Voltage Regulation in Distribution Systems using Distributed Energy Resources

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Voltage Regulation in Distribution Systems using Distributed Energy Resources

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Abstract- **There has been a growth in the development of Distributed Energy Resources (DERs) in recent years. However, further penetration of DERs is being limited by voltage rise problems caused by reverse power flows. The IEEE 1547 standard, the national standard for interconnection of DERs to the distribution grid, was amended in 2014 to allow DERs to provide voltage/ frequency regulation, which has led to the development of smart inverters with inverter reactive and frequency control modes. Due to the original IEEE 1547 standard's enforcement, most DERs still employ the unity power factor control strategy, and the voltage capability of DERs has not been widely used or studied. Therefore, this study evaluates the different reactive control modes and ranks them based on the Voltage Regulation Index, Overvoltage Instances, Maximum and Average Voltages, and the impact on the distribution system PV hosting capacity. The analysis is performed on a modified IEEE 13 bus distribution system, through six hundred seconds of quasi-steady-state simulation with a second-time step size using a changing irradiance profile. The simulation is carried out with the CYME software. The simulation results show that the Volt-VAR (Vars Precedence) control mode provides the best performance. In contrast, the Unity Power Factor control strategy provides the worst performance for all selected metrics.**

***Keywords*—Distributed Energy Resources, Inverter Reactive Control, Smart Inverters, Voltage Regulation**

I. INTRODUCTION

Distributed Energy Resources (DER) have been defined by the Electric Power Research Institute (EPRI) as small power energy sources that can be aggregated to supply power to regular consumers [1]. The National Electrical Manufacturers Association explained it as power sources usually smaller than typical utility power plants and are mostly positioned to demand centers [2]. The European Commission, in a report, presented DER's as small to medium-scale energy sources connected to the low voltage system or near customers [3]. This paper combines the three definitions and describes DERs as small to medium-scale power sources aggregated and connected to the low voltage distribution system to supply power to customers. Various examples of DERs are solar photovoltaic (PV) panels, wind turbines, battery energy storage systems, combined heat and power plants, small diesel or natural gas engines, fuel cells, and controllable loads [4], [5].

In recent years, there has been a sharp increase in the development of some of these DERs, such as solar PVs, with the installed capacity increasing by almost ten times since 2010 and reaching 508.1 GW by 2019 [6]. In the United States, the consumption of some of these DER's such as solar and wind energy, is nearly three times greater than in 2000, accounting for about 17% of total electricity generation [7]. However, further penetration of DERs, such as PVs, is limited by voltage rise problems caused by reverse power flows [8]-[10]. Various ideas to address the voltage rise problems have been proposed, such as using On-Load Tap Changing (OLTC) Transformers, Capacitor Banks, and Step Voltage Regulators (SVR) [11], [12]. Some of these devices' operations could affect other sections of the system's voltage profiles and may be slow to operate. The intermittency of the PV systems could lead to excessive operations of OLTCs, SVRs, and Capacitor Banks [13], which could negatively impact these devices.

Some standards have been issued in other jurisdictions such as Germany and France to regulate DER's integration [14]. In the United States, California, the state with the highest PV penetration [4], has updated its interconnection requirements to govern and facilitate the integration of PVs [15]. The IEEE 1547 Series of Standards for Distributed Resources Interconnection and Interoperability with the Grid is the only American National Standard that regulates the interconnection of DERs with the distribution grid and has had a tremendous influence on how the industry operates [16]. The first version of the IEEE 1547 Standard did not require DER's to provide voltage or frequency regulation. This led to DER's operating in the Unity Power Factor, where the DER's only provided active power to the grid. In 2014, the standard was amended to allow DER's participation in voltage and frequency regulation in coordination with, and approval of the system operators [2].

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This has led to the development of smart inverters that can operate in different control modes to provide voltage and frequency regulation. The voltage regulation modes are Fixed Power Factor (FPF), Volt-Var (VV) Control, and Volt-Watt (VW) Control, while the Frequency-Watt Mode provides frequency regulation support [18]. Even though smart PV inverters providing voltage control through the generation of reactive power is one of the easiest and economical ways to solve the voltage rise issue [13], the unity power factor strategy is still the most common strategy[4] due to the enforcement of the original IEEE 1547 standard. The voltage capability of the smart inverter DERs has also not been widely used and studied.

