 pu). Meanwhile, under extreme conditions, the steady state undervoltage (UV) and overvoltage (OV) limits are 212 V (0.88 pu) and 254 V (1.058 pu), respectively. Most Canadian utilities follow CAN3-C235 to define their normal operation range (NR), and therefore it is used in this work as a reference to assess the inverter's performance in different case studies. This study addresses a very short time window with high variability and will thus focus on temporary violations. It is worth mentioning that networks are allowed to operate outside the normal and extreme conditions ranges for 5% and 0.1% of the time respectively (on a 7-day period basis) before corrective measures are required.

1) Unity Power Factor

This base case considers the conventional operation of PV inverters, in which the inverters operate at unity PF (i.e., inject active power only). Fig. 2 shows the solar irradiance (a), the PV inverters' active powers (b), as well as the voltage profile at each house (c) on LV Feeder 1. Note that in the figure, plots representing houses connected to the same drop node (e.g., H13 and H18 drop from node LVF1a) use the same colour but different plotting patterns (i.e., continuous line, dashed line … etc.).

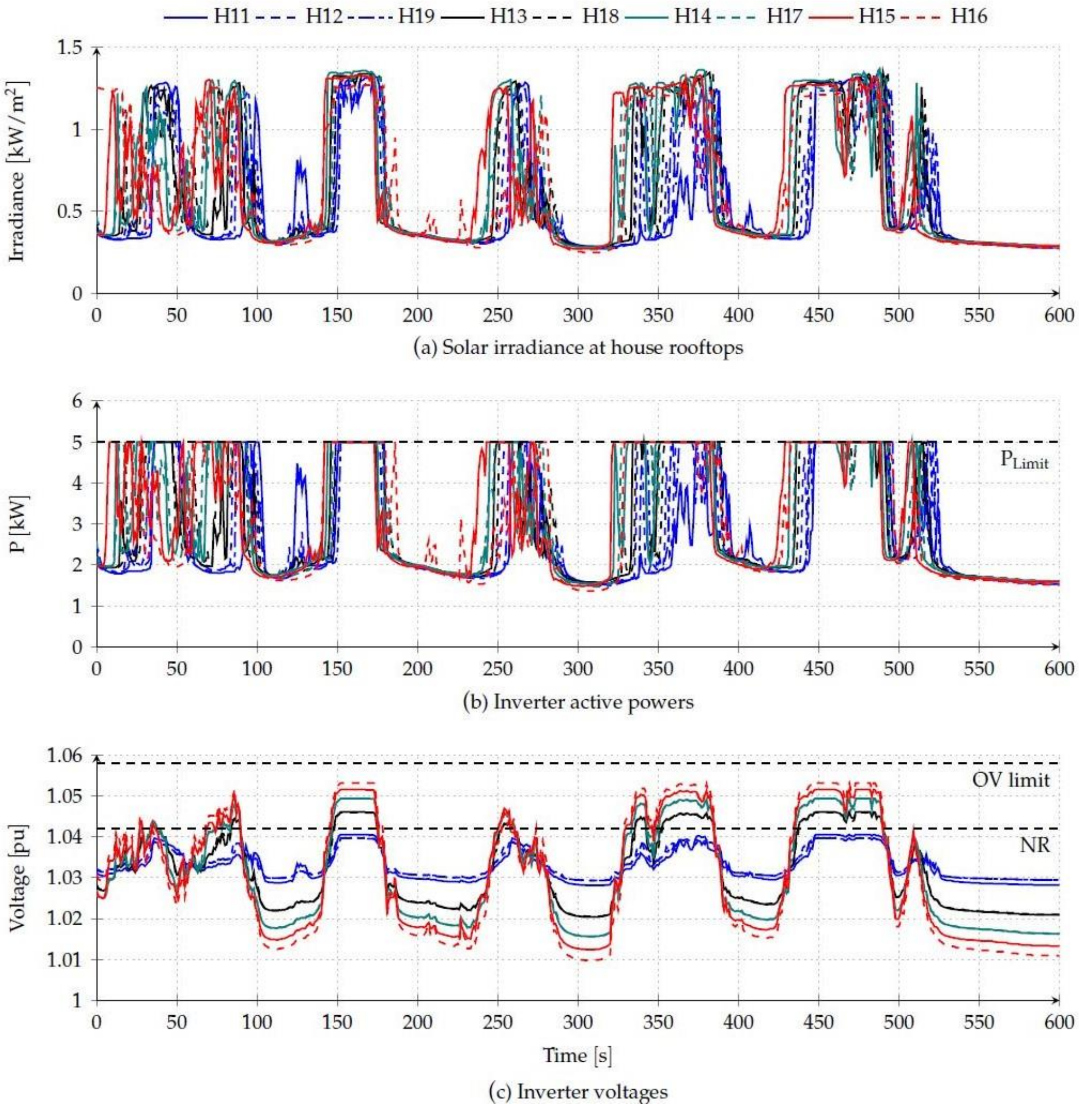


Fig. 2 Simulation results of LV Feeder 1 with PV inverters at unity PF.