Therefore, this paper evaluates the voltage regulation performance of the Smart Inverter's various control modes to provide guidelines on the effectiveness of the methods using the Voltage Regulation Index metric. Analysis of different PV penetration levels is carried out to evaluate the control modes performance on the grid's hosting capacity considering system voltages. Ten minutes' worth of one-second irradiance measurement data was used to simulate irradiance fluctuations. A quasi-steady simulation employing one second time step for the ten minutes is run. Based on the simulation results, the FPF, VV, and VW control modes are evaluated. The case study is a modified IEEE 13-bus test feeder with four PV systems added to the unbalanced system. The paper has been organized as follows: Section 2 discusses the different types of inverter reactive control modes. The Case Study and Simulation results are presented in Section 3, and based on those results, conclusions and guidelines will be drawn in section 4.

II. INVERTER REACTIVE CONTROL MODES

This section explains the logic and characteristics of the three inverter control modes:

A. Fixed Power Factor (FPF)

For the FPF control, the PV system's power factor is set to a fixed value that does not consider the system parameters. From IEC 61850, the power factor is in the range of -1.00 to +1.00. A power factor of +1 or -1 is termed as Unity Power Factor, and both parameters allow the PV system to produce only watts with no vars. The standards do not allow the power factor to be set to zero. The power factor value sign determines whether the inverter operates in capacitive mode or lagging mode, dependent on the convention used [17].

The inverter can regulate the power factor by either producing/ curtailing reactive power or regulating real power [4]. The different power factor quadrants showing the real and reactive power injection/ absorption are illustrated in Fig 1 [17].

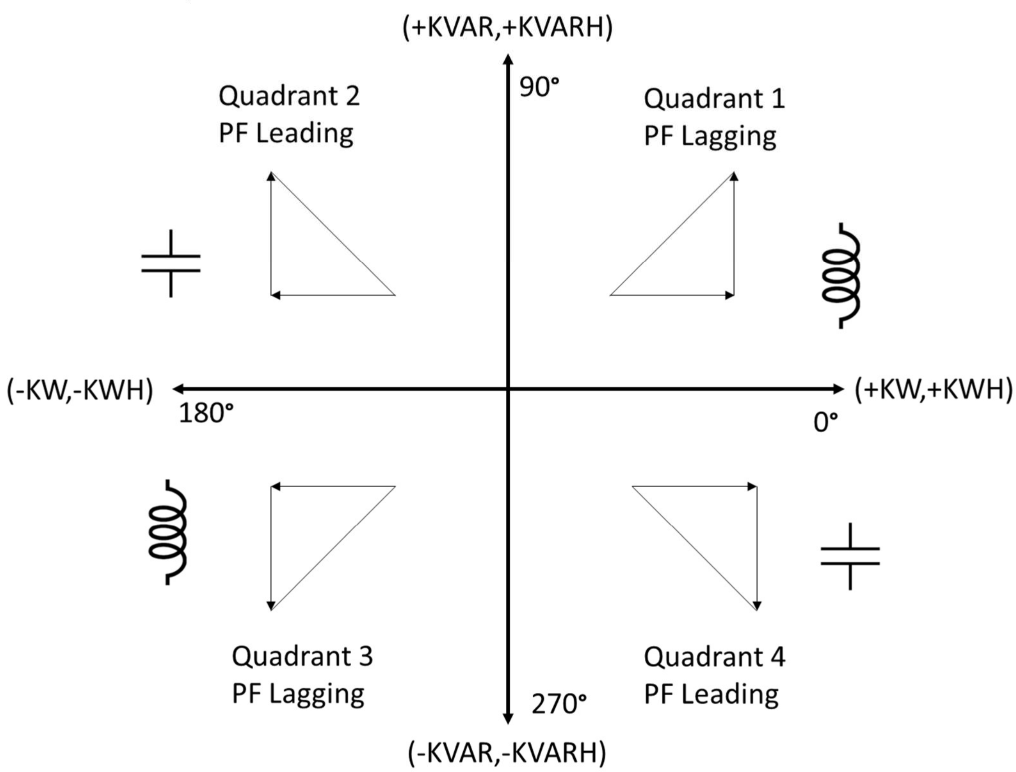

Figure 1. Operating Quadrants in FPF control strategy [17]

B. Volt-Var

The Volt-Var control function changes the reactive power output of the DER as a response to the local service voltage. For this control strategy, if the voltage at the point of common coupling falls below a specified level, reactive power is injected into the system to increase the voltage. Also, if the voltage goes above a specified level, reactive power is absorbed from the system. The way this is done is determined by the volt-var curve configured for that system and illustrated in Fig. 2. The volt-var control function could operate in either the Vars Precedence or Watts precedence mode. The vars precedence mode means that priority will be given to producing requested vars over watts if the inverter's apparent power limit is exceeded while the watts precedence mode works vice versa. In some scenarios, it is desired to employ hysteresis in Volt-Var settings [17].

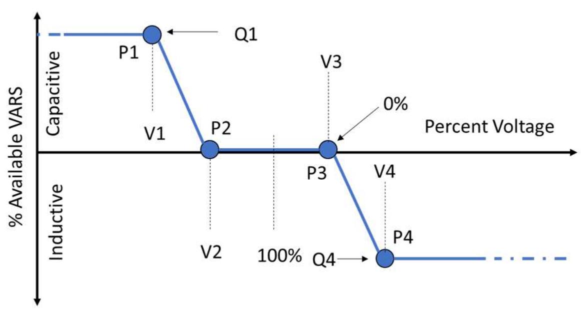

Figure 2. Volt-Var Control Strategy Curve Characteristics [17]

C. Volt-Watt

The Volt-Watt control function changes the DER's active power output in response to the local service voltage. If the local service voltage is in a high range, the active power output is reduced. There is a maximum voltage upper limit at which the PV generates no power at all. This is based on the volt-watt curve, an example shown below, configured for that inverter. Depending on the curve chosen, the voltage regulation performance desired could be achieved. The curve in Fig. 3 shows that the PV produces maximum power if the voltage is below 100% or above 100% but below V2. From V2 to V3, the power to be generated would be determined by the line. For voltage V3 and above, no power is generated at all. This control function is beneficial when there is a high PV generation but a low load, which cannot be prevented by other existing distributing controls [17].

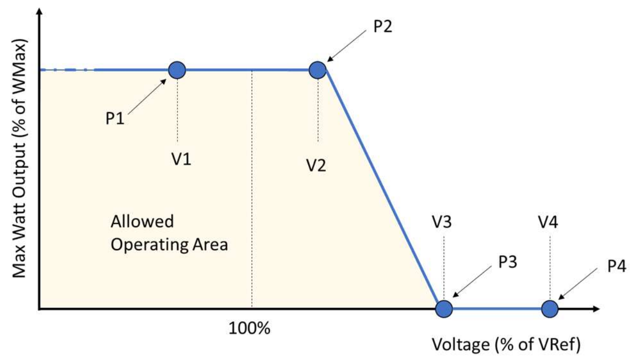

Figure 3. Volt-Watt Control Strategy Curve Characteristics [17]

III. CASE STUDY AND RESULTS

This paper's case study is a modified IEEE 13 bus test feeder, which is supplied by a 115/4.16kV transformer. The buses operate at a nominal voltage of 4.16kV and have a maximum active power connected load of approximately 3600KW. Four 3-phase PV generators are connected to buses 634,671,675 and 692. The generators were connected to three-phase nodes, which have loads connected to it. The PV generator's capacity connected to each bus for the different penetration levels is shown in Table 1. To evaluate the controls' voltage performance, one-second step size quasi dynamic steady-state simulations are performed for 10 minutes, 600 seconds, of operation. The simulation is performed with the CYME software and uses a fluctuating irradiance profile for testing smart inverter controls for the 600-second time-space. The solar irradiance profile, Fig 4, simulates changing solar irradiance with an irradiance of 0 W/m2 and 1252 W/m2 at another point within the 600 seconds time frame.

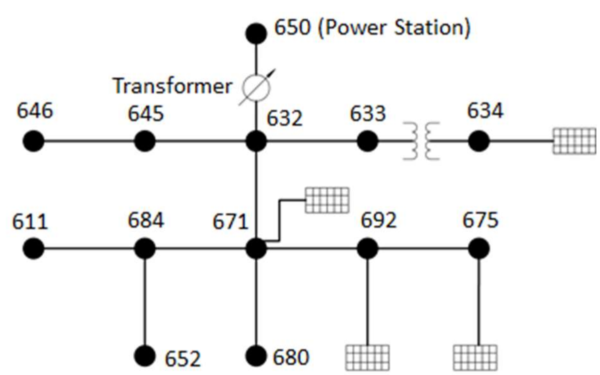

Figure 4. Modified IEEE 13 Bus Network

Table 1. PV CAPACITY CONNECTED FOR DIFFERENT PENETRATION LEVELS

Bus	No PV	25%	50%	75%	100%
634	0	225 kW	450 kW	675 kW	900 kW
671	0	225 kW	450 kW	675 kW	900 kW
675	0	225 kW	450 kW	675 kW	900 kW
692	0	225 kW	450 kW	675 kW	900 kW