Fig. 2(b) shows that the inverters' active powers are curtailed and limited at 5.0 kW at periods of high solar irradiance (Fig. 2(a)). Furthermore, Fig. 2(c) shows that houses connected to the same drop node tend to exhibit close voltage profiles, due to their proximity and similar electrical connections. Inspecting Fig. 2(c), temporary voltage violations are observed on LV Feeder 1 as voltages of H13, H18, H14, H17, H15 and H16 exceed the NR limit multiple times. The maximum detected voltage on the feeder belongs to H16 and is equal to 1.053 pu. It is worth noting that houses closer to the MV network (i.e., beginning of the feeder) exhibit less voltage variations, whereas houses farther from the

MV feeding point exhibit larger variations. For example, on LV Feeder 1, small voltage variations are observed at H11, H12, and H19, which are all connected at the distribution transformer, whereas the largest variations are observed for H15 and H16, as they are connected at the feeder end.

2) Volt-var with Default Settings

In this case study, PV inverters are equipped with volt-var function, thus injecting or absorbing reactive power based on the inverter terminal voltage. Fig. 3 shows a typical volt-var curve, where the points (V1, Q1) to (V4, Q4) define the inverter's reactive power behaviour. Furthermore, the user defines an open loop response time, which dictates the speed at which the reactive power changes in response to voltage variations. Table 1 presents the default and aggressive values of these parameters, as per IEEE 1547.1 [12]. Note that the inverters are assumed to be of Category B, with reactive power capacity of 0.44 pu (2.2 kvar).

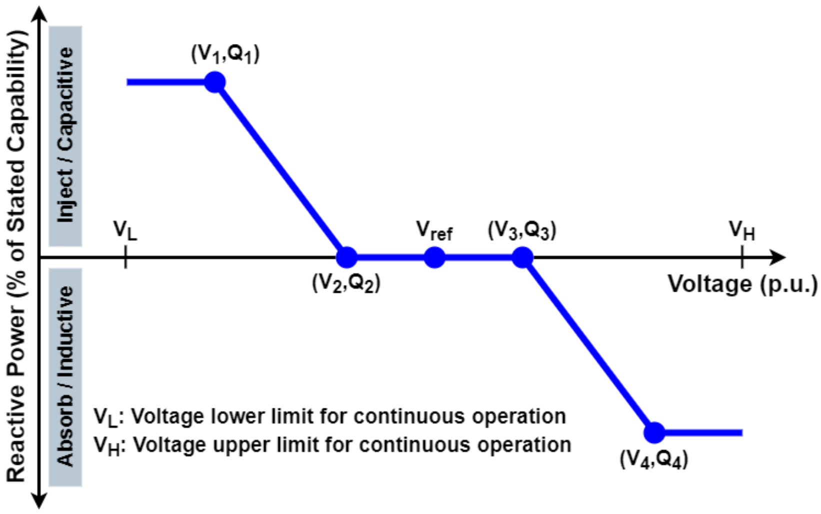


Fig. 3 Volt-var curve.