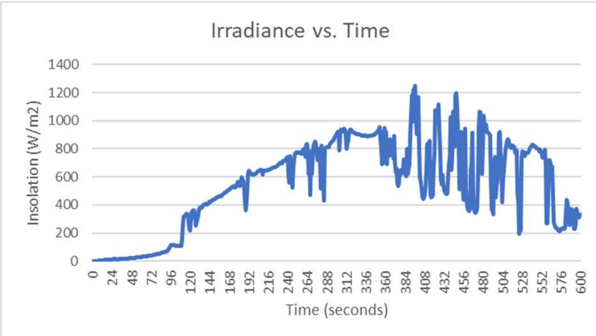

Figure 5. Irradiance Profile for Simulation Time

A. Control Strategy Mode Scenarios

This study evaluated the control strategies in this study: the FPF, Volt-Var, and Volt-Watt. 6 control strategy modes were evaluated. The FPF (Unity), FPF (0.9 Leading), FPF (0.8 Leading), Volt-Var (Watts Precedence), Volt-Var (Vars Precedence), and Volt-Watt method. The configurable curves used, adopted from the CYME software, for the Volt-Var and Volt-Watt modes are shown respectively in Fig 5 and Fig 6.

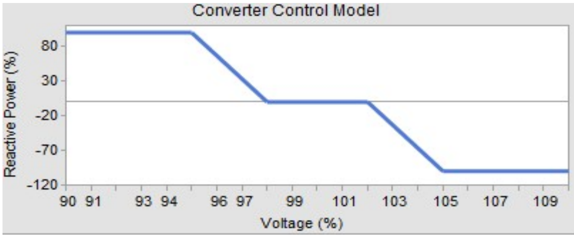

Figure 6. Volt-Var Configurable Curve

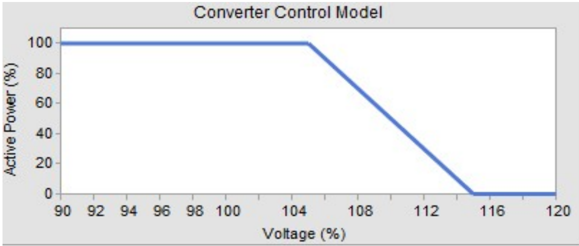

Figure 7. Volt-Watt Configurable Curve

B. Voltage Performance Evaluation Metrics

To evaluate the voltage regulation performance of the various control strategy modes, four metrics were used. The Voltage Regulation Index, Overvoltage, and Maximum and Average Voltages of the system.

A cost function referred to as the Voltage Regulation Index (VRI) was adopted [4]. The VRI is calculated as follows:

$$VRI = \sum_{t=1}^{t=T} |\, V(t)_{PU} - 1|$$

T is the simulation time, in this study, 600 seconds, and V(t) pu is the per-unit voltage. The absolute values of the voltage deviations from the per-unit voltage, 1, are summed for the simulation time—the lower the VRI, the better the voltage regulation performance.

An overvoltage is any second-time size simulation voltage which is above 1.05 pu, the maximum allowable voltage. The number of overvoltage instances for the simulation of 600 seconds is summed for the three phases leading to a maximum of 1800 overvoltage instances or a minimum number of 0 instances. If the number of overvoltage situations is 1800, it means that for every second-time step simulation, the voltages on all the phases were above 1.05 pu. Lower overvoltage instances show a better voltage regulation performance.

The maximum voltage is the highest recorded over the 600-second frame per phase. In contrast, the average voltage is the average over the 600-second frame - the lower the voltages, the better the performance of the inverter control mode in handling the voltage rise issue, and the better voltage regulation performance.

C. Results

The VRI, overvoltage, maximum, and average voltage situations are computed for the six control strategy modes and a no PV case. The simulation results are summarized in Figures 8-17 and Table 2. The results are arranged to show trends. The different penetration levels did not show any change in trends; select results are shown to show the trends. The performance of the control strategies is ranked according to the voltage regulation metrics**.** The performance of the 0.9 and 0.8 power factor modes are evaluated as the PV penetration level increases and shown in graphs and tables below. The overvoltage situations, maximum, and average voltages for different penetration levels are shown in graphs and tables below.