Table 1 Volt-var parameters

Setting	V1 (pu)	V2 (pu)	V3 (pu)	V4 (pu)	Q1 (pu)	Q2 (pu)	Q3 (pu)	Q4 (pu)	T (s)
Default	0.92	0.98	1.02	1.08	-0.44	0	0	0.44	5
Most Agg.	0.98	1.00	1.00	1.02	-0.44	0	0	0.44	1

Fig. 4 presents the simulation results of LV Feeder 1 with inverters implementing the volt-var function with Default settings. As seen from the results, the inverters start absorbing reactive power only when the voltage exceeds the dead band range (i.e., voltage > 1.02 pu), and the reactive power draw increases as the voltage increases. The reactive power, in turn, results in voltage reduction. Furthermore, when an inverter absorbs reactive power, its active power injection slightly decreases if it is operating at its capacity limit. This reduction in active power further reduces the inverter voltage at its terminals. Accordingly, the volt-var function successfully regulates some house voltages (Fig. 4(c)) within their NR limits. However, some houses (e.g., H14, H17, H15 and H16) still experience overvoltage beyond the NR limit.

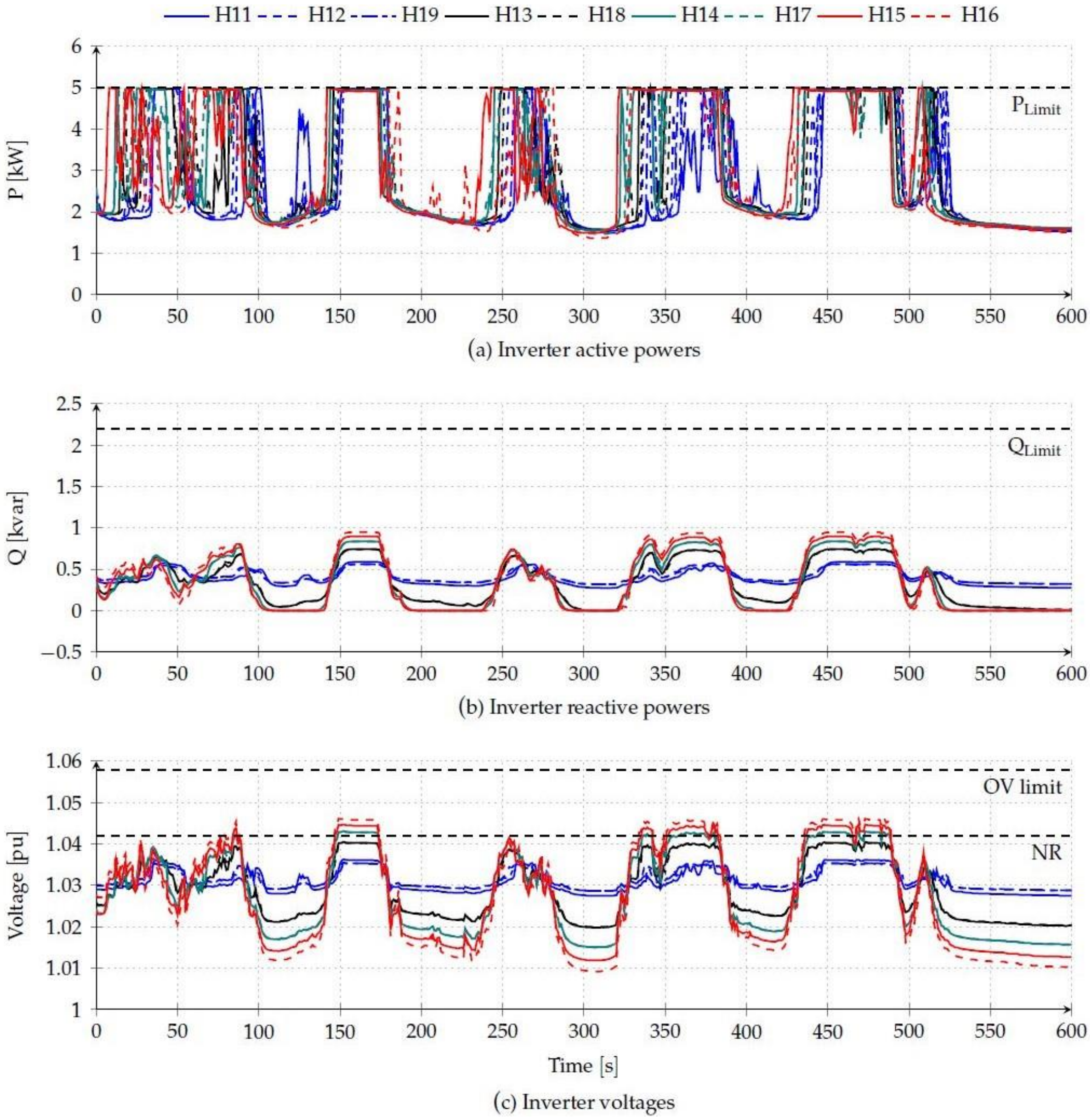


Fig. 4 Simulation results of LV Feeder 1 with PV inverters employing volt-var function with Default settings.

3) Volt-var with Aggressive Settings

With the volt-var function parameters set to the Most Aggressive values, the inverters respond to any deviation of voltage from the reference value, as the volt-var curve does not include a dead band. Furthermore, with the smaller V1, V4, and response time values, the reactive power changes more aggressively and rapidly with voltage variations, thus regulating the voltage more tightly. As seen Fig. 5(b), the reactive power magnitudes are much larger compared with default settings. Furthermore, the reactive power changes continuously with voltage variations. Therefore, the voltages are tightly regulated and do not exceed 1.02 pu. However, as observed in Fig. 5(a), larger portions of active powers are curtailed to free capacity for higher reactive powers. This increased curtailment of active powers further helps with voltage regulation, yet in the expense of active power delivery.