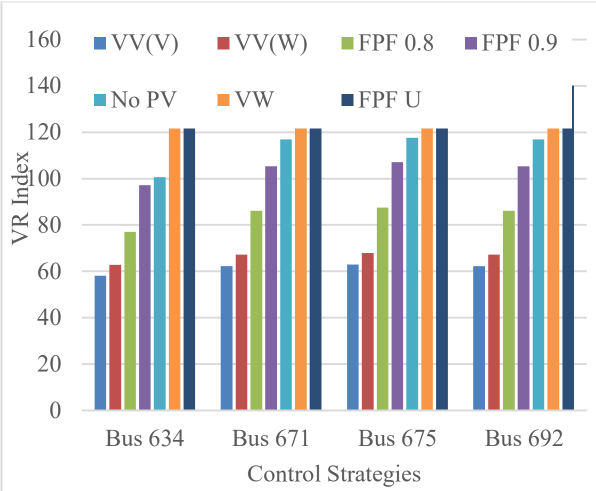

Figure 8. VRI for the Different Control Modes for 100% Penetration

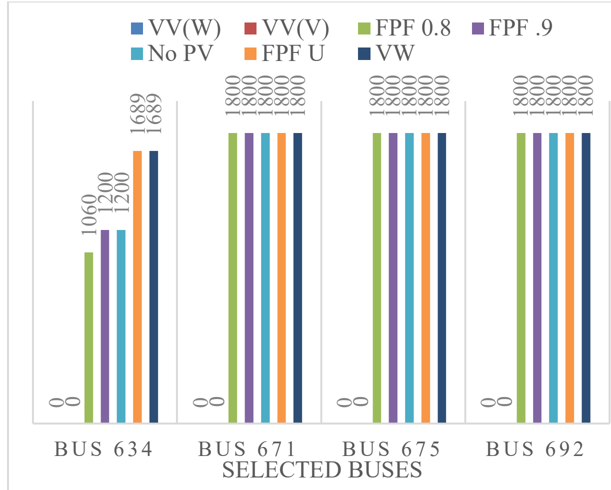

Figure 11. Overvoltage Instances at 25% PV Penetration

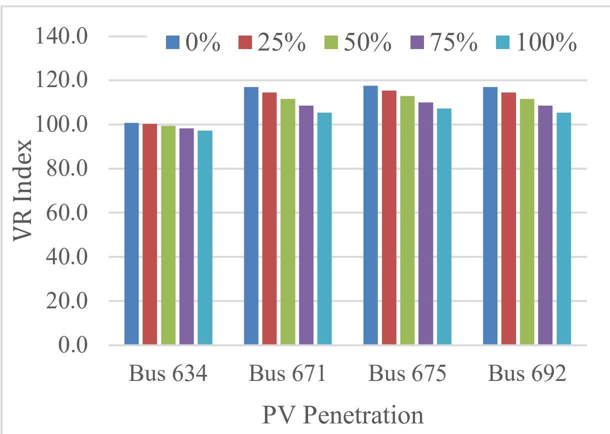

Figure 9. VRI for Different Penetration Levels for 0.9 Power Factor

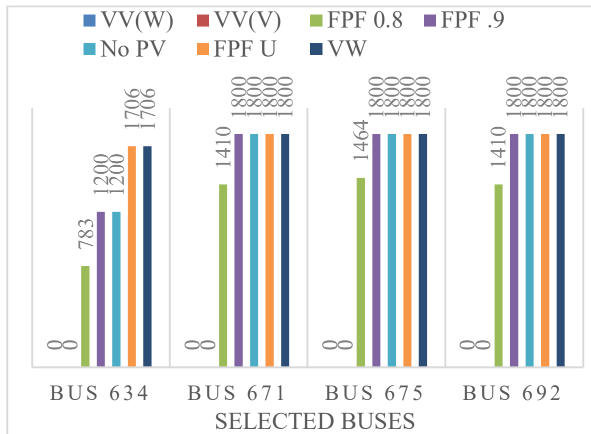

Figure 12. Overvoltage Instances at 50% PV Penetration

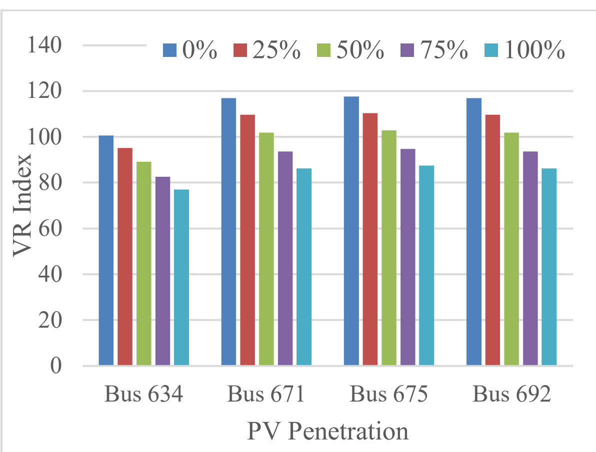

Figure 10. VRI for Different Penetration Levels for 0.8 Power Factor

Figure 13. Overvoltage Instances at 75% PV Penetration

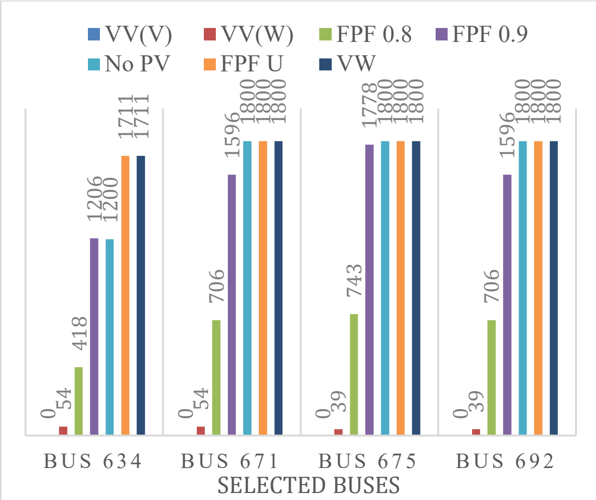

Figure 14. Overvoltage Instances at 100% PV Penetration

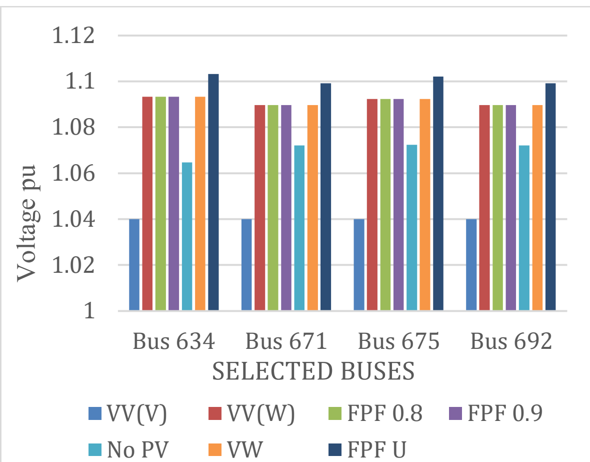

Figure 15. Maximum Voltages for Control Mode Scenarios at 100% PV Penetration

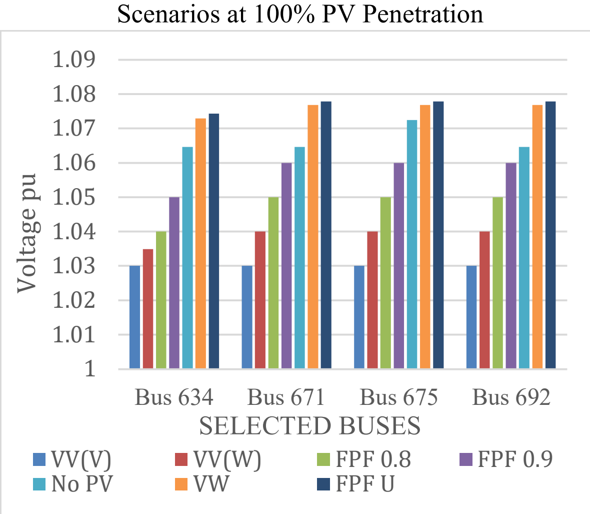

Figure 16. Average Voltages for Control Mode Scenarios at 100% PV Penetration

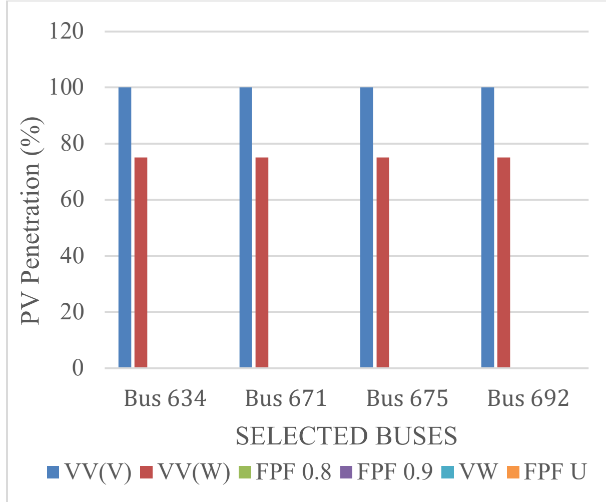

Figure 17. Allowable PV Penetration for Control Mode Scenarios at 100% PV Penetration

Table 2. SUMMARY OF RESULTS FOR BUS 634

Bus 634	**VR Index**			
Control Strategies	**25%**	**50%**	**75%**	**100%**
FPF U	109.4	117.8	125.9	133.7
FPF 0.9	100.2	99.4	98.3	97.2
FPF 0.8	95.1	89.1	82.6	77.0
Volt-Var (Watts)	51.5	54.5	57.7	62.8
Volt-Var (Vars)	51.4	53.9	56.0	58.1
Volt-Watt	109.3	117.3	124.7	131.3

D. Discussions

Based on the results, we see that the Volt-Var (Vars precedence) provided a better voltage performance than the other control modes. According to the Voltage Regulation Index Metric, both the Volt-Var, Watts, and Vars precedence, the 0.8 Fixed power factor performed better than