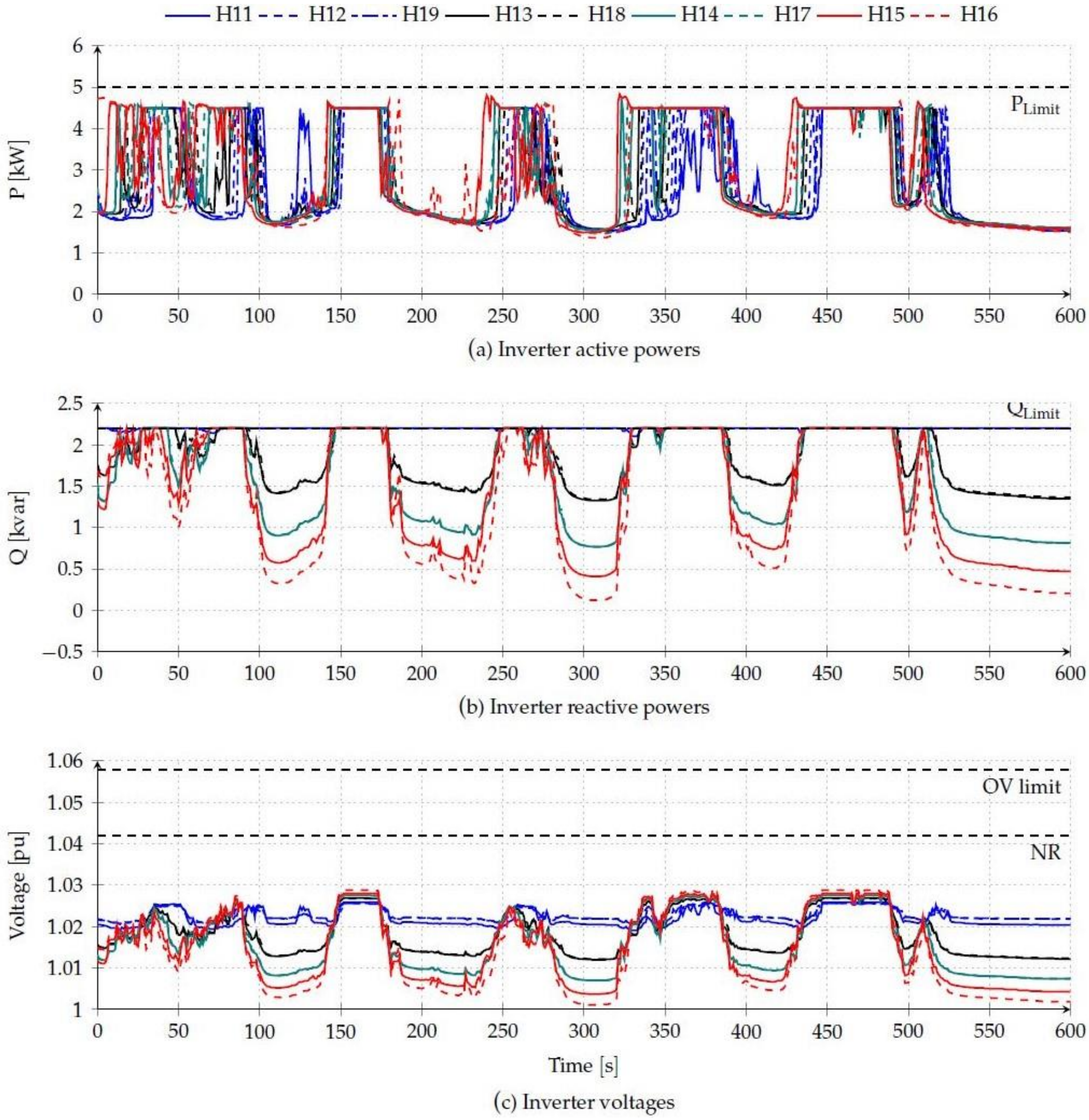


Fig. 5 Simulation results of LV Feeder 1 with PV inverters employing volt-var function with Most Aggressive settings.

IV. DISCUSSION AND CONCLUSIONS

This paper assesses the performance of PV inverters equipped with the volt-var function in a synthetic residential distribution network. The network is constructed at a location in the city of Varennes, Quebec, Canada, where measured solar irradiance data were collected. A sample of 10-minute data was selected to simulate the system under high solar irradiance variability. Different settings of the volt-var function were examined and compared with the base case of conventional distributed generators (DGs) operating at unity power factor.

The results demonstrate that the volt-var function with aggressive settings shows the best voltage regulation. However, the aggressive settings result in active power curtailment to accommodate the increased reactive power. On the other hand, volt-var function with default settings does not offer the same tight voltage regulation, but it regulates the voltages to a good extent. In addition, it would react more aggressively for more severe voltage violations. It also shows an advantage over aggressive settings in terms of active power curtailment.

It is worth noting that a period with highly variable solar irradiance was chosen to examine the inverters' behaviours under challenging conditions. However, both conventional and volt-var-equipped inverters demonstrated normal performance with no noticeable issues with their powers or voltage profiles. Nonetheless, in real-life, under such challenging conditions, some inverters might show maximum power point tracking (MPPT) issues that may introduce disturbances to the system.

This study provides a basic platform to examine the behaviours of AIFs in time domain, which is suitable for short time periods with detailed analysis. The work here can be extended to further analyze the performance of each AIF under various settings. Furthermore, different distribution networks can be considered to study the effect of the network configuration and X/R ratio on each AIF's performance.

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