the case with no PV for all penetration levels. Decreasing the fixed power factor from 1.0 to 0.9 and further to 0.8 reduced the VRI, which shows a better voltage regulation performance. We achieve a lower VRI for the fixed power factor settings as the PV penetration increases. For FPF control, regardless of the local service voltage, reactive power is either injected or absorbed from the system, resulting in unwanted voltage deviations.

We also see that the initial system voltage affects the number of overvoltage instances. Depending on how close the system voltage is to the set target voltage of 1.05, some control strategies may perform better than others. We can also see that both volt-var control strategies perform better than other control strategies. As the penetration level increases, the 0.9 and 0.8 power factors have better overvoltage performances.

The volt-var (vars precedence) achieves a lower maximum voltage than the no PV system. It is also noted that all the control strategies used with their current configurable curves produce a better result than the unity power factor control strategy. This could be important in the interconnection of PV systems to a grid where at 100% penetration, the volt-var (vars precedence) is below the maximum allowable voltage of 1.05 pu, which the case study before the connection of the PV's was operating over.

Even though the volt-var (watts precedence) did not show a good performance concerning the maximum voltage, it achieves around the same average voltage as the Volt-Var (Vars precedence). The same trend is noted on all the buses with PV's connected.

Because the Volt-Var (Vars precedence) control can achieve a lower maximum voltage, the allowable PV penetration for the system could be up to 100%. The Volt-Var (Watts precedence) achieved about 75 % penetration while the other control strategies cannot host any amount of PV penetration.

Due to the initial high voltages of the IEEE 13 bus, most of the control strategies could not reduce the voltages below the initial values. This affects the hosting capacity of the network and leads to higher voltages on the network.

IV. CONCLUSION

In this study, the smart inverters' voltage capability performance is evaluated by adding 4 PVs to the IEEE 13-bus feeder. A fluctuating irradiance profile of 600 seconds and configurable curves for the Volt-Var and Volt-Watt Control is obtained from the CYME Smart Inverters module and used for the performance evaluation. The results are evaluated based on the Voltage Regulation Index, Overvoltage situations, and the buses' maximum and average voltages. From the simulation results, we note that:

- Volt-Var (Vars Precedence) provides the best voltage regulation performance
- Volt-Var Control allowed a higher PV penetration
- Performance of the Control Strategies depends on the initial system voltage
- Non-Unity FPF provides better voltage regulation at higher penetration
- For the same configurable curve, Volt-Var (Vars) produces better results than Volt-Var (Watts)
- Unity Power Factor produced the worst voltage regulation performance

Future work could evaluate the impact of the different configurable curves and setting of power factor limits on the performance of the Volt-Var Control.

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